Sediment-Quality Assessment of Franklin D. Roosevelt Lake and the Upstream Reach of the Columbia River, Washington, 1992

U.S. GEOLOGICAL SURVEY
Open-File Report 94-315

Prepared in cooperation with
U.S. ENVIRONMENTAL PROTECTION AGENCY

U.S. DEPARTMENT OF THE INTERIOR
MARCH 3, 1849

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By G.C. Bortleson,* S.E. Cox,* M.D. Munn,* R.J. Schumaker,** E.K. Block,***
L.R. Bucy,** and S.B. Cornelius**

* U.S. Geological Survey
** Washington State University
***U.S. Fish and Wildlife Service

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BRUCE BABBITT, Secretary

U.S. GEOLOGICAL SURVEY

Gordon P. Eaton, Director

For additional information write to:

District Chief
U.S. Geological Survey
1201 Pacific Avenue - Suite 600
Tacoma, Washington 98402

Copies of this report may be purchased from:

U.S. Geological Survey
Earth Science Information Center
Box 25286, MS 517
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CONVERSION FACTORS, VERTICAL DATUM, AND ABBREVIATIONS

[SI = International System of units]

Multiply	*By*	*To Obtain*
Inch-pound to International system units		
foot (ft)	30.48	centimeter
foot (ft)	0.3048	meter
foot per second (ft/s)	0.3048	meter per second
cubic foot per second (ft^3/s)	0.02832	meter per second
square foot (ft^2)	0.09290	square meter
mile (mi)	1.609	kilometer
acre	0.4047	hectacre
acre-foot (acre-ft)	43,560	cubic feet
pound (lb)	0.4536	kilogram
pound per day (lb/d)	0.4536	kilogram per day
ton	0.9078	tons (metric)
gallon (gal)	3.785	liter
gallon (gal)	.003785	cubic meter
million gallons per day (Mgal/d)	0.04381	cubic meter per second

CONVERSION FACTORS, VERTICAL DATUM, AND ABBREVIATIONS--Cont.

Multiply	*By*	*To Obtain*
International system units to inch-pound units		
micrometer (µm)	0.003937	inch
millimeter (mm)	0.03937	inch
square meter (m^2)	10.76	square foot
grams per second (g/s)	.002205	pounds per second
grams per second (g/s)	190.5	pounds per day
milligrams per day (mg/d)	$.002205\text{x}10^{-3}$	pounds per day
liter per second (L/s)	15.85	gallons per minute
Factors for converting SI metric units to other miscellaneous units		
	Concentration, in water	
milligrams per liter (mg/L)	1	parts per million
micrograms per liter (µg/L)	1	parts per billion
picograms per liter (pg/L)	1	parts per quadrillion
	Concentration, in bed sediment	
milligrams per kilogram (mg/kg)	1	parts per million
micrograms per gram (µg/g)	1	parts per million
micrograms per kilogram (µg/kg)	1	parts per billion
picograms per gram (pg/g)	1	parts per trillion

Temperature: To correct temperature given in this report in degrees Fahrenheit (°F), to degrees Celsius (°C), use the following equation: °C = 5/9(°F-32)

Sea Level: In this report "sea level" refers to the National Geodetic Vertical Datum of 1929 (NGVD of 1929)--a geodetic datum derived from a general adjustment of the first-order level nets of both the United States and Canada, formerly called Sea Level Datum of 1929.

Electrical conductivity is measured as specific electrical conductances, in units of microsiemens per centimeter (µS/cm) at 25 degrees Celsius.

Abbreviations

DDE	dichlorodiphenyldichloroethylene
DDT	dichlordiphenyltrichloroethane
PCB	polychlorinated biphenyl

SEDIMENT-QUALITY ASSESSMENT OF FRANKLIN D. ROOSEVELT LAKE AND THE UPSTREAM REACH OF THE COLUMBIA RIVER, WASHINGTON, 1992

By G.C. Bortleson, S.E. Cox, M.D. Munn, R.J. Schumaker, E.K. Block, L.R. Bucy, and S.B. Cornelius

ABSTRACT

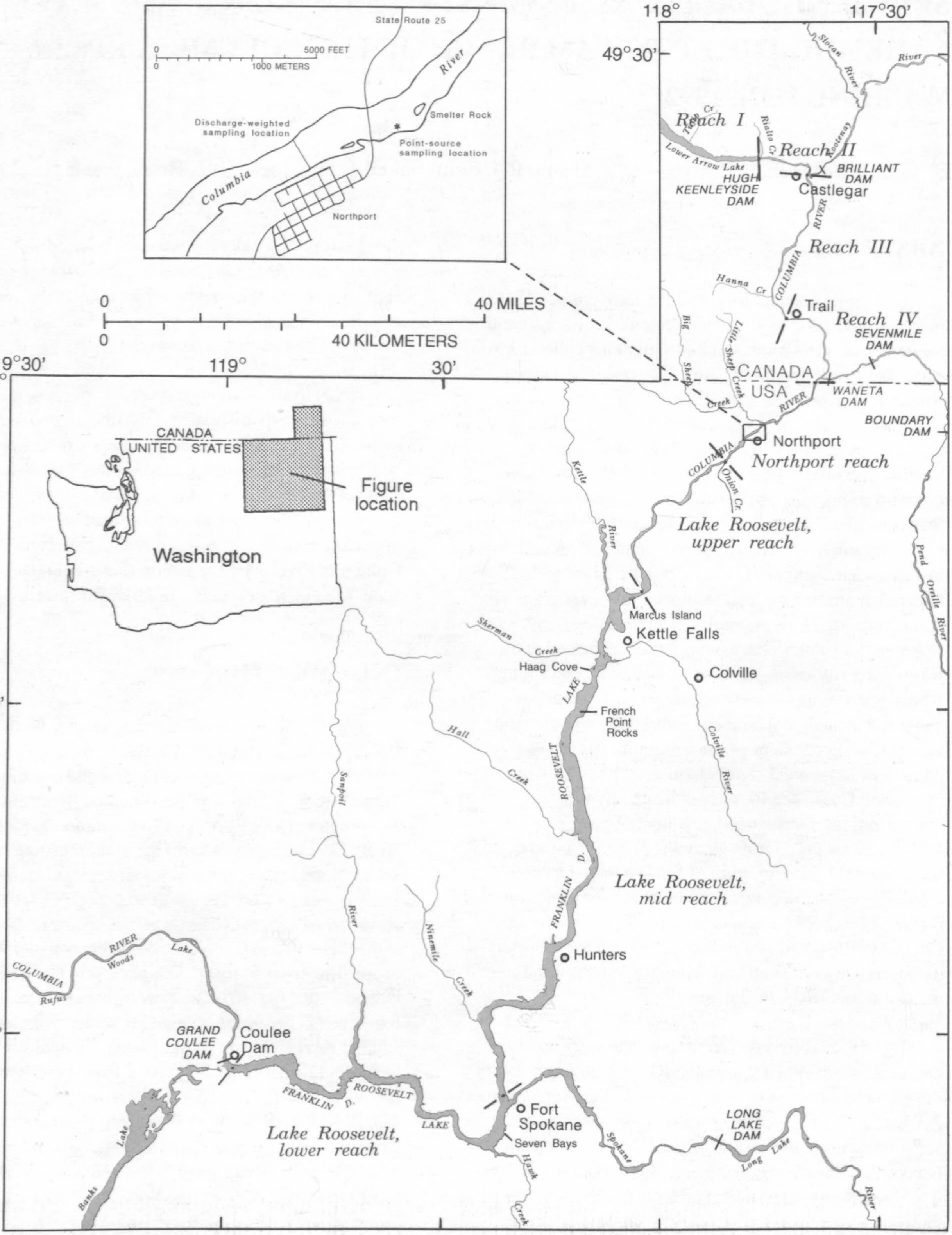
Concentrations of arsenic, cadmium, copper, lead, mercury, and zinc were elevated relative to background reference sites in samples of bed sediments collected from Lake Roosevelt and the Columbia River, its principal source of inflow. The trace elements that most often exceeded the sediment-quality guidelines developed by the Ontario Ministry of Environment and Energy for benthic organisms were copper, lead, and zinc. Median concentrations of copper, lead, and zinc in the bed sediment of Lake Roosevelt were 85, 310, and 970 milligrams per kilogram, respectively. Trace-element concentrations in suspended sediment in the Columbia River were larger than concentrations in bed sediment; however, trace-element concentrations in whole-water samples (suspended-sediment and water phases) did not exceed criteria for fresh-water organisms. Trace-element concentrations in whole-water samples were relatively small, reflecting the small suspended-sediment concentrations and the large water-diluting capacity of the Columbia River. The paucity of suspended sediment in the extensively dam-controlled Columbia River is indicated by the small concentration of suspended sediment of only 2 to 19 milligrams per liter measured for river discharges at high flows since completion of the last major reservoir in 1976. Elevated concentrations of trace elements in sediments of Lake Roosevelt and the upstream reach of the Columbia River are largely attributable to the transport of metallurgical waste and slag from a smelter discharging to the Columbia River in Canada.

Dioxins and furans were in both the suspended sediment and water of the Columbia River, but only a few of the 17 targeted isomers were detected. The dioxin isomer 2,3,7,8-tetrachlorodibenzo-*p*-dioxin, the most toxic to some laboratory animals, was not detected. The furan isomer 2,3,7,8-tetrachlorodibenzofuran, commonly found in effluent from pulp and paper mills that use chlorine in the bleaching process, was found in suspended sediment but not in the water phase. Octachlorodibenzo-*p*-dioxin was detected in suspended sediment and water phases, suggesting that atmospheric deposition contributes to dioxins found in Lake Roosevelt. Aside from dioxins and furans, few of the many other organic compounds associated with wood-pulp waste, urban runoff, and industrial activities were detected in the bed sediments of Lake Roosevelt and its major tributaries.

An analysis of benthic invertebrate communities in the Columbia River showed evidence of environmental stress, most likely due to the presence of trace elements in bed sediments or from the loss of physical habitat from slag deposition. Lethal and sublethal effects were observed in laboratory toxicity tests of selected aquatic organisms exposed to bed sediments collected from the Columbia River near the international boundary and from some sites in other reaches of Lake Roosevelt.

INTRODUCTION

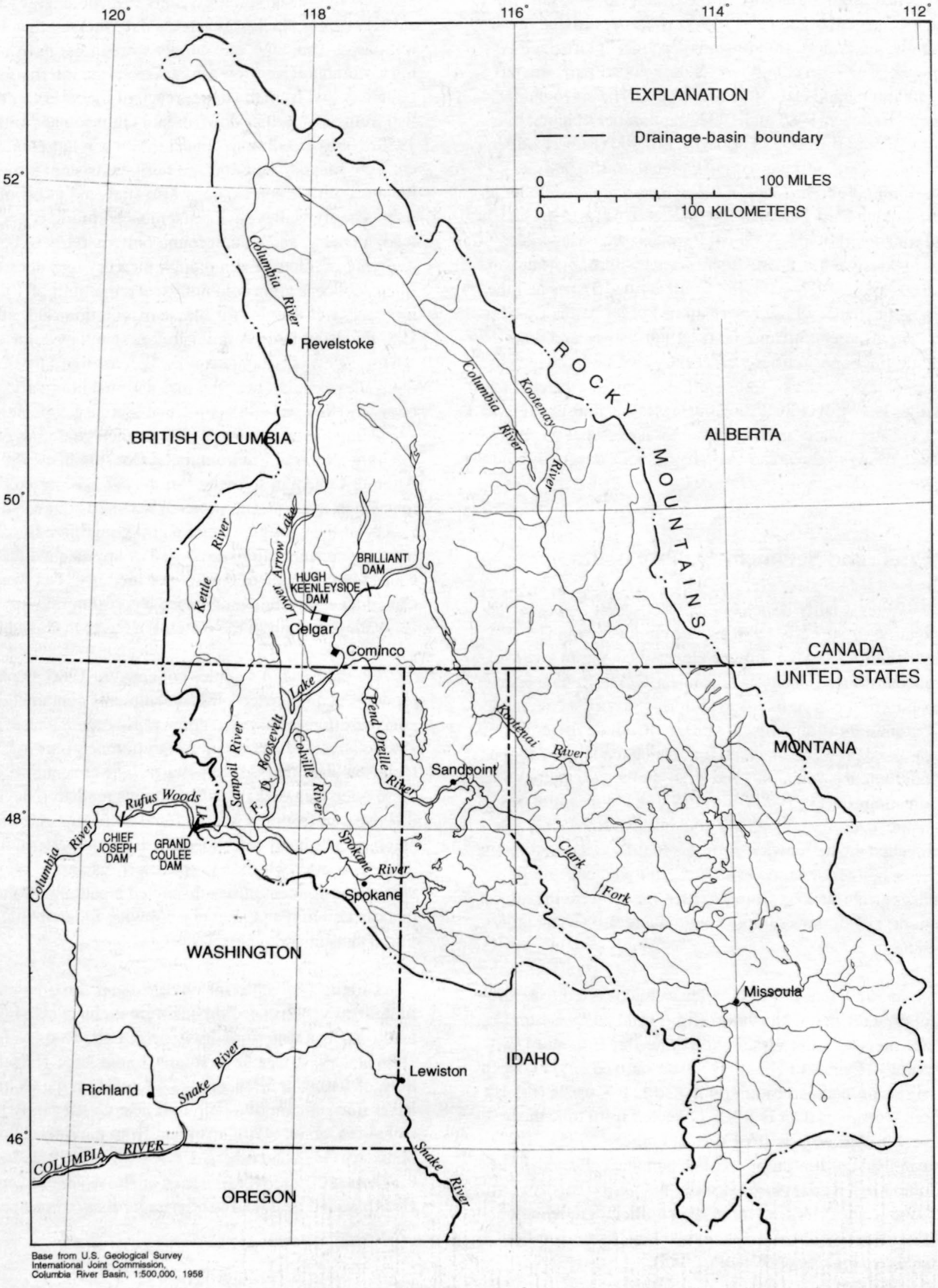
Franklin D. Roosevelt Lake, a reservoir formed on the Columbia River by Grand Coulee Dam, is the largest reservoir, by volume, in Washington and one of the largest in the Nation in total storage. Located in north-central Washington, Lake Roosevelt (its common name) extends about 135 mi upstream from the dam, reaching to within 15 mi of the international boundary with Canada (fig.1), and has a surface area of about 80,000 acres and a full pool elevation of 1,289 ft. The principal inflow to the reservoir is the Columbia River, which contributes about 90 percent of the flow from a large drainage area in Canada and the United States (fig. 2). The flow upstream from Lake Roosevelt is regulated by nine large reservoirs and many smaller reservoirs and power plants. In addition to the Columbia River, four other rivers flow directly to the lake—the Kettle, Colville, Spokane, and Sanpoil Rivers. The Pend D'Oreille River flows into the main stem of the Columbia River just north of the international boundary. The lake is bounded by the reservations of the Colville Confederated Tribes and the Spokane Tribe and by Ferry, Stevens, and Lincoln Counties (pl. 1).



Base from U.S. Geological Survey
Washington State base map, 1:500,000, 1982

Canadian portion is based on information from the National Topographic System map sheet number NTS 82-5 Nelson, edition 3 copyright 1986. Her Majesty the Queen in Right of Canada with permission of Energy, Mines and Resources Canada, 1:250,000

Figure 1.--Location of the Franklin D. Roosevelt Lake study area and the boundaries of the reaches on the Columbia River and the reservoir. The inset shows the location of sampling sites on the Northport reach.



Base from U.S. Geological Survey
International Joint Commission,
Columbia River Basin, 1:500,000, 1958

Figure 2.--Drainage basin of Lake Roosevelt.

The original purpose of the Grand Coulee Dam, built in the late 1930's and early 1940's, was to provide irrigation water, control flooding, and produce hydroelectric power. The reservoir, however, developed into a major recreational and economic resource for the surrounding area. Between 1985 and 1992, the number of annual visitors increased from 519,000 to 1,140,000 (Robert Miller, National Park Service, Grand Coulee, Wash., oral commun., February 1993). Lake Roosevelt is included in the Coulee Dam National Recreation Area (pl. 1), which is administered by the National Park Service. Many lake residents own businesses such as sport shops, marinas, and campgrounds. The Colville Confederated Tribes and the Spokane Tribe, whose reservations border parts of the reservoir, also benefit from the reservoir fishery and other economic opportunities. In recent years, with the increase in popularity of Lake Roosevelt as a recreation area, the Tribes have developed such businesses as houseboat rentals. Water quality is an important issue to visitors and to those living in the area whose livelihoods depend on the lake.

Water- and Sediment-Quality Issues

Water-quality issues in Lake Roosevelt first received attention in the early 1980's when studies by the U.S. Fish and Wildlife Service showed elevated cadmium and lead concentrations in fish collected near Grand Coulee Dam. As part of the U.S. Fish and Wildlife Service's National Contaminant Biomonitoring Program, whole fish collected near the dam were analyzed for arsenic, cadmium, copper, lead, mercury, selenium, and zinc. In the two nationwide collections during 1978-79 and 1980-81, concentrations of arsenic, cadmium, lead, and zinc in Lake Roosevelt fish exceeded the nationwide 85th- percentile concentration for one or both collection periods. Cadmium concentrations in largescale suckers from Lake Roosevelt were the largest among 112 stations sampled nationwide (Lowe and others, 1985).

In 1984, fish-tissue samples were collected from the Columbia River at Northport (fig. 1) and analyzed for trace metals by the Washington State Department of Ecology (Ecology). Ecology's data showed larger concentrations of lead and cadmium in edible fish tissue (fillets) from Northport than in fillets collected from nine other rivers in Washington (Hopkins and others, 1985). The mean lead concentration in fillet samples collected at the Columbia River at Northport was 6.4 μg/g. This concentration is about 90 percent of the unofficial guideline of 7.0 μg/g set by the U.S. Food and Drug Administration (cited by Hopkins and others, 1985).

In 1986, when Ecology analyzed whole largescale suckers from Lake Roosevelt, its data showed that concentrations of lead, zinc, and copper were larger in fish from the Columbia River downstream from the international boundary and from the upper reach of the reservoir than in fish from sites farther downstream (Johnson and others, 1989; 1990). Cadmium concentrations in largescale suckers were found to be large and fairly consistent throughout the reservoir. When Ecology also analyzed fillets of sportfish—chiefly walleye—for arsenic, cadmium, copper, lead, mercury, and zinc, it found only mercury to be accumulating in fillets. Even though mercury was detected in fillets, concentrations did not exceed the limit of 1 μg/g of mercury (wet weight) for food consumption set by the U.S. Food and Drug Administration (cited by Johnson and others, 1989). Canadian studies showed that 11 percent of the walleye caught near the international boundary between 1980 and 1988 contained mercury concentrations exceeding the Health Protection Branch guideline of 0.5 μg/g (Norecol Environmental Consultants, 1989). Another Canadian study by Smith (1987) reported that mean mercury concentrations in northern squawfish exceeded the 0.5 μg/g (wet weight) guideline. Because mercury concentrations exceeded or approached the Canadian guideline of 0.5 μg/g of mercury (wet weight), Canadian authorities established a consumption advisory for walleye caught in the Columbia River in Canada.

On the basis of samples collected in 1986, Ecology reported that the reservoir bed sediments contained large concentrations of arsenic, copper, iron, manganese, and zinc relative to concentrations at reference sites in Canada (Johnson and others, 1989; 1990). The concentrations of these trace elements in bed sediments tended to decrease downstream from the international boundary. Cadmium and mercury, however, showed a different pattern, having the largest concentration in the lower reaches of the reservoir. Lead concentrations displayed a pattern similar to that of cadmium and mercury but with wider spatial variation (Johnson and others, 1989).

Dioxins (polychlorinated dibenzo-*p*-dioxins) and furans (polychlorinated dibenzofurans) have also been identified as a water-quality issue in Lake Roosevelt. In 1988 and 1990, Canadian studies found large concentrations of furans in fillets of lake whitefish in the Columbia River downstream of a pulp mill near Castlegar, British Columbia, about 30 mi upstream from the international boundary (Mah and others, 1989; Crozier, 1991). In 1992, the British Columbia Ministries of Environment and Health issued health advisories regarding consumption of lake whitefish and mountain whitefish caught in the Columbia River directly downstream of the pulp mill near Castlegar (Kirkpatrick, 1989).

In 1989, Ecology analyzed two sturgeon and two walleye fillets in Lake Roosevelt for dioxins and furans. The results were mixed. One of each species had dioxin and furan concentrations approaching those found in lake whitefish in Canada, but the other fish had small concentrations (Arthur Johnson, Washington State Department of Ecology, written commun., 1990). Ecology conducted subsequent surveys in 1990 to ascertain whether dioxins and furans had accumulated in fillets of sport fish and to determine, by analyzing whole largescale suckers, whether concentrations of dioxins and furans declined in a downstream direction. In 1990, when Ecology (Johnson, Serdar, and Magoon, 1991) analyzed dioxins and furans in six sportfish species—burbot, walleye, rainbow trout, kokanee, lake whitefish, and white sturgeon—it found elevated furan concentrations in lake whitefish and white sturgeon. In other species, furan concentrations decreased in this order: kokanee, rainbow trout, walleye, burbot. In most cases, the furan concentrations were one to two orders of magnitude larger than dioxin concentrations in fillets. Furan concentrations in whole largescale suckers generally decreased from the international boundary through Rufus Woods Lake, downstream from the Grand Coulee Dam (Johnson, Serdar, and Norton, 1991).

The U.S. Environmental Protection Agency (USEPA) conducted a nationwide survey of chemical residues in fish in 1986 and 1987. Compared with concentrations in fish from the nationwide survey, the concentrations of dioxins in fish from Lake Roosevelt ranked in the 55 to 80 percentile range, but furan concentrations were in the 75 to 100 percentile range (Johnson, Serdar, and Magoon, 1991; Serdar, 1993).

The findings of measurable concentrations of dioxins and furans in fish tissue and of elevated concentrations of metals in bed sediments in Lake Roosevelt in the mid-1980's prompted the formation of several citizen action groups, and ultimately the creation of the Lake Roosevelt Water Quality Council (Council). The Council, which includes members from Federal, State, and local governments, Indian tribes, and the public, was established to manage and coordinate water-quality studies on the lake and to prepare a Lake Water Quality Management Plan. Under the Council's direction, the Lake Roosevelt Water Quality Study was developed, with the goal of obtaining data needed to develop management strategies for the lake's protection. The Council established priorities for study goals, one of the highest being an assessment of the extent and significance of trace elements and wood-pulp-related compounds in sediments and of the effect these elements and compounds may have on benthic invertebrate communities.

The sediment-quality assessment study was done by the U.S. Geological Survey (USGS) in cooperation with the U.S. Environmental Protection Agency. The study included analysis of trace elements and organic compounds in the sediments, bed-sediment toxicity, and benthic community structure in Lake Roosevelt and the upstream reaches of the Columbia River to the international boundary (fig. 3). The data-collection phase of this study (September and October 1992) was coordinated with two other data-collection programs, one in the same study area by Ecology and the other in the lower reaches of the Columbia River upstream from the international boundary in British Columbia by the Columbia River Integrated Environmental Monitoring Program (CRIEMP), a coalition of environmental agencies and industries that study and monitor the Columbia River upstream from the international boundary.

The Ecology study, also supported by USEPA as a separate but related trend-monitoring study, measured, over time, the concentrations of dioxins and furans in lake whitefish and concentrations of trace metals in the tissue of largescale sucker. The Ecology study also involved the collection and analysis of suspended sediment for dioxins and furans and trace elements in the Columbia River at Northport. Personnel of the USGS and Ecology worked jointly to obtain samples and share data collected at Northport (see later sections in the report). The timing of the USGS and Ecology studies corresponded to the CRIEMP study, which analyzed sediment samples and fish tissue from the lower Columbia River in British Columbia for trace elements and dioxins and furans. A comparison of data-collection activities for the Lake Roosevelt study and the CRIEMP study is shown in table 1.

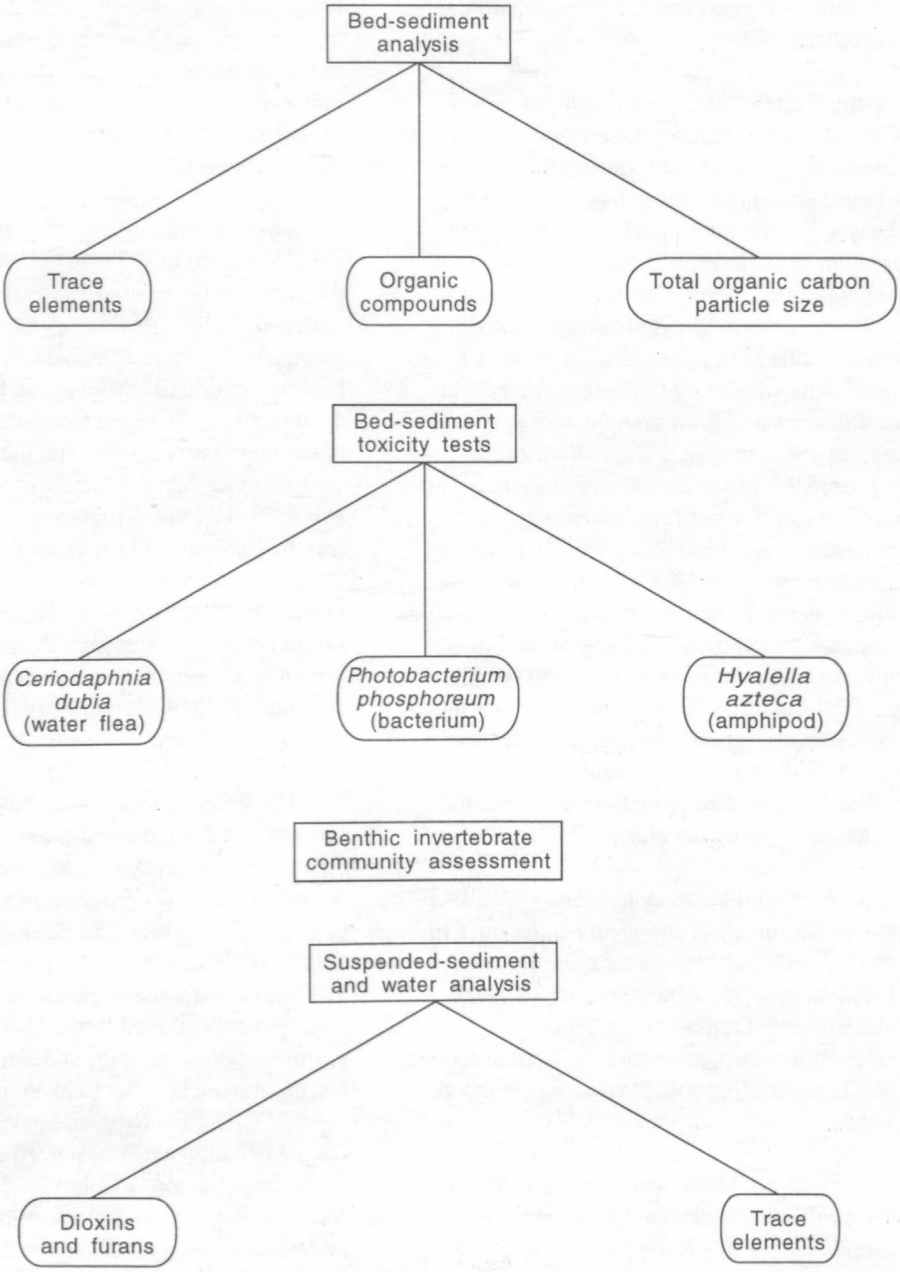


Figure 3.--Major study components and general sampling scheme.

Table 1.--*Summary of data-collection activities for the Lake Roosevelt study and the Columbia River Integrated Environmental Monitoring Program (CRIEMP) in 1992*

[X, samples collected; --, not sampled]

Analysis	Type of survey	Lake Roosevelt study	CRIEMP
	Community structure		
Benthic invertebrates		X	X
Periphyton		--	X
Macrophyte		--	X
	Fish tissue		
White sturgeon	Dioxins and furans, muscle	--	X
Mountain whitefish[1]	Trace elements, dioxins and furans, muscle	X	X
	Non-fish tissue		
Snails	Trace elements, dioxins and furans, soft tissue	--	X
Caddisflies	Trace elements, dioxins and furans, whole	--	X
	Bed sediment		
Particle size		X	X
Total volatile residue		--	X
Trace elements		X	X
Extractable organic halogens		X	X
Dioxins and furans		X	X
Chlorinated phenols		X	X
Resin acids		X	X
Total Kjeldahl nitrogen		--	X
	Sediment toxicity tests		
Microtox®, bacterium		X	X
Ceriodaphnia dubia, water flea		X	--
Hyalella azteca, amphipod		X	X
Rainbow trout		--	X
Daphnia magna, water flea		--	X
Rainbow trout		--	X

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[1] Lake whitefish instead of mountain whitefish collected by the Washington State Department of Ecology during Lake Roosevelt study.

Purpose and Scope

This report presents the results of the sediment-quality assessment of Lake Roosevelt and an upstream reach of the Columbia River. The report describes the following aspects of the study:

1. The occurrence and distribution of trace elements in the bed sediments of the study area;
2. The concentrations and discharge of trace elements, dioxins, and furans in water and suspended sediment in the Columbia River entering Lake Roosevelt;
3. The occurrence in bed sediments of selected trace-organic compounds related to urban, industrial, or wood-pulp waste;
4. Results of laboratory tests of the toxicity of bed sediment;
5. The benthic invertebrate community structure; and
6. Identification of potential long-term monitoring and investigative studies.

These aspects are discussed in the major sections of the report, and each discussion includes a description of a subset of pertinent secondary objectives, an overview of the results, and a description of specific sampling methods.

Description of the Study Area

The study area included Lake Roosevelt and the Columbia River upstream from the reservoir to the international boundary (fig. 1). Lake Roosevelt is situated in two distinct physiographic subdivisions. The mid to upper reaches of the reservoir are surrounded by mountainous terrain of moderate slopes covered by coniferous forests. The lower reach of the reservoir is a high-steppe, semiarid desert, characteristic of central Washington.

The study area is divided into four reaches: the Northport reach of the Columbia River and the upper, mid, and lower reaches of Lake Roosevelt (fig. 1).

Northport reach.—The Northport reach of the Columbia River extends from the international boundary (river mile, RM, 745) to Onion Creek (RM 730). The river in this reach is characterized as mainly a swift river run. The river-reservoir transition zone shifts depending on the flow and surface elevation to the reservoir.

Upper reach.—The upper reach is a narrow channel in the reservoir with few shoreline embayments and irregularities. It extends from Onion Creek (RM 730) to Marcus Island (RM 708).

Mid reach.—The mid reach has a wider channel with an irregular shoreline and extends from Marcus Island (RM 708) to the Spokane River confluence (RM 639). It is the longest reach in the reservoir.

Lower reach.—The lower reach has a deep channel and is influenced by flows from the Spokane River. It extends from the Spokane River confluence (RM 639) to Grand Coulee Dam (RM 596).

The Columbia River upstream from the international boundary has been divided into four reaches by CRIEMP (fig.1). There are CRIEMP monitoring sites in each of the four reaches.

Sediment Sources

The drainage basin of Lake Roosevelt contains a wide variety of igneous, metamorphic, and sedimentary rocks, as well as unconsolidated surficial deposits. Water and sediment entering the reservoir are from diverse geologic and physiographic regions. About 90 percent of the flow to the reservoir is from the Columbia River, with headwaters in the Rocky Mountains (fig. 2). However, regulation of inflow to Lake Roosevelt by nine major reservoirs in Canada and the United States has affected the sediment transport in the Columbia River. Sediment is trapped and stored by upstream reservoirs, and only small concentrations of suspended sediment are carried by the Columbia River into Lake Roosevelt. Suspended-sediment concentrations have been measured routinely in the Columbia River at Northport, Wash., between 1974 and 1992 (Miles and others, 1993). The 142 suspended-sediment concentrations ranged from 0 to 42 mg/L, with a median concentration of 5 mg/L (Miles and others, 1993). A daily suspended-sediment discharge based on the median suspended-sediment concentration of 5 mg/L and the average daily discharge of 99,700 ft^3/s (based on 55 years of record) is 1,350 tons per day.

Much of the bed sediment found in the mid and lower reaches of the reservoir is probably derived from erosion and slumping of bank deposits along the shoreline of the reservoir (Jones and others, 1961). Erosion and slumping of bank sediment is an active process. Before Grand Coulee Dam was constructed and the reservoir filled, bank sediments were dry and stable, but some of these sediments are now saturated and less stable, and therefore more susceptible to slumping and sliding (Jones and others, 1961). Bank sliding is increased by variations in lake levels that occur in response to dam operations.

Physical and Chemical Characteristics of the Reservoir

The maximum depth of the reservoir is about 375 ft, the mean depth at full pool is 117 ft, and the total storage capacity is 9,385,000 acre-ft. From January through June, the reservoir is drawn down in preparation for spring runoff; minimum surface elevations normally occur during April and May. Then from July through December, the highest surface elevations normally occur. The mean daily water elevation for the period 1983-92 is shown on figure 4. The shortest time the water resides in the reservoir (computed by dividing stored volume in the reservoir by discharge at Grand Coulee Dam) generally occurs from March through June, and the longest time water resides in the reservoir is from September through January. The mean annual water retention time is about 40 days. High flows into the reservoir normally occur in May and June and peak in June; stable low flows usually occur from September through April. Pool elevations and river discharge can vary daily because of electric power demand and the operations of hydroelectric facilities.

The mixing of Columbia River and reservoir water can be determined from seasonal temperature profiles obtained in 1980 by Stober and others (1981). In 1980, in a water year when the mean discharge was about 10 percent less than the average discharge for the period of record, the reservoir water to about French Point Rocks (RM 691) was vertically well mixed the year round with respect to temperature because of the large flow of the Columbia River into the reservoir. Temperature profile measurements from the surface to the bottom showed a uniform or nearly uniform temperature in the reservoir from mid-October to mid-April, indicating a well-mixed water column. After mid-April, parts of the reservoir had begun to show a vertical temperature gradient. By mid-May, the reservoir from Ninemile Creek (RM 648) downstream to Grand Coulee Dam had a distinct temperature gradient of 8 °C between the surface and bottom. On the other hand, the reservoir upstream from Ninemile Creek in mid-May was mixed, as shown by the nearly uniform temperatures throughout the water column. As the summer progressed, more of the reservoir developed a temperature gradient. In July and August 1980, the reservoir developed a moderate temperature gradient from Grand Coulee Dam (RM 596) to Hunters (RM 662); from Hunters (RM 662) to French Point Rocks (RM 691) the reservoir had only a weakly mixed water column. Upstream from French Point Rocks, the reservoir was well mixed, or nearly so, even in the summer.

Because of mixing induced by large flows of the Columbia River and the short water-retention time, much of the reservoir is oxygenated throughout the year. In 1980, the mean percentage of oxygen saturation in the reservoir ranged from 80 to 119 percent (Stober and others, 1981).

Columbia River water entering the reservoir has relatively small concentrations of dissolved solids. From the water years 1974 to 1993 (20 years), dissolved-solids concentrations ranged from 61 to 106 mg/L, and the average concentration was 81 mg/L (Miles and others, 1993). The smallest dissolved-solids concentrations occurred from May through August, concurrent with the largest volume of runoff to the reservoir.

The transparency of the reservoir water varies seasonally and is affected by the amount of suspended material, according to Beckman and others (1985). Generally, the water is most transparent during the summer and least transparent in the spring when surface runoff from upstream tributaries carries suspended sediment and reservoir drawdown triggers erosion and bank slumping.

Lake Roosevelt is moderately enriched in nutrients at some locations according to Stober and others (1981). When Welch and others (1992) applied their nutrient model, they found that algal growth in the main body of the reservoir was limited by nitrogen. Stober and others (1981) also concluded that nitrogen concentrations limited the algal productivity in the main body of the reservoir. The effects of nitrogen or phosphorus on algal growth may be different in local areas and embayments of the reservoir.

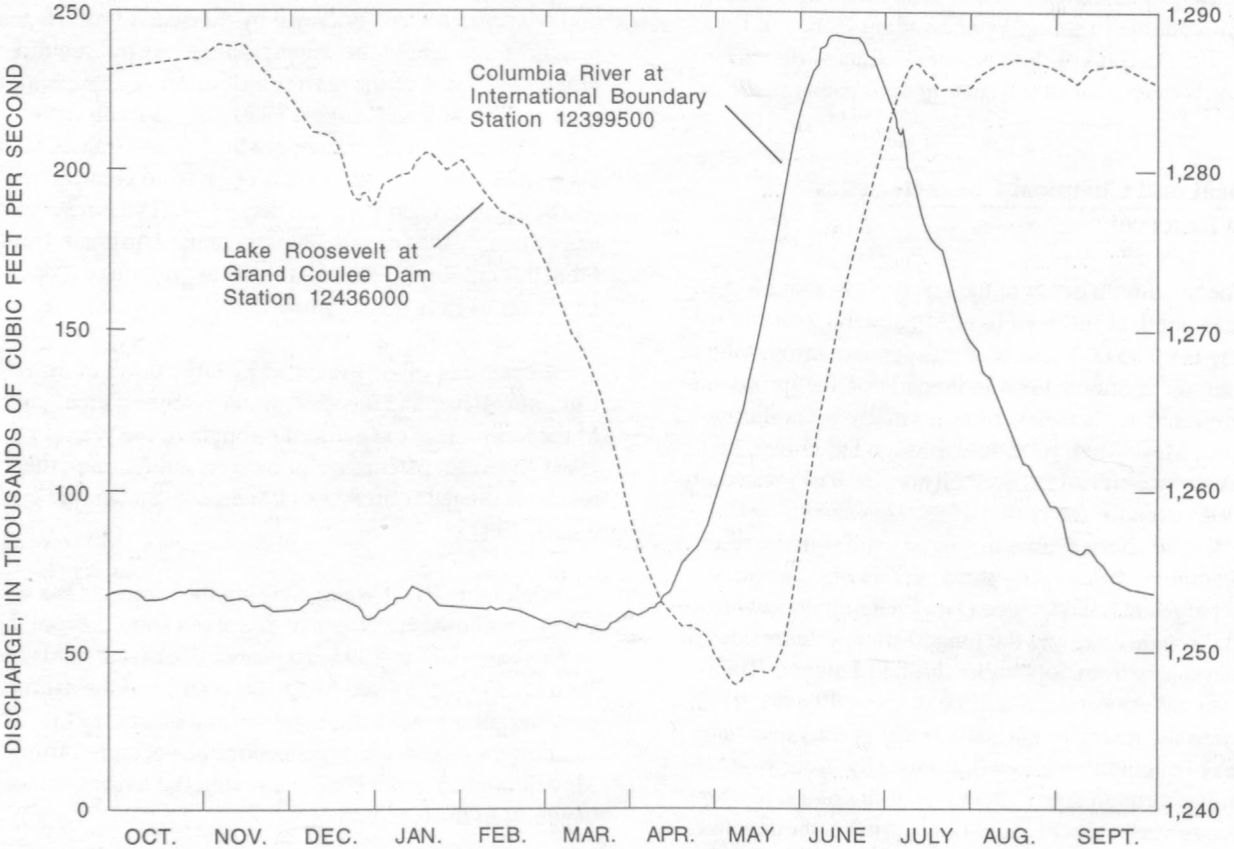

Figure 4.--Mean daily discharge of the Columbia River at International Boundary and mean daily elevation of Lake Roosevelt at Grand Coulee Dam, 1983-92.

Sources of Trace Elements and Organic Compounds

Trace elements, dioxins and furans, and other constituents in Lake Roosevelt can originate from the point and the nonpoint sources discussed below.

Point Sources

Chlorinated organic compounds are discharged to the Columbia River from a pulp mill located 2 river miles downstream of Hugh Keenleyside Dam near Castlegar, British Columbia, (fig. 2) about 30 river miles upstream from the international boundary. This mill began operation in 1961 and, until mid-1993, primarily used chlorine in its bleaching process. During the bleaching process, chlorine reacts with compounds in wood and PCP's (polychlorinated phenols used in wood preservation) if present. PCP's are found in wood chips made from wood previously treated with PCP's (Butcher, 1992a,b). Some of the products from these reactions include polychlorinated dibenzo-*p*-dioxins and polychlorinated dibenzofurans. The pulp mill discharges effluent containing organic compounds into the Columbia River (Butcher, 1992a). However, in 1991 the pulp mill began modernizing and enlarging its facilities. In the process of modernization, which included reduction of chlorine usage, the plant reduced discharges of furans and by 1993 had reduced dioxin and furan concentrations in effluent to below minimum detection limits (Celgar Pulp Company, 1992). The pulp mill has also modified its process so that the amount of dioxin and furan precursor compounds is reduced (Butcher, 1992b).

A lead and zinc smelter located at Trail, British Columbia, about 10 river miles upstream from the international boundary, began operation near the turn of the century and expanded operations over the years, and has discharged large quantities of slag to the Columbia River. Blast furnace slag is treated in a fume recovery process to remove additional metals before discharge to the Columbia River. This treated slag is principally black sand-size material and until recently has been considered inert and nontoxic (Nener, 1992). Under the assumption that treated granulated slag was inert, the smelter was permitted to discharge up to 1,000 tons per day. The amount of slag discharged was reduced in the mid-1980's and remains at about 450 tons per day (Cominco Metals, 1991a). Treated slag is referred to as slag in this report. The granulated slag also contains fines; Nener (1992) reported about 0.5 percent of slag is silt and clay size—less than 0.062 mm in diameter. Silt- and clay-size material can be transported long distances as suspended sediment in the Columbia River and Lake Roosevelt system.

The smelting facility also discharges about 43 Mgal/d of effluent as a slurry of dissolved and suspended material into the Columbia River (K.W. Kuit, Cominco Metals, written commun., 1991). The effluent contains such trace elements as arsenic, cadmium, lead, mercury, and zinc. Since a plan to decrease the trace-element concentrations in effluent was implemented in the late 1970's, arsenic, cadmium, lead, mercury, and zinc concentrations in the effluent reportedly are substantially reduced (K.W. Kuit, Cominco Metals, written commun., 1991). A new smelter for lead, built in the late 1980's, has further reduced the mercury concentration in the effluent (Cominco Metals, 1991a). Current plans call for further reductions in effluent discharges at the smelter by 1995 (Graham Kenyon, Cominco Metals, written commun., April 1993). The smelter company also operates an ammonia phosphate plant that discharges about 2.5 tons per day of phosphate into the river (Cominco Metals, 1991a).

Other permitted waste discharges in the Columbia River downstream from Lower Arrow Lake are from the municipal wastewater treatment facilities in Castlegar and Trail, British Columbia. Both cities have secondary sewage treatment plants that discharge to the river. The municipal treatment system at Trail overloads during and immediately following intense storm flow, causing untreated sewage to discharge directly to the river (Carl Johnson, British Columbia Ministry of Environment, oral commun., February 1993). Permitted waste discharges also enter Lake Roosevelt indirectly. They are mostly the treated municipal wastes from the city of Spokane discharged to the Spokane River (fig. 2) and the wastes from the cities of Colville and nearby Chewelah discharged to the Colville River tributary.

Nonpoint Sources

Mining activities in the drainage basin may contribute trace elements to the reservoir. Four major mining districts in the basin are shown on figure 5. Historically, this area has been intensely mined for zinc and lead, and less intensively mined for copper, gold, silver, tin, tungsten, and molybdenum (Bunning, 1985; Mills, 1977). Other mining activities included the excavation of dolomite, silica, and clay. Today, mining activities in the drainage basin have declined to a comparatively low level, especially those for metal ore production, with the exception of an active magnesium mine located about 15 mi south of Colville. Even though most mines are no longer active, runoff still may carry trace elements associated with mine tailings into the reservoir.

A vast part of the drainage basin in the United States and Canada is forest land. Only a small part of the basin land use is used for agriculture, urban, or industrial activities. Nonpoint-source runoff related to forest practices and agriculture may contribute herbicides, fertilizers, and sediment to the reservoir. The bulk of the runoff related to urban activities most likely originates from the city of Spokane, located on the Spokane River about 70 river miles upstream of Lake Roosevelt (fig. 2).

Notable atmospheric sources of pollution near the study area are wood incineration near Kettle Falls, air emissions from the smelter operation at Trail, British Columbia, and urban and industrial emissions from the city of Spokane (figs. 1 and 2). Evaluation of these potential sources of trace elements and organic compounds in the Columbia River and Lake Roosevelt is beyond the scope of this investigation.

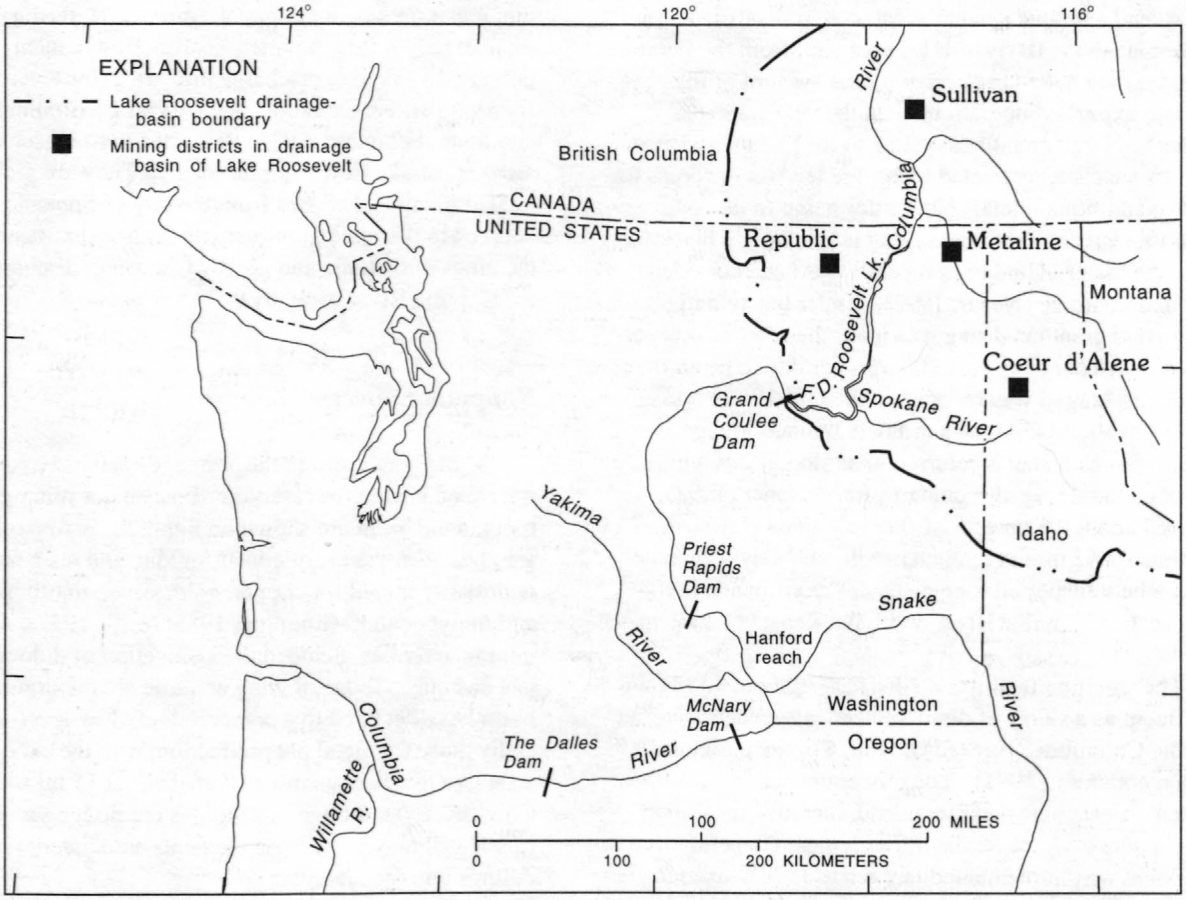

Figure 5.--Location of major mining districts in the drainage basin of Lake Roosevelt and major dams on the lower Columbia River.

Methods of Sampling

This section of the report outlines general procedures used in the study. Later sections will present specific details for the trace-element and organic-compound analyses, the sediment bioassay, and the characterization of benthic communities. Table 2 lists the analyzing laboratory and types of analyses done on bed-sediment, suspended-sediment, and centrifuged water samples.

Bed-sediment analyses included determinations of trace-element and organic-compound concentrations, sediment-toxicity tests, and benthic invertebrate community structure as shown on figure 3. The constituents, tests, and properties determined in bed sediment are shown in table 2. In addition to the bed-sediment analyses from the reservoir and the Columbia River, suspended-sediment and centrifuged water samples were analyzed for trace elements and dioxins and furans at one site in the Columbia River upstream of Lake Roosevelt.

The general strategies and equipment used to sample the Columbia River in this study were similar to those discussed by Meade and Stevens (1990), who have done extensive studies on large rivers. Procedures for collecting and processing samples are outlined by the American Society of Testing Materials (1991a,b) for sediment toxicity tests, by Edwards and Glysson (1988) for bed and suspended sediment, and by Britton and Greeson (1987) for benthic invertebrates. Some of the analytical procedures are discussed by Fishman and Friedman (1989) for inorganic constituents and by Wershaw and others (1987) for organic constituents.

Table 2.--*Laboratories conducting various analyses from the Lake Roosevelt study area, 1992*

Analysis	Laboratory
	Bed-sediment samples
Trace elements	- Nuclear Radiation Center, Washington State University, Pullman, Wash. - GeoAnalytical Laboratory, Washington State University, Pullman, Wash. - U.S. Environmental Protection Agency and Washington State Department of Ecology Laboratory, Manchester, Wash. - Battelle Marine Science Laboratory, Sequim, Wash. - Zenon Environmental Laboratories, British Columbia, Canada
Total organic carbon	- U.S. Department of Agriculture Agricultural Research Services Laboratory, Washington State University, Pullman, Wash.
Particle size	- U.S. Geological Survey, Vancouver, Wash.
Methylene-chloride extractable compounds	- U.S. Geological Survey National Water Quality Laboratory, Arvada, Colo.
Chlorinated phenols, resin and fatty acids, extractable organic halides	- Zenon Environmental Laboratories, British Columbia, Canada
Benthic invertebrates	- Chadwick and Associates, Littleton, Colo.
Microtox®	- U.S. Fish and Wildlife Service, Ecological Services, Moses Lake, Wash.
Sediment toxicity tests	- Wright State University, Dayton, Ohio
	Water and suspended-sediment samples
Dioxins and furans	- Enseco, Sacramento, Calif.
Trace elements in water	- U.S. Geological Survey National Water Quality Laboratory, Arvada, Colo.
Dissolved organic carbon	- U.S. Geological Survey National Water Quality Laboratory, Arvada, Colo.
Trace elements, suspended sediment	- Battelle Marine Science Laboratory, Sequim, Wash.
Total organic carbon, suspended sediment	- U.S. Environmental Protection Agency and Washington State Department of Ecology Laboratory, Manchester, Wash. - Battelle Marine Science Laboratory, Sequim, Wash.

Bed Sediment

Bed sediment was collected for the present study from sites along the Columbia River, along the length of Lake Roosevelt, at the mouths of several tributaries to the lake, at banks along the lake, at public beaches, at one site downstream from Lake Roosevelt, and from reference sites in British Columbia (see plate 1 for site locations). The results of Ecology's 1986 survey (Johnson and others, 1990) of metals concentration gradients in Lake Roosevelt had showed larger variations in the upper reach of the reservoir. Consequently, for this study, sample sites in the Columbia River and the reservoir were spaced at slightly closer intervals in the upstream reach of Lake Roosevelt and the Northport reach of the Columbia River and were spaced more widely but uniformly in the downstream part of the reservoir (pl. 1). The sample site numbers, names, and river mile locations are shown in table 3. Because samples were collected at sites at midstream or toward either bank, the site designations include the letters RB, LB, and MS (pl. 1) to indicate that samples were collected on the right side (toward the right bank from mid channel when facing downstream), on the left side (toward the left bank from mid channel when facing downstream), and near the midsection (middle) of the channel, respectively. Numbers 1 and 2 denote different sites toward the same bank.

Most bed-sediment samples were collected with a stainless steel van Veen sampler (fig. 6). From each site, equal volumes of sediment from three to five nearby locations were mixed to make a composite sample to increase the area at each site represented by the sample. For each sample, the top 0.5 to 1 inch layer of sediment was removed for compositing. The relatively undisturbed top layer of sediment in the van Veen sampler indicated that the sediment sampler had not mixed the sample substantially. Each composite sample was mixed with Teflon blades in a glass bowl and then subsampled for selected bed-sediment analyses according to processes shown on figure 7.

Sample processing on the RV *Estero* took place in a lab room separated from the main cabin by bulkheads fore and aft to minimize possible contamination from the motor exhaust. A second boat, a 22-foot jet boat equipped with a large plastic working platform for sample processing, was used to collect samples from the swift-moving reaches of the Columbia River downstream from the international boundary and at sampling sites in British Columbia. Samples collected on the jet boat were temporarily stored in Teflon bags and brought back to the RV *Estero* for processing.

Trace elements analyzed included but were not limited to the six key elements of interest: arsenic, cadmium, copper, lead, mercury, and zinc. Trace-organic compounds selected for analyses included methylene-chloride extractable compounds and wood-pulp-related compounds such as chlorinated phenols. Total organic carbon and particle-size distributions were determined for samples from most sites.

Bed-sediment toxicity testing determined whether the bed sediment would produce toxic effects—death or reduced reproduction—on three selected organisms: *Hyalella azteca*, an amphipod that lives both in the water column and in the upper layer of bed sediment; *Ceriodaphnia dubia*, a water flea that lives primarily in the water column but is commonly observed near the sediment surface; and *Photobacterium phosphoreum*, a marine bacterium. This marine bacterium is used in the rapid and inexpensive Microtox® toxicity test to identify areas of toxicity at a large number of sites (Burton, 1992).

The community structure of benthic invertebrates was characterized at a number of sites within the Northport reach of the Columbia River and Lake Roosevelt. Measures of benthic community structure included abundance and diversity of species, abundance of selected taxonomic groups, and percentage composition of selected taxonomic groups.

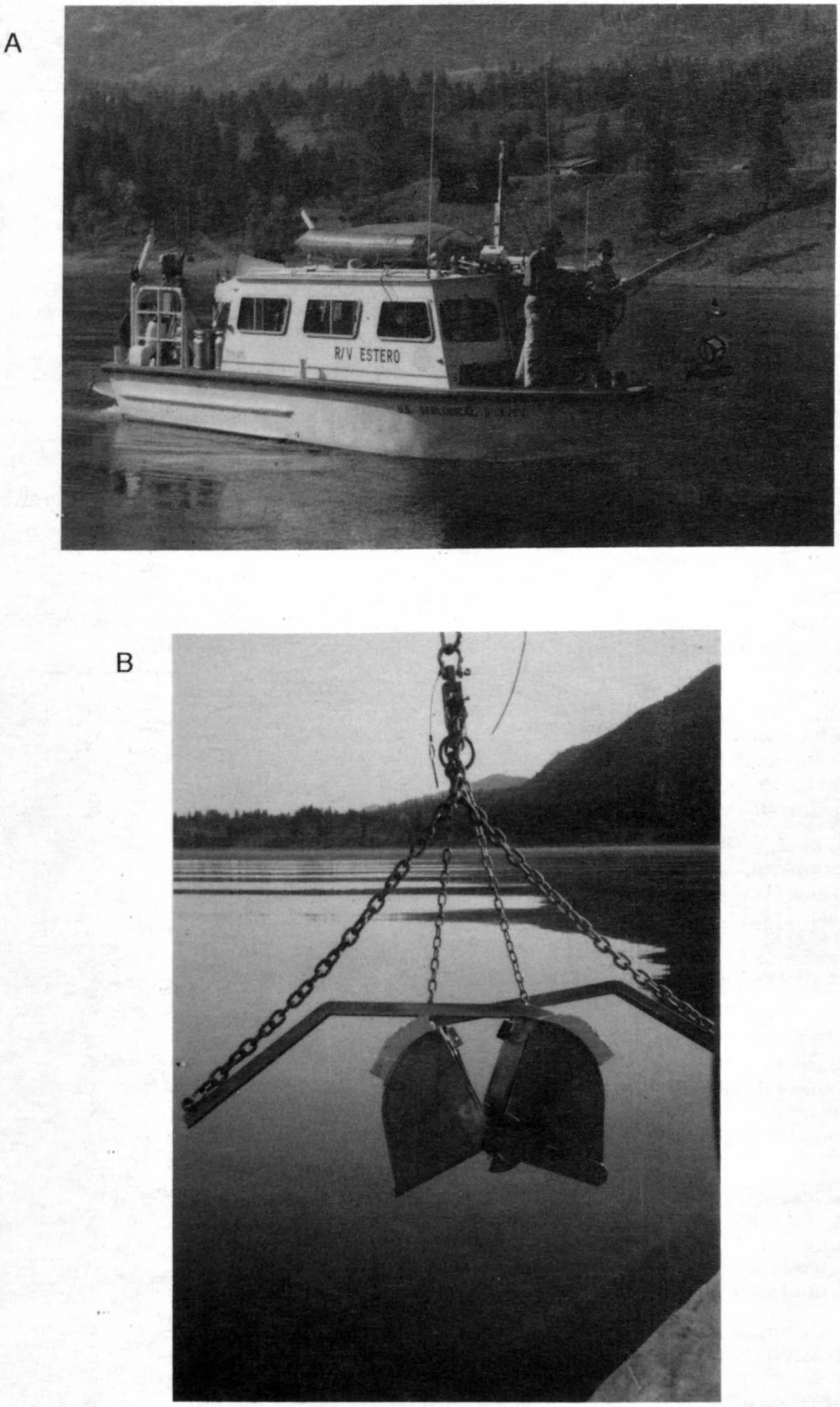

Figure 6.--(A) The research vessel R/V *Estero*, used for collecting and processing of samples, and (B) stainless steel van Veen grab sampler.

Table 3.-- *Site location, types of sampling, and analyses conducted at sites in the Lake Roosevelt study area*

[LB, RB, and MS indicate samples were collected on right side (toward the "right bank" from mid channel), left side (toward the "left bank" from mid channel), and near the mid-section channel, respectively, numbers 1 and 2 denote different sites toward the same bank; X, sample collected for constituent or property; --, not sampled or not applicable for tributary river mile; H, *Hyalella azteca*; C, *Ceriodaphnia dubia*]

Site number	Site name (see plate 1 for complete name)	River mile	Tributary river mile	Trace elements	Total organic carbon	Methylene-chloride extractable compounds	Wood-pulp related compounds[1]	Photobacterium phosphoreum (Microtox®)	Benthic invertebrate	Sediment toxicity test
					Columbia River and major tributaries					
3	Keenleyside Dam LB	781	--	X	X	--	--	X	--	--
4	Kootenay River MS	775	12	X	X	X	--	X	X	H C
5	Kootenay River LB	775	11	X	X	--	--	X	--	--
6	Pend D'Oreille River LB	746	2	X	X	X	--	X	--	H C
7	Boundary RB	745	--	X	X	--	--	X	X	--
8	Boundary LB	745	--	X	X	--	--	X	--	H C
9	Auxiliary Gage RB	743	--	X	X	--	--	X	--	--
10	Auxiliary Gage LB	743	--	X	X	--	--	X	X	H C
11	Goodeve Creek RB	738	--	X	X	--	--	X	X	H C
12	Goodeve Creek LB	738	--	X	X	--	--	X	--	--
14	Fivemile Creek LB	733	--	X	X	--	--	X	--	H C
15	Onion Creek LB	730	--	X	X	--	--	X	X	H C
16	Onion Creek RB	730	--	X	X	--	--	X	--	--
25	Kettle River RB1	707	4.3	X	X	X	--	X	--	H C
26	Kettle River RB2	707	4.3	X	X	--	--	--	--	--
27	Kettle River LB	707	4.3	X	X	--	--	--	--	--
29	Colville River MS	700	0.9	X	X	X	--	X	--	H C
30	Colville River RB	700	0.9	X	X	--	--	--	X	--
31	Colville River LB	700	0.9	X	X	--	--	--	--	--
52	Spokane River MS	639	6.2	X	X	--	--	X	--	--
53	Spokane River LB	639	5.3	X	X	X	--	X	X	H C
54	Spokane River RB	639	5.9	X	X	--	--	--	--	--
62	Sanpoil River MS	616	7.2	X	X	X	--	X	X	H C
63	Sanpoil River LB	616	7.2	X	X	--	--	--	--	--
64	Sanpoil River RB	616	7.2	X	X	--	--	--	--	--
72	Rufus Woods Lake LB	587	--	X	X	--	--	X	--	--
					Reservoir					
1	Lower Arrow Lake LB1	787	--	X	X	X	X	X	X	H C
2	Lower Arrow Lake LB2	787	--	X	X	--	--	X	--	H C
17	China Bend RB	724	--	X	X	--	--	X	X	H C
18	China Bend MS	724	--	X	--	--	--	--	--	--
19	Bossborg RB	717	--	X	X	--	--	X	X	H C
20	Summer Island RB1	710	--	X	X	--	--	X	X	H C
21	Summer Island RB2	711	--	X	X	--	--	X	--	--
22	Marcus Island MS	708	--	X	X	X	X	X	--	H C
23	Marcus Island RB	708	--	X	X	--	--	--	--	--
24	Marcus Island LB	708	--	X	X	--	--	--	X	--
28	West Kettle Falls LB	702	--	X	X	X	--	X	--	--
35	Haag Cove RB	697	--	X	X	--	--	X	X	--
36	Haag Cove MS	697	--	X	X	--	--	--	--	--
37	French Point Rocks RB	691	--	X	X	--	--	--	--	--
38	French Point Rocks MS	691	--	X	X	X	X	X	X	H C

Table 3.-- *Site location, types of sampling, and analyses conducted at sites in the Lake Roosevelt study area--Cont.*

Site number	Site name (see plate 1 for complete name)	River mile	Tributary river mile	Trace elements	Total organic carbon	Methylene-chloride extractable compounds	Wood-pulp related compounds[1]	Photobacterium phosphoreum (Microtox®)	Benthic invertebrate	Sediment toxicity test
					Reservoir--Continued					
39	French Point Rocks LB	691	--	X	X	--	--	--	--	--
40	Cheweka Creek LB	681	--	X	X	--	--	X	X	--
41	Gifford MS	676	--	X	X	--	--	X	--	--
42	Gifford LB	676	--	X	X	--	--	--	--	--
43	Gifford RB	676	--	X	X	--	--	--	--	--
46	Hunters LB	662	--	X	X	--	--	X	--	HC
47	Ninemile Creek MS	648	--	X	X	--	--	--	--	--
48	Ninemile Creek LB	648	--	X	X	--	--	--	X	--
49	Ninemile Creek RB	648	--	X	X	--	--	X	--	--
51	Fort Spokane RB	640	--	X	X	--	--	X	--	--
56	Seven Bays MS	634	--	X	X	X	--	--	--	--
57	Seven Bays RB	634	--	X	X	--	--	X	X	HC
58	Seven Bays LB	634	--	X	X	--	--	--	--	--
61	Whitestone Creek MS	621	--	X	X	--	--	X	--	HC
66	Keller Ferry RB	612	--	Z	X	--	--	X	--	--
68	Swawilla Basin RB	605	--	X	X	--	--	--	--	--
69	Swawilla Basin LB	605	--	X	X	--	--	X	X	--
70	Swawilla Basin MS	605	--	X	X	X	--	--	--	--
71	Grand Coulee Dam RB	596	--	X	X	--	--	X	--	HC
					Minor tributaries					
33	Sherman Creek MS	700	0.3	X	X	--	--	X	--	--
44	Hall Creek LB	675	0.9	X	X	--	--	--	--	--
45	Hall Creek MS	675	0.9	X	X	--	--	X	--	--
55	Hawk Creek RB	634	1.6	X	X	--	--	X	--	--
					Beach					
13	Big Sheep Creek RB[2]	736	--	X	X	--	--	--	--	--
32	Colville River LB	699	--	X	X	--	--	--	--	--
34	Bradbury LB	694	--	X	X	--	--	--	--	--
67	Keller Ferry LB	615	--	X	X	--	--	--	--	--
					Bank					
50	Ninemile Creek RB	648	--	X	--	--	--	--	--	--
59	Seven Bays LB1	636	--	X	--	--	--	--	--	--
60	Seven Bays LB2	636	--	X	--	--	--	--	--	--
65	Sanpoil River RB	616	--	X	--	--	--	--	--	--

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[1] Not including dioxins and furans collected in the Columbia River at Northport.

[2] Delta deposit.

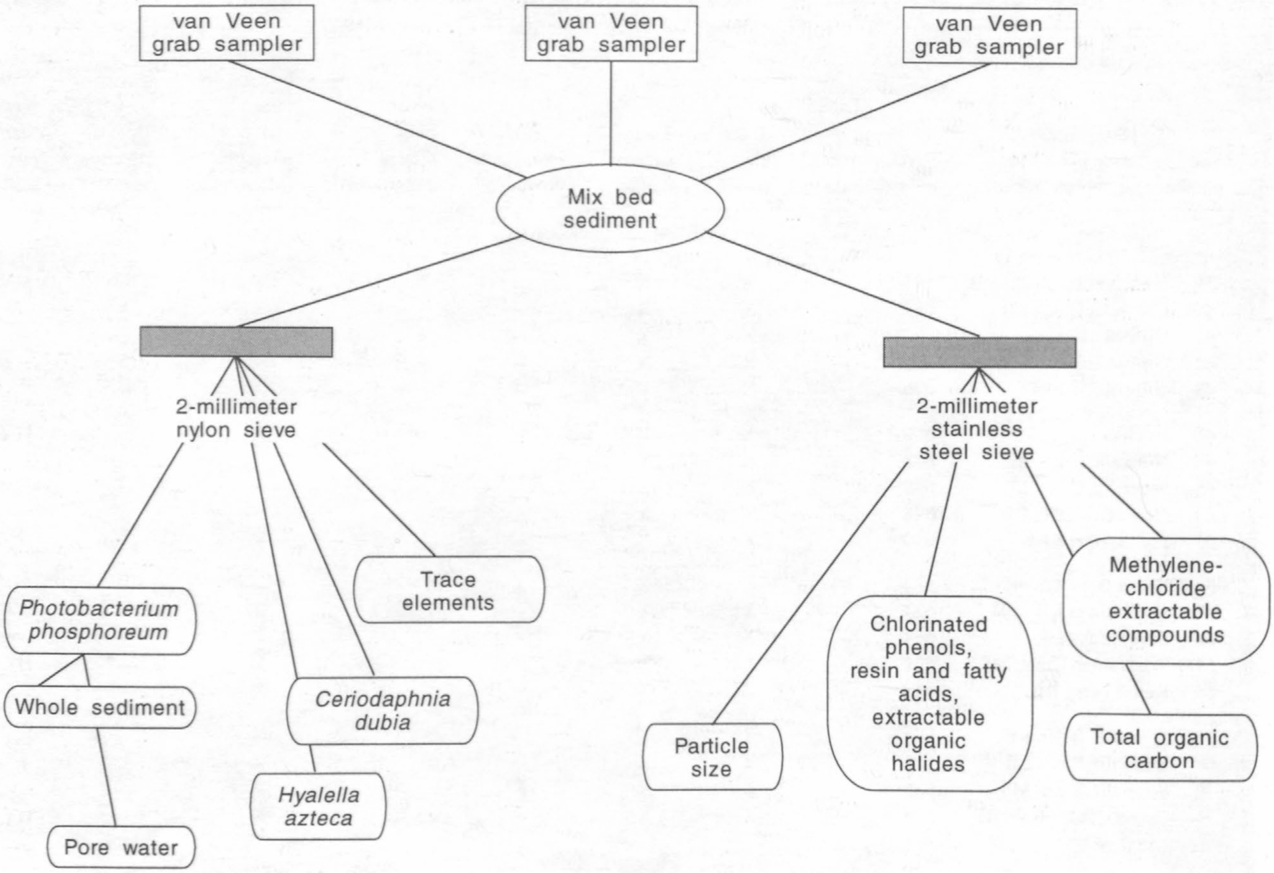

Figure 7.--Schematic of sediment sample processing, sediment-toxicity tests, and sediment chemistry.

Water and Suspended Sediment

Water and suspended sediment from the main stem of the Columbia River at Northport were collected for analysis of trace elements, dioxins, and furans, as shown on figure 8. Depth-width integrated samples obtained from a boat and point-source pumped samples obtained from near the shore were collected from the Columbia River at Northport. River water was centrifuged to separate the suspended and water phases to determine the relative distributions of trace elements, dioxins, and furans associated with each phase of the Columbia River entering Lake Roosevelt. Discharge and concentration data were combined for estimating daily discharges of selected trace elements and dioxins and furans. Discharge was measured at the time of sampling and continuously monitored at the international boundary.

Two aspects of the Columbia River flow at Northport create challenges to obtaining representative suspended-sediment samples for chemical analysis. First, the concentrations of suspended sediments are small, on the order of 5 mg/L; thus, obtaining sufficient amounts of suspended sediments required several hundred or thousand liters of water to provide enough sediment for chemical analyses of environmental and quality-control samples. Second, the mouth of the Pend D'Oreille at the Columbia River is located 9 mi upstream of the sampling section, and mixing of the two rivers may be incomplete at the sampling locations on the Columbia River at Northport. An analysis of mixing within this reach, performed by Sigma Engineering (1987), was based on transverse mixing by turbulent diffusion (described by Fischer and others, 1979) and used channel characteristics for the Columbia River upstream from the mouth of the Pend D'Oreille River (fig. 1; pl. 1). The transverse mixing calculation indicated that mixing was incomplete at about 5 mi downstream from the mouth and would probably still be incomplete at the sampling section at Northport (9 mi downstream from the confluence), even though flow conditions near Northport are affected by backwater from Lake Roosevelt.

The authors of the current study duplicated the analysis described by Fischer and others (1979); the analysis included river channel and flow characteristics measured at a gaging station located midway between the confluence and the sampling section at Northport. The results were similar to the earlier work. Because the two rivers were suspected to be incompletely mixed, this study used depth-width integrated sampling (Horowitz, Rinella, and others, 1989; Martin and others, 1992).

To provide a general comparison, water and suspended- sediment samples were collected using two procedures, each of which was designed to overcome one of the major challenges to obtaining representative samples of the Columbia River at Northport. First, depth- and width-integrating techniques were used to collect representative samples of the total flow in the river cross section. However, the small concentrations of suspended sediment (20-year median value, 5 mg/L) in the Columbia River at Northport limited the amount of sample that could be obtained in a reasonable time. Second, point-source pumping techniques were used to collect larger quantities of water and suspended sediment. However, only a small fraction of the river's cross section was sampled, rendering the sample non-representative of flow in the cross section.

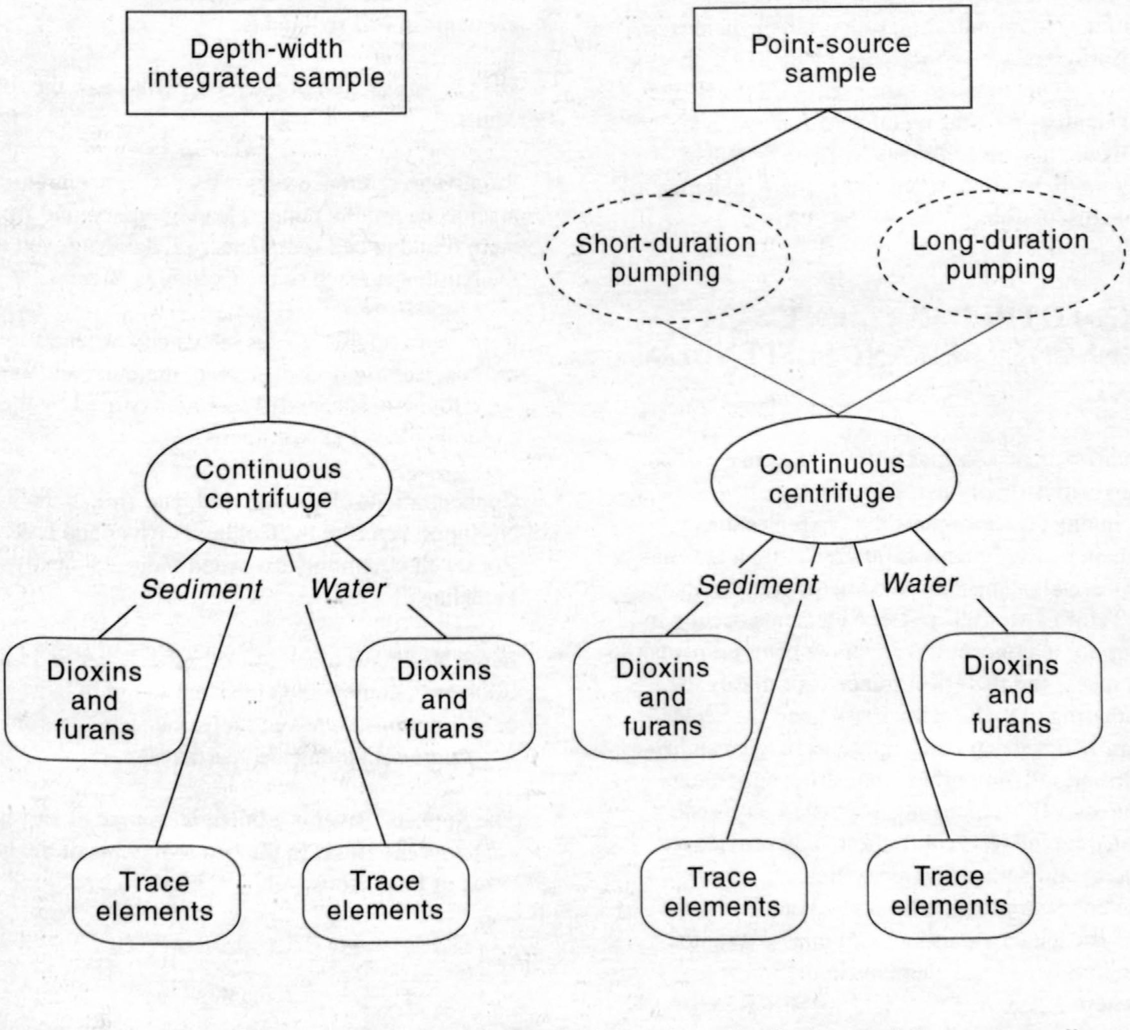

Figure 8.--Simplified schematic of trace-element and dioxin and furan sampling of the Columbia River at Northport, Washington.

Acknowledgments

Field-data collection and processing and part of the data analysis were conducted as a cooperative agreement between the U.S. Geological Survey and the Water Research Center at Washington State University. The U.S. Geological Survey extends its appreciation to William Funk, Director of the Water Research Center, for his support. Many local volunteers, including high school students, assisted during the 3 weeks of field activity that included collecting, processing, and shipping samples. The U.S. Geological Survey also extends recognition to James Romero, Frank Ossiander, and Robert Jackman for their dedicated efforts in recruiting and organizing work schedules for volunteers. David Serdar, Arthur Johnson, and Keith Seider of the Washington State Department of Ecology shared equipment and samples with the U.S. Geological Survey during the collection of water and suspended-sediment samples in the Columbia River at Northport, Wash. The U.S. Geological Survey appreciates their cooperation. Communication support in the field was provided by National Park Service personnel. The authors also extend their appreciation to members of CRIEMP and to Canadian scientists for sharing information and data. The authors would also like to thank William Foreman, Arthur Horowitz, Bernadine Bonn, and Frank Rinella for much valuable discussion.

TRACE AND OTHER ELEMENT OCCURRENCE IN BED AND SUSPENDED SEDIMENT

Most trace elements, such as arsenic, mercury, cadmium, and lead, are strongly associated with bed sediment. Thus, in most river systems the concentration of trace elements in bed sediments is far greater than the concentration of trace elements dissolved in the water column (Gibbs, 1977; Horowitz, 1991). Trace elements occur naturally, at a variety of concentrations, in the bed sediments of rivers and lakes, and their occurrence is primarily the result of weathering of rocks at the Earth's surface. Added to these naturally occurring concentrations may be anthropogenic contributions from urban, industrial, agricultural, and other sources. Trace elements associated with sediments deposited on the reservoir bottom may provide a record of natural and anthropogenic sources. Data on trace-element concentrations in suspended and bottom sediments are needed as a starting point in assessing the potential availability of trace elements in the Lake Roosevelt system.

This part of the study addressed the following specific objectives:

1. To determine the concentrations of selected trace elements in the bed sediments of the Columbia River, Lake Roosevelt, and its other tributaries;

2. To determine the concentrations of trace and other elements in suspended sediment from the Columbia River as it enters Lake Roosevelt by using a limited number of samples and available data;

3. To compare the observed concentrations of selected trace elements in bed sediments to sediment-quality guidelines and to concentrations found in other sediments at reference sites including those outside the drainage basin of Lake Roosevelt; and

4. To identify trace-element sources and other factors influencing the spatial distribution of trace and other elements in bed sediments.

Data in this section of the report will show the following results.

- Relative to reference sites, elevated concentrations of arsenic, cadmium, copper, lead, mercury, and zinc were found in bed sediments of Lake Roosevelt and the Northport reach of the Columbia River.

- Relative to reference sites, elevated concentrations of arsenic, cadmium, copper, lead, mercury, and zinc were found in suspended sediment carried by the Columbia River at Northport.

- Concentrations of copper, lead, and zinc in the Northport reach of the Columbia River and Lake Roosevelt commonly exceeded sediment-quality guidelines.

- In the Northport reach of Columbia River and Lake Roosevelt, copper and zinc were found in large concentrations, relative to reference sites, in sand-size sediments containing slag particles.

- The Spokane River is a potential source of elevated zinc concentrations in the bed sediments of the lower reach of Lake Roosevelt.

Methods

Bed-sediment samples were collected from Lake Roosevelt, the Northport reach of the Columbia River, major and minor tributaries, and beaches. A limited number of samples were also collected from bank deposits along the mid and lower reaches of the reservoir. Sediment samples for trace-element analyses were collected from a total of 72 sites. Total trace-element concentrations were determined in bed sediment at all sites, and at 18 sites total-recoverable concentrations also were determined.

Sediment collection and processing procedures used for this study employed noncontaminating techniques. Collected sediment came in contact with only glass, plastic, or Teflon during handling. For example, samples were taken by a Teflon scoop from the center of a stainless steel sampler without touching the sides of the sampler, and the samples were placed in a glass mixing bowl for homogenizing. Homogenized samples were wet sieved with a teflon blade through a 2-mm nylon screen, and material passing through the sieve was split into polyethylene sample containers. All equipment was cleaned between sites as detailed in appendix A. Before analysis of total trace elements, sediment samples and quartz sediment blanks were dried in the sample containers at 60°C for 3 to 5 days and then ground to a powder of approximately 0.04 mm size by use of a tungsten-carbide mill. Sediment samples for total recoverable trace-element analysis were dried but not ground. Methods of collecting and processing suspended sediment are discussed in the next major section.

Quality-control samples were submitted to analyzing laboratories to assess analytical accuracy and precision. The accuracy of sediment-sample analyses for total arsenic, cadmium, copper, lead, mercury, and zinc was evaluated by comparing four laboratory analyses with certified values for the standard reference materials (table 4). The laboratory-determined concentrations were within the certified concentrations in 19 of 24 analyses (six elements times concentrations of the four blind samples). None of the concentrations of the six elements (arsenic, cadmium, copper, lead, mercury, and zinc) was consistently outside of the certification ranges. Accuracy also was evaluated by comparisons of trace-element analysis from two laboratories using different methods (table 5). Analysis of bed-sediment samples resulted in the following relative percent differences (see glossary): arsenic (0-43), cadmium (12-33), copper (2-60), lead (0-6), mercury (12-40), and zinc (0-15). Thirteen of 18 interlaboratory samples had relative percent difference values of 25 or less. The precision of the sediment chemistry analyses was evaluated by comparing analytical results of duplicates of a composite sediment sample (table 6). Most sediment analyses agreed within a range of 0 to 15 relative percent difference; 22 of 24 duplicates had a relative percent difference value of 10 or less. The analytical methods are summarized in table 7. Data from quality-control samples from this study indicate good overall data quality.

Selected bed-sediment samples also were analyzed by the Department of Geology at Washington State University to determine the proportion of slag particles (by grain count) in the sample. For each sediment sample, the percentage of slag particles was determined by counting the number of slag particles per 200 grains under a microscope.

Observed Concentrations

Relative to reference sites, elevated concentrations of total arsenic, cadmium, copper, lead, mercury, and zinc were found in bed sediments of Lake Roosevelt and the Northport reach of the Columbia River. Median bed-sediment concentrations for all reaches of Lake Roosevelt were 16, 6.2, 85, 310, 1.3, and 970 mg/kg for arsenic, cadmium, copper, lead, mercury, and zinc, respectively (table 8). Median concentrations of arsenic, copper, and zinc in bed sediment of the Northport reach of the Columbia River were considerably larger than median concentrations in Lake Roosevelt; in the Columbia River, median concentrations of total arsenic, copper, and zinc were 32, 2,600, and 13,000 mg/kg, respectively. Sediments and soils used as reference sites commonly contained concentrations of trace elements that were smaller by an order of magnitude. These reference sites were shale rock, local soils in northeastern Washington, soils in western United States, bed and suspended sediments in Lower Arrow Lake in Canada, and bed sediment from rivers and lakes in other parts of the Nation.

Summary data for trace-element concentrations in bed sediment for reaches of Lake Roosevelt and the Columbia River, major and minor tributaries, beach and banks, and other sediment and soil are shown in table 8. Concentrations of total arsenic, cadmium, copper, lead, mercury, and zinc are given for each site in table 35 at the end of the report.

Table 4.--*Analyzed concentrations of total arsenic, cadmium, copper, lead, mercury, and zinc and certified concentrations of standard reference material*

[Concentrations are in milligrams per kilogram; ICP-MS, inductively coupled plasma mass spectroscopy; INAA, instrumental neutron activation analysis; cold vapor AAS, atomic absorption spectroscopy; <, less than]

			Analyzed concentrations			Analyzed concentrations	
Total trace element	Method	Standard reference material 1646--Estuarine sediment, certified concentration	Estuarine sediment blind 1	Estuarine sediment blind 2	Standard reference material 2704--Buffalo River sediment, certified concentration	Buffalo River sediment blind 3	Buffalo River sediment blind 4
Arsenic	INAA	11.6 ± 1.3	10	12	23.4 ± 0.8	[1]21	25
Cadmium	ICP-MS	.36 ± .07	<5	[1].5	3.45 ± .22	3.5	[1]3.8
Copper	ICP-MS	18 ± 3	21	19	98.6 ± 5.0	100	98
Lead	ICP-MS	28.2 ± 1.8	28	28	161 ± 17	152	165
Mercury	Cold vapor AAS	.063 ± .012	.08	.08	1.47 ± .07	1.5	1.5
Zinc	ICP-MS	138 ± 6	135	136	438 ± 12	437	[1]429

[1] Not within certified range

Table 5.--*Interlaboratory comparison of total trace-element concentrations for three selected bed-sediment samples*

[LB, RB, and MS indicate samples were collected on right side (toward the "right bank" from mid channel), left side (toward the "left bank" from mid channel), and near the mid-section channel, respectively, numbers 1 and 2 denote different sites toward the same bank; Laboratory 1, Geoanalytical Laboratory, Geology Department, Washington State University (WSU), Nuclear Radiation Center, WSU; Laboratory 2, Battelle Marine Sciences Laboratory; see table 7 for method of analysis; relative percent difference of duplicate analysis (see glossary) is shown in parentheses]

				Concentration, in milligrams per kilogram				
Site number	Site name (see plate 1 for complete name)	Laboratory-method	Arsenic	Cadmium	Copper	Lead	Mercury	Zinc
2	Lower Arrow Lake LB2	1	1.9	0.5	7	32	<0.05	60
		2	2.8 (38)	0.7 (33)	13 (60)	34 (6)	0.06 (18)	70 (15)
12	Goodeve Creek LB	1	24	5.7	670	370	0.9	3,200
		2	37 (43)	7.3 (25)	620 (8)	370 (0)	0.8 (12)	3,200 (0)
57	Seven Bays RB	1	22	2.3	40	75	0.2	320
		2	22 (0)	2.6 (12)	39 (2)	72 (4)	0.3 (40)	320 (0)

Table 6.--*Concentrations of trace elements in replicate and duplicate samples*

[Replicate samples are from five individual grabs at a sampling site; duplicate samples are identical samples taken from composite sample; relative percent difference of duplicate analysis (see glossary) is shown in parentheses; LB, RB, and MB indicate samples were collected on right side (toward the "right bank" from mid channel), left side (toward the "left bank" from mid channel), and near the mid-section channel, respectively), numbers 1 and 2 denote different sites toward the same bank; --, no data; <, less than]

Site number	Site name (see plate 1 for complete name)	Date	Time	Concentration, in milligrams per kilogram					
				Arsenic	Cadmium	Copper	Lead	Mercury	Zinc
				Columbia River and tributary					
3	Kootenay River LB	10-10-92	1600	<7.0	0.5	20	27	<0.05	120
		10-10-92	1601	2.6	<0.5	--	30	<0.05	--
		10-10-92	1602	<5.0	<0.5	--	27	<0.05	--
		10-10-92	1603	2.0	<0.5	--	25	<0.05	--
		10-10-92	1604	<5.0	0.9	--	26	<0.05	--
9	Auxilary Gage RB	10-05-92	1640	43	1.1	2,600	270	0.2	13,000
		10-05-92	1641	45	1.3	--	360	0.1	--
		10-05-92	1642	59	1.0	--	430	0.1	--
		10-05-92	1643	50	1.1	--	380	0.2	--
		10-05-92	1644	66	1.8	--	420	0.2	--
12	Goodeve Creek LB	10-03-92	1430	22	5.7	670	370	0.9	3,200
		10-03-92	1431	24 (8.6)	5.4 (5.4)	680 (1.5)	380 (2.6)	0.8 (12)	3,200 (0)
				Reservoir					
1	Lower Arrow Lake LB1	10-10-92	0900	2.0	0.5	7.0	28	<0.05	49
		10-10-92	0901	1.9 (5.1)	<0.5 (0)	--	28 (0)	<0.05 (0)	--
20	Summer Island RB1	10-07-92	1440	20	11	300	660	2.7	1,800
		10-07-92	1441	16	10	--	630	1.2	--
		10-07-92	1442	20	11	--	640	2.7	--
		10-07-92	1443	20	11	--	630	2.7	--
		10-07-92	1444	18	10	--	640	2.3	--
51	Fort Spokane RB	10-12-92	1710	21	6.0	79	240	1.1	550
		10-12-92	1711	22 (4.6)	5.7 (5.1)	79 (0)	240 (0)	1.1 (0)	540 (1.8)
61	Whitestone Creek MS	10-14-92	1345	16	9.8	76	290	1.4	1,000
		10-14-92	1346	18	10	--	310	1.5	--
		10-14-92	1347	--	10	--	310	1.5	--
		10-14-92	1348	19	10	--	310	1.6	--
		10-14-92	1349	18	11	--	290	1.5	--
66	Keller Ferry RB	10-15-92	1130	15	3.9	52	200	0.5	570
		10-15-92	1131	14 (6.8)	3.9 (0)	--	200 (0)	0.5 (0)	--
				Minor tributary					
44	Hall Creek LB	10-10-92	1430	8.0	1.2	30	50	0.1	150
		10-10-92	1431	8.1 (1.2)	1.4 (15)	--	47 (6.1)	0.1 (0)	--

Table 7.--*Methods used for trace-element analysis for samples of suspended and bed sediment*

Method	Digestion used	Elements analyzed	Sample medium	Laboratory
Inductively coupled plasma mass spectroscopy	Perchloric-hydrofluoric hydrochloric nitric acid	Total aluminum, cadmium, copper, lead, manganese, and zinc	Bed sediment	GeoAnalytical Laboratory Geology Department Washington State University (WSU)
Instrumental neutron activation analysis	None	Total antimony, arsenic, barium, chromium, and iron	Bed sediment	Nuclear Radiation Center WSU
Cold vapor atomic absorption spectroscopy (AAS)	Nitric-sulfuric acid and stannous chloride reduction	Total mercury	Bed sediment	Zenon Environmental Laboratories, Burnaby, Canada
Graphite furnace AAS, cold vapor AAS	Nitric-sulfuric acids	Total recoverable arsenic, cadmium, copper, lead, mercury, and zinc	Bed sediment	Washington State Department of Ecology and U.S. Environmental Protection Agency Manchester Laboratory, Port Orchard, Wash.
Energy dispersive X-ray fluorescence	None	Total arsenic, copper, iron, manganese, lead, and zinc	Suspended sediment	Battelle Marine Sciences Laboratory Sequim, Wash.[1]
Graphite furnace AAS	Perchloric-hydrofluoric-nitric acids	Total cadmium	Suspended sediment	Battelle Marine Sciences Laboratory Sequim, Wash.[1]
Cold vapor AAS	Nitric-sulfuric acid and stannous chloride reduction	Total mercury	Suspended sediment	Battelle Marine Sciences Laboratory Sequim, Wash.[1]

[1] Bed sediment also analyzed by Battelle for interlaboratory comparison.

Table 8.--*Concentration of trace elements in sediment, rock, soil, and slag*

[Concentrations are in milligrams per kilogram; median or mean concentrations of trace elements are in parentheses; sediment concentrations larger than median concentrations of all reaches in Lake Roosevelt bed sediment are in bold type; --, no data or not applicable]

Location	Number of samples	Arsenic	Cadmium	Copper	Lead	Mercury	Zinc
Bed sediments, Lake Roosevelt							
Lake Roosevelt, upper reach	5 (median)	20	6.3	300	430	1.4	2,000
Lake Roosevelt, middle reach	18 (median)	15	7.0	98	380	1.4	930
Lake Roosevelt, lower reach	9 (median)	16	4.7	55	190	.5	570
Lake Roosevelt, all reaches	32 (median)	16	6.2	85	310	1.3	970
Bed sediments, Columbia River/Lower Arrow Lake							
Columbia River, reach IV[1,7]	6 (median)	**17**	2.8	**510**	**360**	0.6	**3,800**
Columbia River, Northport reach	9 (median)	**32**	1.2	**2,600**	310	.3	**13,000**
Lower Arrow Lake, reach I	2 (mean)	1.7	.5	7.0	30	<.05	54
Suspended sediments, Columbia River/Lower Arrow Lake							
Columbia River, reach IV[1,7]	3 (median)	**47**	**18**	**250**	**840**	**5.5**	**1,400**
Columbia River, at Northport	3 (median)	**40**	**13**	**360**	**490**	[8]**1.7**	**1,500**
Lower Arrow Lake, reach I[1,7]	3 (median)	3.4	<1	48	46	.05	310
Bed sediment, major and minor tributaries							
Colville River	3 (median)	6.0	3.3	39	68	0.2	260
Kettle River	3 (median)	2.4	<.5	23	20	<.05	44
Sanpoil River	3 (median)	7.3	.9	36	23	.05	160
Spokane River	3 (median)	**19**	6.0	42	120	.1	**1,000**
Hall Creek	2 (mean)	6.8	1.3	30	38	.09	140
Hawk Creek	1 --	**20**	1.0	29	35	<.05	170
Sherman Creek	1 --	1.4	1.8	9.0	49	.10	140
Beach and bank sediments							
Beach	3 (median)	3.2	<.5	9.0	23	<.05	75
Bank	4 (median)	**19**	<.5	--	21	<.05	90
Other sediment and soil							
World average shale[2]	-- --	13	0.3	45	20	0.4	95
Soils, Okanogan County[3]	3 (mean)	3	<2	30	13	.04	75
Soils, Spokane and Stevens Counties[3]	3 (mean)	10	<2	29	19	.07	84
Soils, western United States[4]	-- (mean)	5.5	--	21	17	.05	55
Rivers and lakes, United States[5]	61 (median)	4	--	11	15	.03	47
Slag							
Slag, treated[6]	-- --	**100**	**10**	**6,000**	**870**	<.005	**25,000**

[1] Taina Tuominen, Environment Canada, written commun., March 1993 (data collected 1990-1991).

[2] Bowen, 1966.

[3] Kenneth Ames, U.S. Geological Survey, written commun., April 1993.

[4] Shacklette and Boerngen, 1984.

[5] Horowitz, Elrick, and Hooper, 1989a.

[6] Cominco Metals, 1991b; Kuit, W.J., Cominco Metals, written commun., October 1991; R.W. Abbey, Cominco Metals, written commun., December, 1993; Nener, 1992.

[7] Total recoverable trace elements.

[8] Two samples instead of three.

To provide a comparison of total trace-element concentrations in Lake Roosevelt with results from other investigations that used total-recoverable analysis, sediment from a subset of 18 sites was split and analyzed for total-recoverable trace elements. Total concentration methods determine the concentrations in all or nearly all of the sediment sample, and concentrations obtained by these methods are regarded as being greater than or equal to 95 percent of the actual concentration (Horowitz, 1991). Total-recoverable methods use strong-acid digestion procedures that are not expected to digest all of the sediment so that the analytical results represent less than the "total" or actual concentration.

A comparison of the results from the total-concentration analysis and the total-recoverable analysis is tabulated in table 9. For cadmium, copper, lead, and zinc, median total-recoverable concentrations ranged from 89 to 96 percent of the total concentrations (95 percent or more of actual); for mercury and arsenic, median total-recoverable concentrations ranged from 44 to 64 percent of total concentrations. However, the range varied from 20 to 134 percent for individual trace-element samples. Percents greater than 100 are possible if the analytical data for total recoverable trace-element concentrations are larger than expected and analytical data for total concentrations are lower than expected.

Comparison of Trace-Element Concentrations in Bed Sediment to Sediment-Quality Guidelines

Concentrations of trace elements in bed sediment were compared with sediment-quality guidelines for fresh-water environments developed by the Water Resources Branch of the Ontario Ministry of Environment and Energy, Canada (Persaud and others, 1991; Jaagumagi, 1993). These guidelines are based on two levels of toxic effects. The first level, termed the lowest-effect level, represents trace-element concentrations that affect sensitive species, but which can be tolerated by most benthic organisms. The second level, the severe-effect level, represents trace-element concentrations at which "pronounced disturbances of the sediment-dwelling community can be expected" (Persaud and others, 1991; Jaagumagi, 1993). Concentrations at or exceeding the severe-effect level are considered detrimental to most benthic species. Guidelines developed by the Ontario Ministry of Environment and Energy were based on a total-recoverable analysis of bulk sediment using dissolution in aqua regia (hydrochloric:nitric, 3:1 acid digestion; Jaagumagi and Persaud, 1993).

The total trace-element concentrations exceeded the severe-effect guidelines at 28 sites in the Northport reach of the Columbia River and Lake Roosevelt (table 10), but because the total trace-element analysis methods yield larger concentrations than total-recoverable methods, the actual number of sites with severe-effects concentrations may be less. A direct comparison of trace-element concentrations from total-recoverable methods used in development of the sediment-quality guidelines and trace-element concentrations from total concentration methods used in this study is not available. However, the total trace-element concentrations would not be expected to exceed the total-recoverable concentrations by more than 100 percent, as shown in table 9. Copper, lead, or zinc exceeded the severe-effects level concentrations by 100 percent or more at 18 sites in the Columbia River and Lake Roosevelt (table 10). At several sites copper and zinc exceeded the severe-effects guideline by more than a factor of 20. The sites where concentrations exceeded severe-effect guidelines by more than 100 percent were clustered in the Columbia River and the upper reach of the reservoir. Total concentrations of arsenic, cadmium, and mercury all exceeded the severe-effects level at several sites, but none by more than 60 percent. Additional sediment guidelines and criteria from various sources are summarized in a report by Bennett and Cubbage (1991). The sediment-quality guidelines described in their report were also exceeded at many sites within Lake Roosevelt and the Northport reach of the Columbia River.

Table 9.--*Analyses of trace-element concentrations in sediments in Lake Roosevelt and tributaries as derived from the total-concentration and total-recoverable methods*

[LB, RB, and MS indicate samples were collected on right side (toward the "right bank" from mid channel), left side (toward the "left bank" from mid channel), and near the mid-section channel, respectively, numbers 1 and 2 denote different sites toward the same bank; TR, total recoverable; TC, total concentration; mg/kg, milligrams per kilogram; --, not detected]

		Arsenic[1] (mg/kg)			Cadmium (mg/kg)			Copper (mg/kg)			Lead (mg/kg)			Mercury[1] (mg/kg)			Zinc (mg/kg)		
Site number	Site name (see plate 1 for complete name)	TR	TC	Percent TC[2]	TR	TC	Percent TC[2]	TR	TC	Percent TC[2]	TR	TC	Percent TC[2]	TR	TC	Percent TC[2]	TR	TC	Percent TC[2]
	Columbia River and major tributaries																		
3	Keenleyside Dam LB	<0.9	<2.0	--	<0.2	<0.5	--	6.9	9.0	77	<4.8	17	--	0.006	<0.05	--	29	47	62
6	Pend D'Oreille River LB	8.4	13	65	6.5	8.7	75	20	18	110	200	220	91	.1	0.1	100	1,400	1,600	88
8	Boundary LB	27	34	79	<2.8	1.0	--	2,500	2,700	93	300	280	107	.1	.2	50	12,000	13,000	92
10	Auxiliary Gage LB	27	35	77	<3.8	1.1	--	2,800	3,000	93	260	310	84	.06	.3	20	14,000	16,000	88
11	Goodeve Creek RB	29	32	91	<2.4	.9	--	2,800	2,900	97	290	310	94	.05	.1	50	16,000	17,000	94
15	Onion Creek LB	12	21	57	5.2	5.1	102	510	540	94	330	340	97	.4	.8	50	3,200	3,600	89
53	Spokane River LB	12	19	63	5.6	6.0	93	24	42	57	100	120	83	.05	.1	50	1,000	1,000	100
62	Sanpoil River MS	3.4	7.3	47	<1.3	1.4	--	25	36	69	15	23	65	.03	.06	50	120	160	75
62	Sanpoil River MS (duplicate)	4.0	7.3	55	<1.4	1.4	--	25	36	69	15	23	65	.02	.06	33	120	160	75
	Reservoir																		
1	Lower Arrow Lake LB1	1.5	2.0	75	<.2	.5	--	9.4	7.0	134	15	28	54	.01	<.05	--	40	49	82
2	Lower Arrow Lake LB2	1.1	1.5	73	<.4	.5	--	7.6	7.0	109	18	32	56	.008	<.05	--	46	60	77
17	China Bend RB	14	24	58	6.5	6.3	103	530	550	96	460	480	96	.6	1.4	43	2,900	3,000	97
19	Bossborg RB	9.4	13	72	4.6	4.5	102	220	230	96	270	280	96	.4	.9	44	1,300	1,400	93
37	French Point Rocks RB	5.8	9.3	62	7.3	7.8	94	98	99	99	380	390	97	.8	1.7	47	870	930	94
38	French Point Rocks MS	11	19	58	11	9.9	110	200	220	91	580	570	102	.7	2.3	30	1,200	1,300	92
48	Ninemile Creek LB	7.0	12	58	3.4	3.6	94	32	45	71	130	140	93	.2	.5	40	350	410	85
58	Seven Bays LB	12	17	71	11	10	110	56	69	81	300	320	94	<.5	1.4	--	1,000	1,100	91
61	Whitestone Creek MS	11	16	69	9.4	9.8	96	66	76	87	280	290	97	.4	1.4	29	950	1,000	95
71	Grand Coulee Dam RB	8.1	18	45	5.6	6.2	90	51	61	84	170	190	89	.2	.8	25	610	730	84
	Number of analysis pair for which neither value is below detection limit		18			11			19			18			15			19	
	Range of total recoverable percent of total concentrations		45-91			75-110			57-134			54-107			20-100			62-100	
	Median value for total recoverable percent of total concentrations		64			96			93			94			44			89	

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[1] Arsenic and mercury are estimated concentrations.

[2] Total recoverable as percentage of total concentration.

Table 10.--*Total trace-element concentrations in bed sediment exceeding sediment-quality guidelines for severe-effect level*

[Total concentrations exceeding guidelines by 100 percent or more are in bold type; R, Lake Roosevelt site; C, Columbia River; T, tributary; D, delta deposit; LB, RB, and MS indicate samples were collected on right side (toward the "right bank" from mid channel), left side (toward the "left bank" from mid channel), and near the mid-section channel, respectively, numbers 1 and 2 denote different sites toward the same bank; a severe-effect level is a concentration that would be detrimental to a majority of benthic species; mg/kg, milligrams per kilogram; --, respective trace-element concentration did not exceed severe-effect level]

Site number	Site name (see plate 1 for for complete name)	Site type	Concentrations of trace elements meeting or exceeding severe-effect level (in parentheses)					
			Arsenic (33 mg/kg)	Cadmium (10 mg/kg)	Copper (110 mg/kg)	Lead (250 mg/kg)	Mercury (2 mg/kg)	Zinc (820 mg/kg)
6	Pend D'Oreille River LB	T	--	--	--	--	--	1,600
7	Boundary RB	C	52	--	**3,300**	480	--	**17,000**
8	Boundary LB	C	34	--	**2,700**	280	--	**13,000**
9	Auxiliary Gage RB	C	43	--	**2,600**	270	--	**13,000**
10	Auxiliary Gage LB	C	35	--	**3,000**	310	--	**16,000**
11	Goodeve Creek RB	C	--	--	**2,900**	310	--	**17,000**
12	Goodeve Creek LB	C	--	--	**670**	370	--	**3,200**
13	Big Sheep Creek RB	D	--	--	--	--	--	1,600
15	Onion Creek LB	C	--	--	**540**	340	--	**3,600**
16	Onion Creek RB	C	--	--	**800**	300	--	**4,600**
17	China Bend RB	R	--	--	**550**	480	--	**3,000**
18	China Bend MS	R	33	--	**3,000**	430	--	**22,000**
19	Bossborg RB	R	--	--	**230**	280	--	1,400
20	Summer Island RB1	R	--	11	**300**	**660**	2.7	**1,800**
21	Summer Island RB2	R	--	--	170	420	--	**2,000**
22	Marcus Island MS	R	--	--	170	310	--	1,000
24	Marcus Island LB	R	--	--	**410**	**510**	--	**2,200**
28	West Kettle Falls LB	R	--	--	**290**	440	--	**1,700**
35	Haag Cove RB	R	--	--	150	490	2.2	1,100
36	Haag Cove MS	R	--	--	**260**	400	--	**1,800**
37	French Point Rocks RB	R	--	--	--	390	--	930
38	French Point Rocks MS	R	--	--	**220**	**570**	2.3	1,300
40	Cheweka Creek LB	R	--	--	--	**550**	--	1,000
41	Gifford MS	R	--	--	110	470	2.8	1,000
42	Gifford LB	R	--	--	110	480	2.5	940
46	Hunters LB	R	--	--	--	380	--	--
47	Ninemile Creek MS	R	--	--	--	270	--	--
52	Spokane River MS	T	--	10	--	--	--	**1,800**
53	Spokane River LB	T	--	--	--	--	--	1,000
54	Spokane River RB	T	--	--	--	--	--	980
58	Seven Bays LB	R	--	10	--	320	--	1,100
61	Whitestone Creek MS	R	--	--	--	290	--	1,000
70	Swawilla Basin MS	R	--	--	--	310	--	1,100

Comparison of Trace-Element Concentrations in Bed Sediment to Upstream and Downstream Sites of Lake Roosevelt

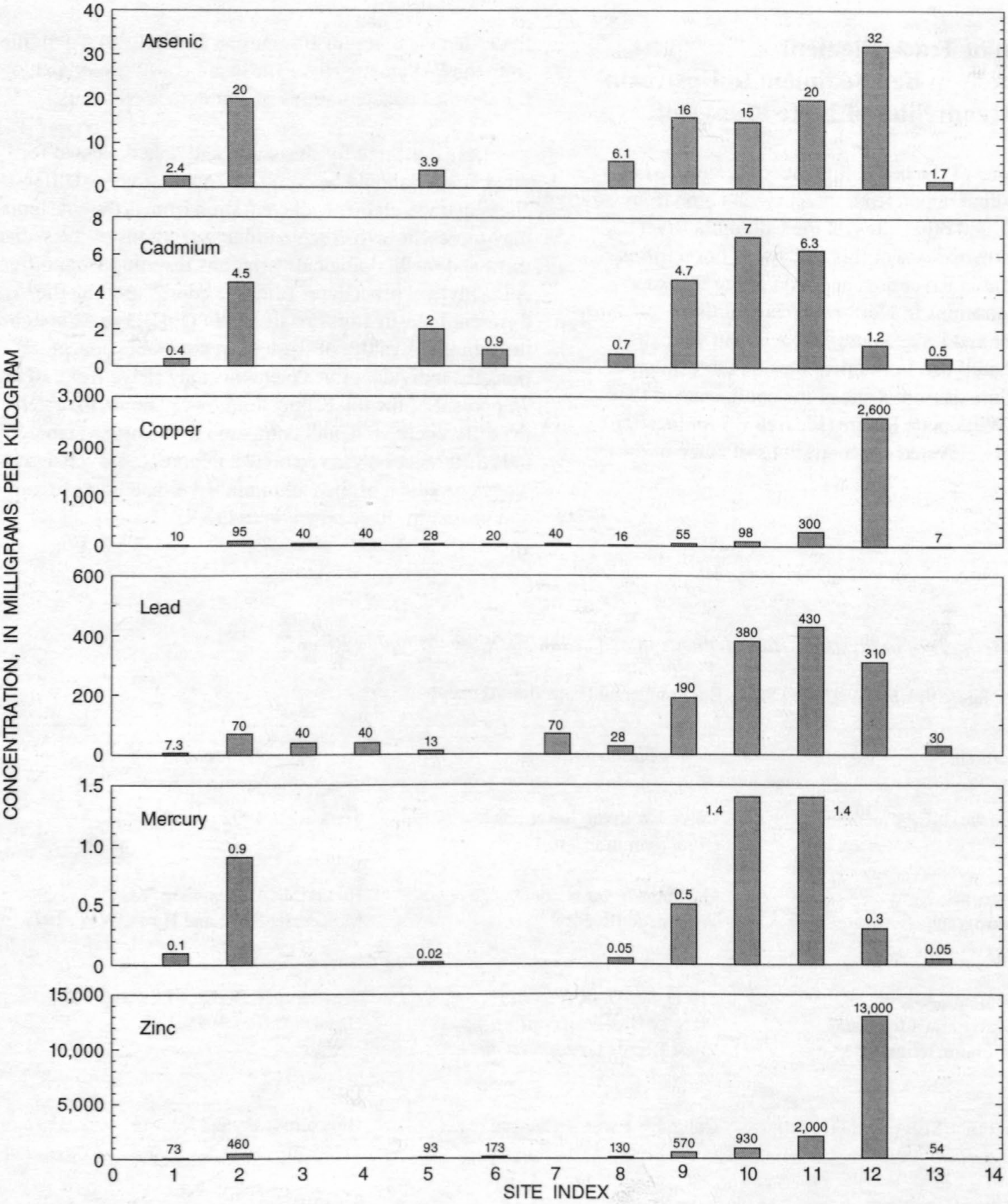
Comparisons of the bed-sediment concentrations of arsenic, cadmium, copper, lead, mercury, and zinc from Lake Roosevelt and other sites on the Columbia River upstream and downstream of this study area or on tributaries to the Columbia River are shown on figure 9. Trace-element concentrations in Northport reach of the Columbia River and Lake Roosevelt sediment were distinctly larger than those from other sites on the Columbia River. Bed sediment from a site at the confluence of the Columbia and Willamette Rivers (see figure 5 for location) showed similarly elevated concentrations of some of the trace elements. Inputs from urban and industrial activities from the Willamette River Basin are possible explanations for elevated concentrations of some trace elements.

Data collected for this study and data collected for other studies should be compared qualitatively. Differences in trace-element concentration from different studies may represent both compositional variations of the sediment and methodological variations resulting from different analytical procedures (the procedures used by the different investigators are shown in table 11). Although the minimum values of the total-recoverable concentrations for individual trace elements may range from 20 to 75 percent of the total concentration as shown in table 9, the differences are small compared to the order-of-magnitude differences observed between Lake Roosevelt and the Northport reach of the Columbia River and downstream and upstream sites shown on figure 9.

Table 11.--*Methods of analysis of trace elements in bed sediment in the Columbia River*

[Data used for figure 9; USEPA, United States Environmental Protection Agency]

Methods	Site description	Reference
Total recoverable, USEPA method 6010	Columbia River, lower reach (from river mile 0 to 146)	Tetra Tech, 1992
Total trace elements; X-ray emission spectrograph	Columbia River at confluence of Willamette River	Rickert, D.A., Kennedy, V.C., McKenzie, S.W., and Hines, W.G., 1977
Total trace elements, X-ray emission spectrograph after fusing samples with lithium tetraborate	The Dalles Dam, reservoir McNary Dam, reservoir Priest Rapids Dam, reservoir	Whetten, J.T., Kelley, J.C., and Hansen, L.G., 1969
Total recoverable, USEPA method 6010	Columbia River at Hanford reach	Peterson, R.E., and Johnson, V.G., 1992
Total trace elements; neutron activation analysis and inductively coupled plasma mass spectroscopy; and total recoverable, USEPA method 6010	Lake Roosevelt, Columbia River, and Rufus Woods Lake	This study



EXPLANATION

SITE INDEX	SITE DESCRIPTION
1	Lower Columbia River, river mile 0 to river mile 146
2	Columbia River at confluence of Willamette River
3	The Dalles Dam, reservoir on Columbia River
4	McNary Dam, reservoir on Columbia River
5	Yakima River Basin
6	Columbia River, Hanford reach riverbank seepage areas
7	Priest Rapids Dam, reservoir on Columbia River
8	Rufus Woods Lake
9	Lake Roosevelt, lower reach
10	Lake Roosevelt, mid reach
11	Lake Roosevelt, upper reach
12	Columbia River, Northport reach
13	Lower Arrow Lake

Figure 9.--Concentrations of arsenic, cadmium, copper, lead, mercury, and zinc in bed sediment at selected sites in the Columbia River and its tributaries and along the reaches in the Lake Roosevelt study area.

Spatial Variability and Sources of Sediment

The spatial variability and sources of trace elements are discussed in three parts corresponding to three distinct bodies of water or potential sources of sediment: the Northport reach of the Columbia River and Lake Roosevelt, the major and minor tributaries, and the banks and beaches.

Northport Reach of the Columbia River and Lake Roosevelt

Total copper and zinc concentrations in bed sediments were elevated in the Northport reach of the Columbia River and then decreased with distance downstream in the reservoir sediments (figs. 10 and 11). Copper and zinc concentrations were larger in the Northport reach of the Columbia River and in the upper reach of Lake Roosevelt and relatively smaller (still large compared to reference sites) in the mid and lower reaches (figs. 10 and 11). For example, median copper and zinc concentrations were 2,600 and 13,000 mg/kg in the Northport reach of the Columbia River, and median concentrations of these elements were 98 and 930 mg/kg in the mid reach of the reservoir (table 8), respectively. Several trace elements followed a pattern similar to copper and zinc—large concentrations in the Northport reach that decreased progressively through the upper and mid reaches. The pattern of total antimony and iron concentrations in bed sediment was almost identical to copper and zinc (fig. 10). Total arsenic, barium, chromium, and manganese concentrations also exhibited similar but less pronounced patterns (fig. 12). The concentrations of eight elements (antimony, arsenic, barium, chromium, copper, iron, manganese, and zinc) were significantly correlated positively with each other and followed the same general pattern of larger concentrations near the international boundary (RM 745) and smaller concentrations down reservoir to French Point Rocks (RM 691). Beyond French Point Rocks the concentrations of seven of these eight elements (manganese was the exception) remained nearly the same downstream to Grand Coulee Dam (fig. 12).

Slag particles discharged to the Columbia River by an upstream smelter facility are a probable source of the elevated trace-element concentrations in the bed sediment of the Northport reach and the upper reach of Lake Roosevelt because (1) slag contains large trace-element concentrations found in these sediments, (2) the dominant fraction of slag is sand size, which is the predominant size of the bed sediments in the Northport reach of the Columbia River and the upper reach of Lake Roosevelt, and (3) suspended sediment entering Lake Roosevelt contained silt-size slag particles enriched in trace elements.

The predominant elements present in the slag particles as determined from X-ray analysis were calcium, iron, and silicon, with minor and varying amounts of aluminum, chromium, copper, manganese, potassium, sodium, sulfur, titanium, and zinc. In addition to the common calcium-iron silicate inclusions (minerals within a glass matrix), other inclusions were copper-zinc-iron sulfides, iron-titanium oxides, iron oxides, and aluminum-manganese-iron-zinc oxide phases. The elevated concentrations of copper and zinc in slag were due in part to the inclusions identified within the glassy slag matrix. Analysis of slag taken from 1991 to 1993 indicated that the slag included but was not limited to the following elements and concentrations: arsenic, 100 mg/kg; antimony, 100 mg/kg; copper, 6,000 mg/kg; manganese, 8,000 mg/kg; iron, 330,000 mg/kg; and zinc, 25,000 mg/kg (Cominco Metals, 1991b; R.W. Abbey, Cominco Metals, written commun., December, 1993). Thus, concentrations of copper and zinc and the associated groups of elements of antimony, arsenic, iron, and manganese are useful indicators of slag deposition in the reservoir. Although it is known from the X-ray analysis that some of these elements are incorporated in the sediment matrix, proportions of trace elements incorporated into the sediment matrix or sorbed to the sediment surface are not known.

About 93 percent of the slag discharged to Columbia River is coarser than 0.062 mm in diameter (sand size) (Nener, 1992). Analysis of slag particle-size distributions by Nener found values similar to those reported by Cominco Metals (1991b). For this study, three samples from submerged sandbars in the Northport reach were analyzed for slag particles. Under a microscope, glass slag particles were easily recognized as morphologically distinct from natural sediment because they commonly consisted of needles and sharply angular grains of sand size (fig. 13). The particles were then counted to determine the slag fraction by particle count. Starting with the most upstream sample and continuing about 15 mi downstream, particle counts showed that dark glassy slag made up 48, 28, and 5 percent of the total sample of sediments for sites Boundary RB (RM 745), Goodeve Creek RB (RM 738), and Onion Creek LB (RM 730), respectively. The percentage of slag at each of the three sites was from a single sample within the channel cross section and therefore does not necessarily represent the mean cross sectional value. A reference bank sample taken near Ninemile Creek (RM 648) contained naturally occurring minerals consistent with the geology of the area.

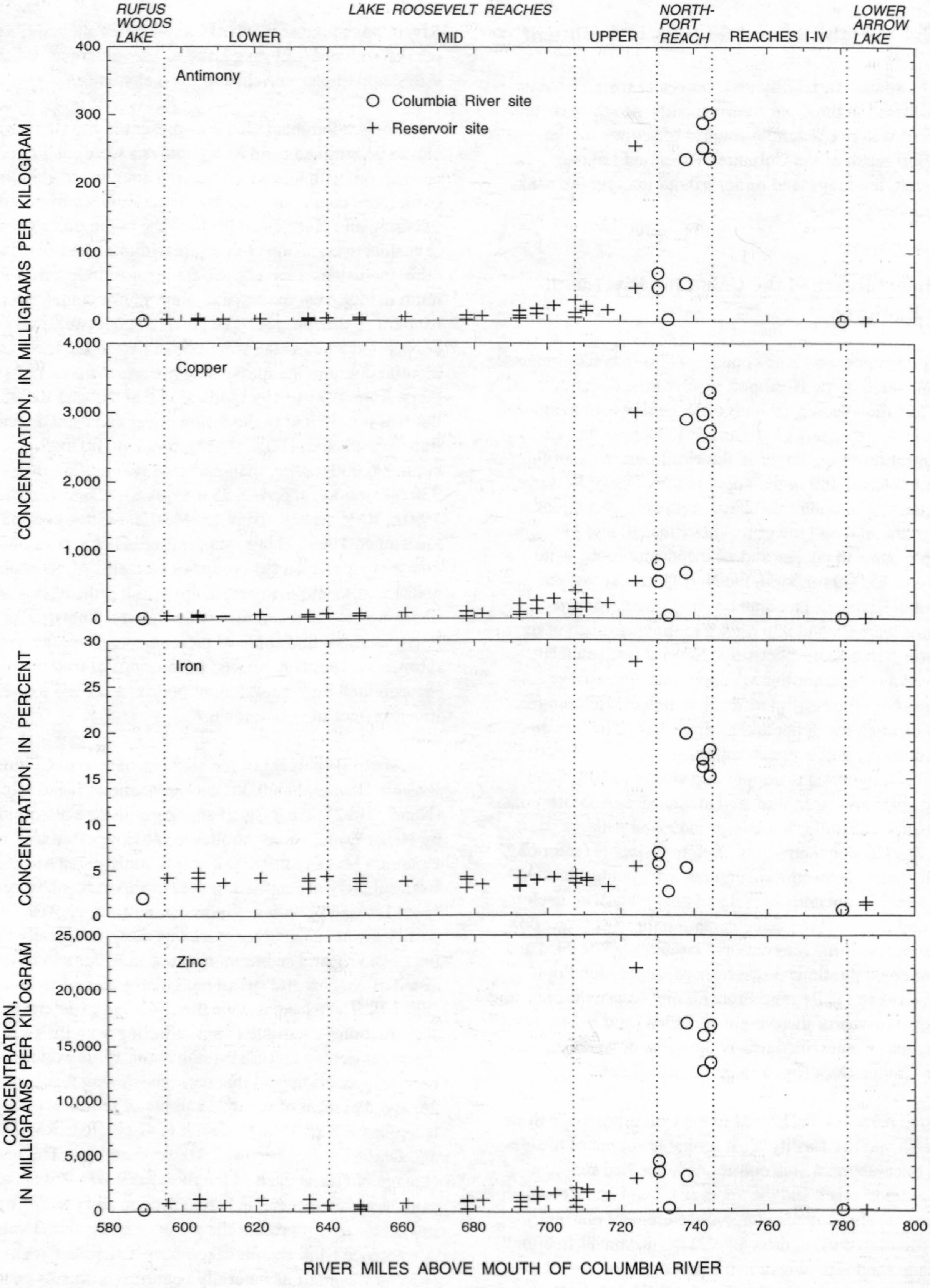


Figure 10.--Longitudinal distribution of total antimony, copper, iron, and zinc concentrations in bed sediment along the reaches in the Lake Roosevelt study area.

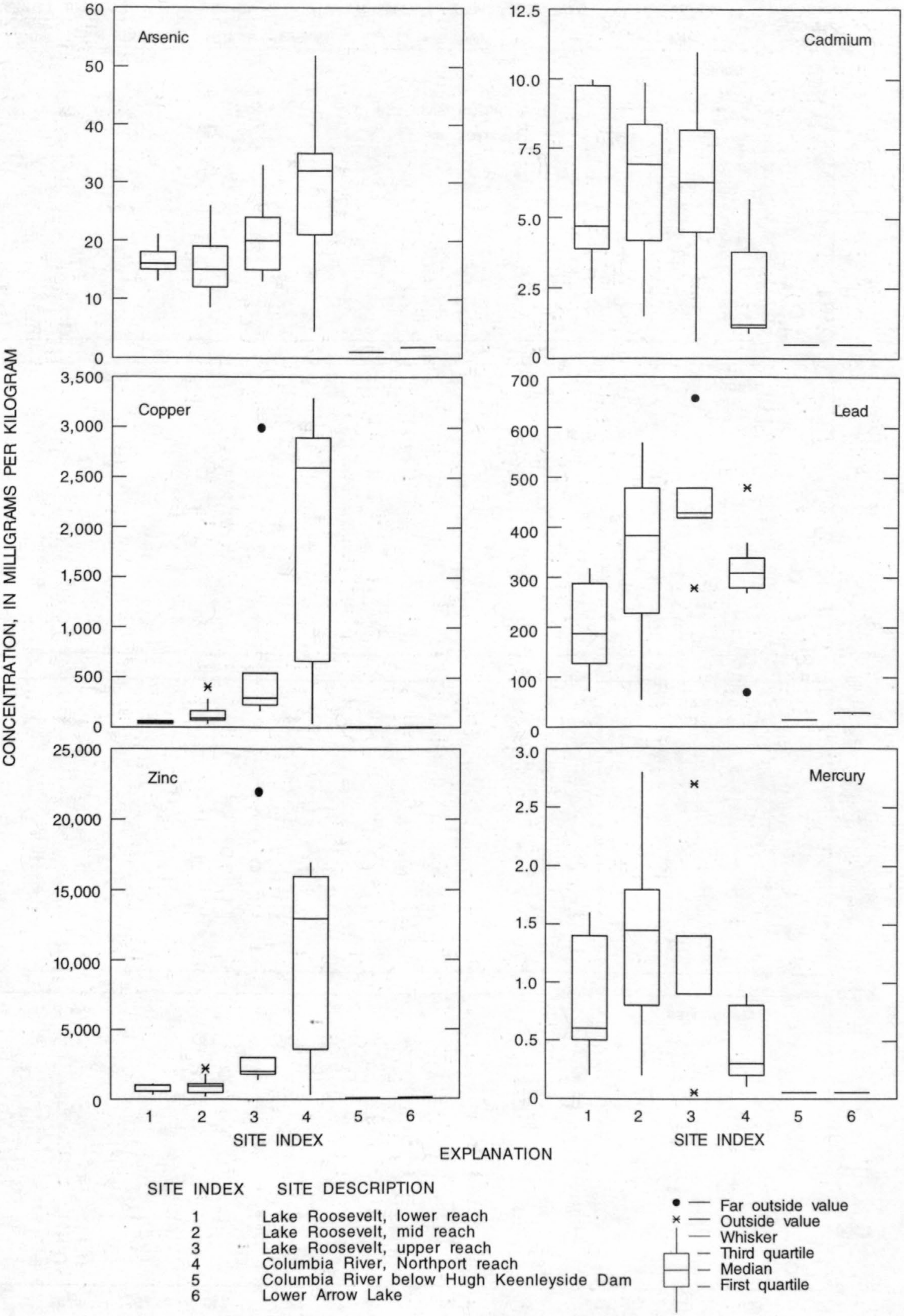


Figure 11.--Distribution of total arsenic, copper, zinc, cadmium, lead, and mercury concentrations in bed sediment along the reaches in the Lake Roosevelt study area.

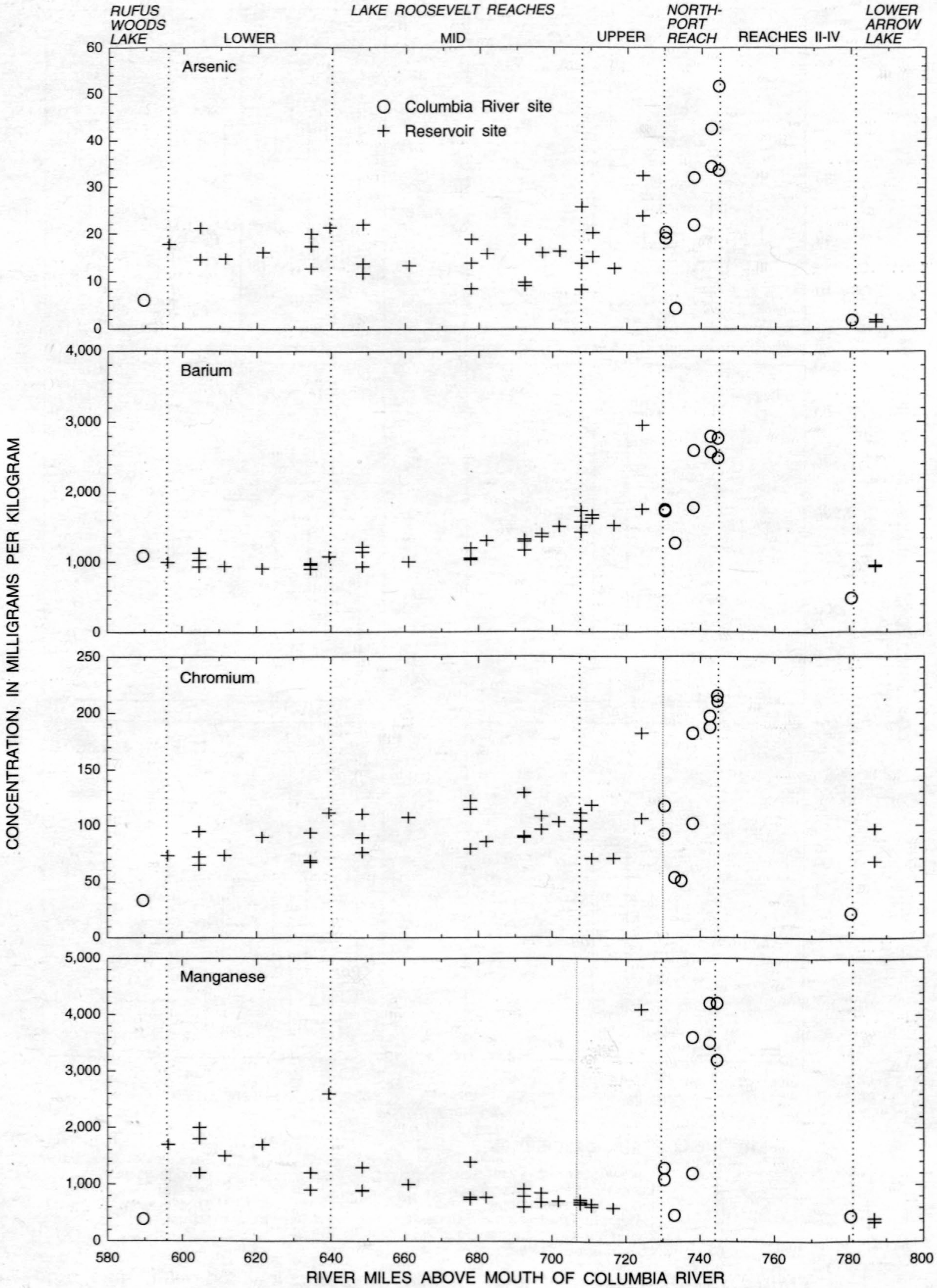


Figure 12.--Longitudinal distribution of total arsenic, barium, chromium, and manganese concentrations in bed sediment along the reaches in the Lake Roosevelt study area.

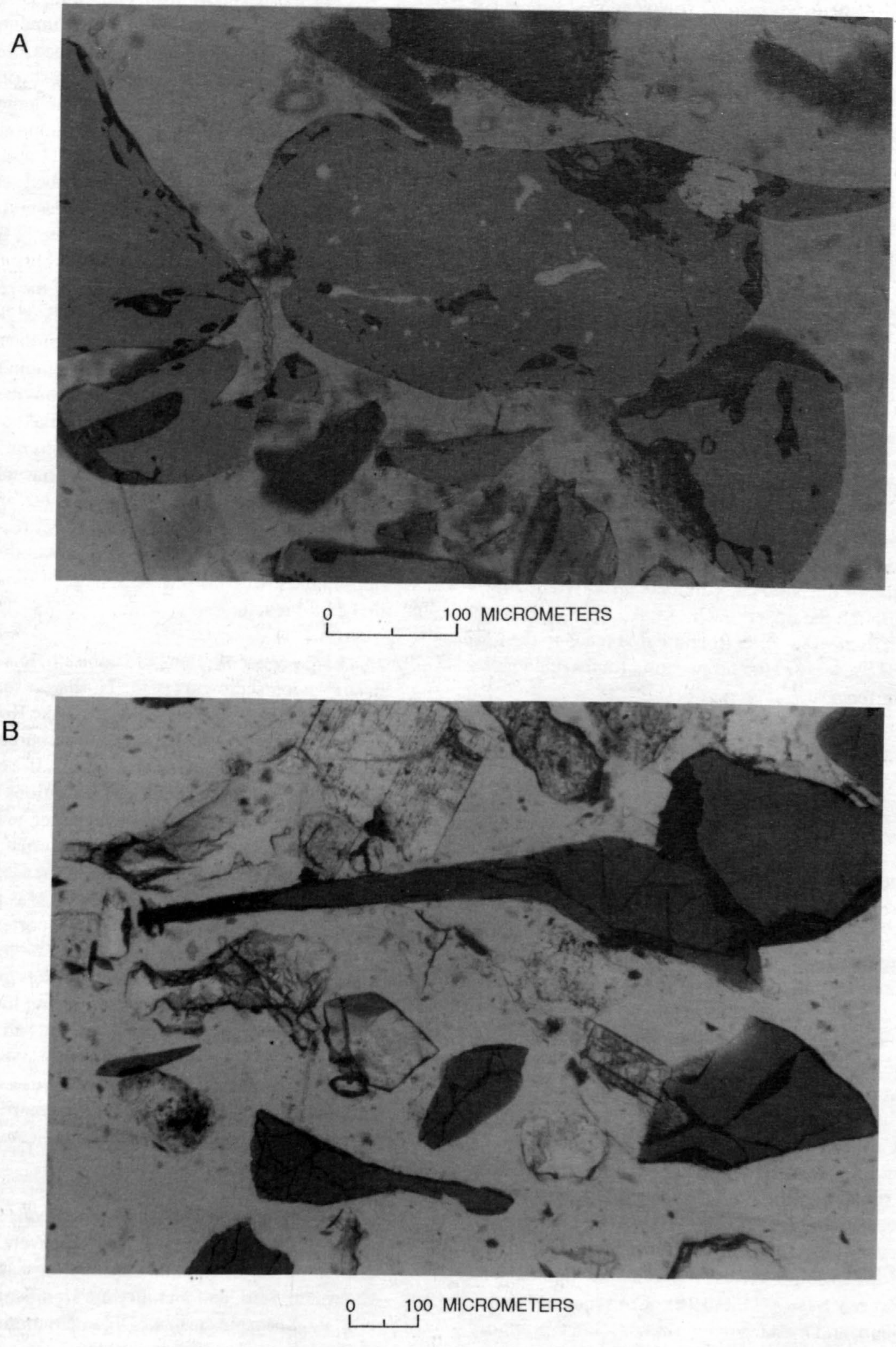


Figure 13.--Magnified view of slag particles from sites (A) Boundary RB and (B) Goodeve Creek RB.

Microscopic examination of suspended sediment collected in the Columbia River in the Northport reach showed that fine silt-size material contained opaque glassy slag particles as well as mineral grains. The predominant size of the suspended sediment was 0.010-0.020 mm (fine silt). Suspended sediment could also originate as part of the waste effluent discharged to the Columbia River from smelter operations; this effluent contains arsenic and zinc in soluble and suspended form (W.J. Kuit, Cominco Metals, written commun., October 1991). Concentrations of arsenic, copper, and zinc were larger in the suspended sediment from the Columbia River (reach IV and the Northport reach) than in the bed sediment of Lake Roosevelt (table 8). Thus, suspended sediment transported by the Columbia River and deposited in Lake Roosevelt is a source of enriched trace-element concentrations in bed sediment.

Slag particles in bed sediment at the three sites analyzed for slag content also became progressively finer at sites downstream. In sampled bed sediments, the predominant grain size in the Northport reach was sand-sized, and the fraction of fines in bed sediments increased downstream through the upper reach of Lake Roosevelt, as shown on figure 14. Then from the mid reach to the lower reach of the reservoir, the proportion of fines remained relatively uniform.

The steep concentration gradients for copper and zinc in bed sediments from the Northport reach of the Columbia River through the upper Roosevelt reservoir and the presence of slag in bed sediments and in suspended sediments to the Columbia River suggest that the main stem of the Columbia River is a source of these trace-element-enriched sediments. The median concentrations of copper and zinc in the Northport reach were six to nine times larger, respectively, than those in the upper reach of Lake Roosevelt. In addition, reference bed sediment from Lower Arrow Lake, which is upstream of the smelter, had concentrations of copper 12 times and zinc 18 times smaller than median concentrations in Lake Roosevelt bed sediments (table 8).

The pattern of spatial variability for concentrations of total cadmium, lead, and mercury in bed sediment was different from that of the slag- associated elements copper and zinc. The largest concentrations of cadmium, lead, and mercury were found downstream of the Northport reach of the Columbia River rather than within the Northport reach (figs. 11 and 15). Consequently, cadmium, lead, and mercury were not associated primarily with the sand-size slag deposits found in the Northport reach.

Larger concentrations of cadmium, lead, and mercury were found in Lake Roosevelt bed sediments than in bed sediments of the Northport reach of the Columbia River; these trace elements showed their largest concentrations in different areas of Lake Roosevelt. The largest total lead and mercury concentrations were found in the upper and mid reaches of Lake Roosevelt (figs. 11 and 15). The median concentrations of total lead in bed sediments of the upper, mid, and lower reaches of the reservoir were 430, 380, and 190 mg/kg, respectively (table 8; fig. 11). Like lead, the largest concentrations of mercury also were found in the upper and mid reaches of the reservoir. The median concentrations of total mercury in bed sediments of the upper, mid, and lower reaches of the reservoir were 1.4, 1.4, and 0.5 mg/kg, respectively (table 8; fig. 11). Cadmium concentrations increased from the Northport reach of the Columbia River through the upper reach of the reservoir (figs. 11 and 15); however, unlike the lead concentrations, large total cadmium concentrations were found throughout the reservoir—6.3, 7.0, and 4.7 mg/kg (medians) for the upper, mid, and lower reaches of the reservoir, respectively (table 8). Some cadmium concentrations in the lower reach were as large as those at some sites in the mid reach.

Large concentrations of cadmium, lead, and mercury in suspended sediments in the Northport reach of the Columbia River (table 8) entering Lake Roosevelt are evidence that suspended sediment are a source of enriched concentrations of these trace elements in bed sediments of Lake Roosevelt. Cadmium concentrations were about 11 times larger, lead about 1.5 times larger, and mercury about 6 times larger in suspended sediment than in bed sediments of the Northport reach of the Columbia River. The suspended sediment at Northport was predominantly the size of fine silt, which can be transported in suspension to the mid and lower reaches of the reservoir. The rate of transport will depend in part on the reservoir operation and availability of sediment. In the mid and lower reaches of the reservoir, a large percentage of the bed sediments was finer than 0.062 mm (silt and clay size; table 12, fig. 14). An increase in aluminum concentrations was found in mid and lower reaches of the reservoir primarily because silts and clays are composed of aluminosilicate materials (fig. 14).

The largest total organic carbon concentrations were found in the mid reach of Lake Roosevelt, where median concentrations of cadmium and mercury also were largest. Cadmium, lead, and mercury are significantly correlated with total organic carbon. Organic material associated with suspended sediment could serve as a substrate for the binding of cadmium, lead, and mercury.

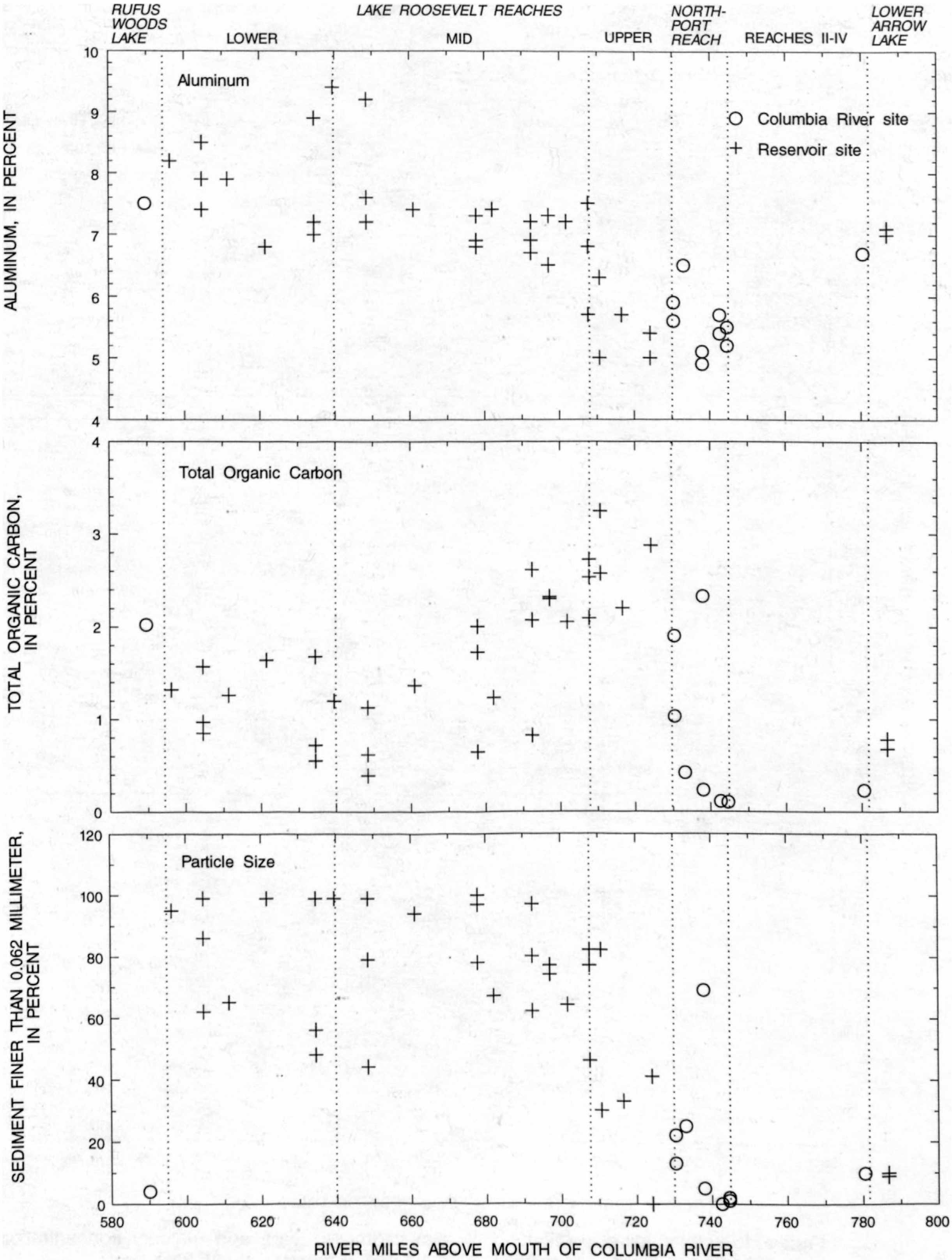


Figure 14.--Longitudinal distribution of percent aluminum, percent total organic carbon, and percentage of sediment finer than 0.062 millimeter in bed sediment along the reaches in the Lake Roosevelt study area.

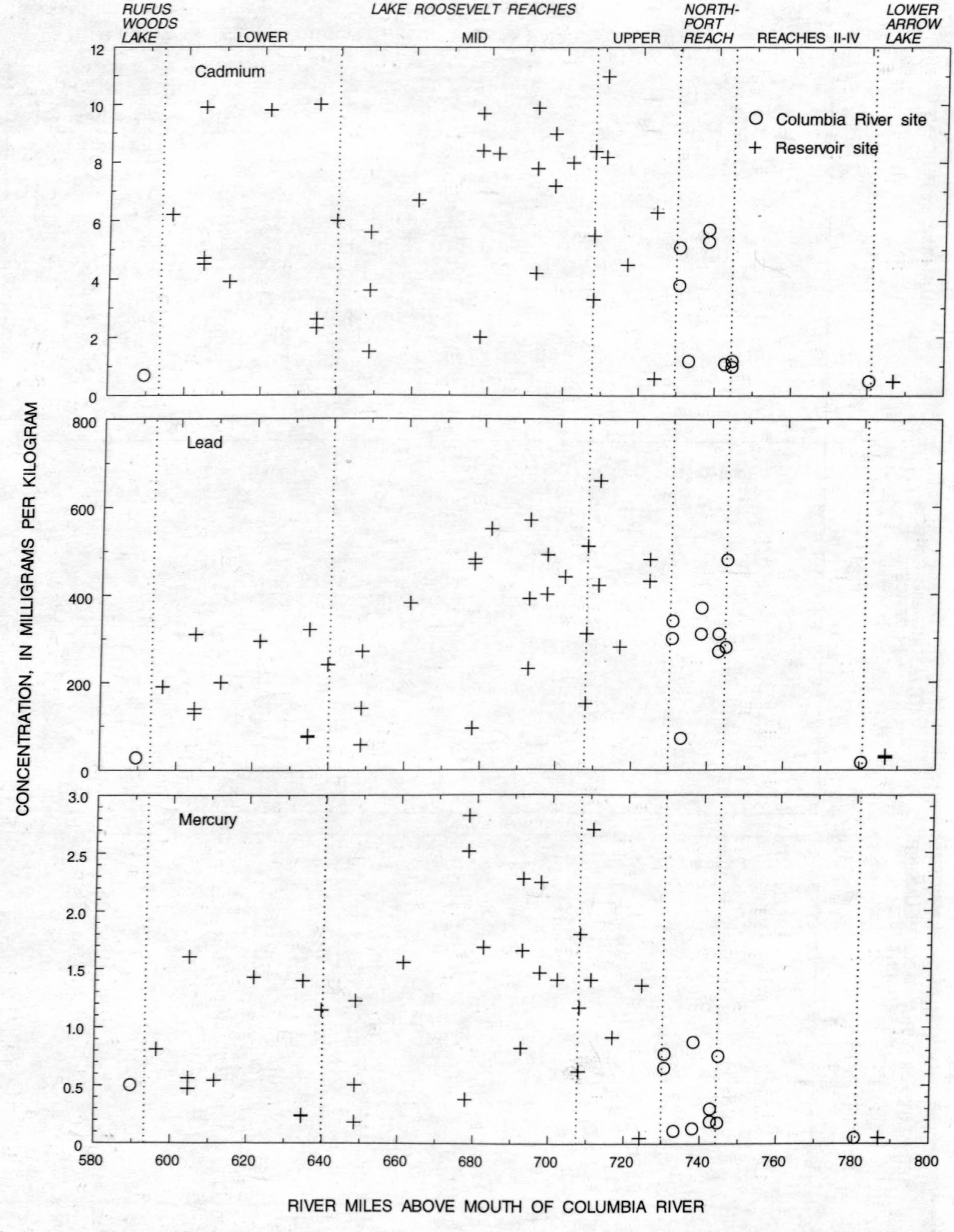


Figure 15.--Longitudinal distribution of total cadmium, lead, and mercury concentrations in bed sediment along the reaches in the Lake Roosevelt study area.

Table 12.--*Total organic carbon and percent bed sediment finer than 0.062 millimeters*

[LB, RB, and MS indicate samples were collected on right side (toward the "right bank" from mid channel), left side (toward the "left bank" from mid channel), and near the mid-section channel, respectively, numbers 1 and 2 denote different sites toward the same bank; --, no data; mm, millimeter]

Site number	Site name (see plate 1 for complete name)	Total organic carbon, in percent	Percent sediment finer than 0.062 mm
	Columbia River and minor tributaries		
3	Keenleyside Dam LB	0.2	10
4	Kootenay River MS	3.4	38
5	Kootenay River LB	.5	4
6	Pend D'Oreille River LB	.1	8
7	Boundary RB	.1	2
8	Boundary LB	.1	1
9	Auxiliary Gage RB	.1	0
10	Auxiliary Gage LB	.1	0
11	Goodeve Creek RB	.2	5
12	Goodeve Creek LB	2.3	69
14	Fivemile Creek LB	.4	25
15	Onion Creek LB	1.9	22
16	Onion Creek RB	1.0	13
25	Kettle River RB1	1.3	44
26	Kettle River RB2	.7	3
27	Kettle River LB	.3	13
29	Colville River MS	2.4	54
30	Colville River RB	3.4	80
31	Colville River LB	3.1	85
52	Spokane River MS	2.4	99
53	Spokane River LB	1.4	53
54	Spokane River RB	1.3	61
62	Sanpoil River MS	2.3	85
63	Sanpoil River LB	1.3	52
64	Sanpoil River RB	2.0	92
72	Rufus Woods Lake LB	2	4
	Reservoir		
1	Lower Arrow Lake LB1	.7	10
2	Lower Arrow Lake LB2	.8	9
17	China Bend RB	2.9	41
18	China Bend MS	--	0
19	Bossborg RB	2.2	33
20	Summer Island RB1	3.2	82
21	Summer Island RB2	2.6	30
22	Marcus Island MS	2.5	82
23	Marcus Island RB	2.7	77
24	Marcus Island LB	2.1	46
	Reservoir--Continued		
28	West Kettle Falls LB	2.1	64
35	Haag Cove RB	2.3	74
36	Haag Cove MS	2.3	80
37	French Point Rocks RB	2.1	62
38	French Point Rocks MS	2.6	97
39	French Point Rocks LB	0.8	80
40	Cheweka Creek LB	1.2	67
41	Gifford MS	2.0	100
42	Gifford LB	1.7	97
43	Gifford RB	.6	78
46	Hunters LB	1.4	94
47	Ninemile Creek MS	1.1	100
48	Ninemile Creek LB	.6	44
49	Ninemile Creek RB	.4	79
51	Fort Spokane RB	1.2	99
56	Seven Bays MS	.7	56
57	Seven Bays RB	.6	48
58	Seven Bays LB	1.7	99
61	Whitestone Creek MS	1.6	99
66	Keller Ferry RB	1.3	65
68	Swawilla Basin RB	.8	62
69	Swawilla Basin LB	1.0	86
70	Swawilla Basin MS	1.6	99
71	Grand Coulee Dam RB	1.3	95
	Minor tributaries		
33	Sherman Creek MS	1.0	14
44	Hall Creek LB	.7	65
45	Hall Creek MS	8.0	73
55	Hawk Creek RB	.3	56
	Beach		
13	Big Sheep Creek RB (delta deposits)	1.5	10
32	Colville River LB	.1	4
34	Bradbury LB	.1	1
67	Keller Ferry LB	.1	--
	Bank		
50	Ninemile Creek RB	--	92
59	Seven Bays LB1	--	4
60	Seven Bays LB2	--	29
65	Sanpoil River RB	--	100

Cadmium, lead, and mercury found in Lake Roosevelt may be associated with the liquid effluent discharged to the Columbia River from smelter operations. The effluent contains soluble and suspended forms of these elements (W.J. Kuit, Cominco Metals, written commun., October 1991), most notably mercury. Mercury concentrations in slag were much smaller (less than 0.005 mg/kg, median) than in reservoir sediments (0.5 to 1.4 mg/kg, median range; table 8). Thus, slag carried by the Columbia River to the reservoir is probably not a source of elevated concentrations of mercury and actually might serve to dilute mercury concentrations in bed sediments. However, lead may be associated with effluent and slag particles. Microscopic examination of Columbia River suspended sediment showed opaque, needle-like particles of slag, which is known to contain enriched lead concentrations (table 8). The primary source of cadmium was not so easily determined. Although analyses of the slag (Nener, 1992; Cominco Metals, 1991b) indicate enriched concentrations (10 mg/kg), bed sediment from the Northport reach and reach IV, which have a high proportion of slag particles, did not contain highly enriched cadmium concentrations (1.2 and 2.8 mg/kg, medians, respectively, table 8).

Tributaries

Bed-sediment concentrations of trace elements in the reservoir result from the deposition of sediment from different sources containing widely disparate trace-element concentrations. In addition to the Columbia River, the other tributaries may contribute sediment containing various concentrations of trace elements to the reservoir. Tributary bed sediments were collected from depositional areas near the mouths of tributaries and are believed to represent sediment that is being transported to Lake Roosevelt.

Colville, Kettle, and Sanpoil Rivers

Median concentrations of total arsenic, cadmium, copper, lead, mercury, and zinc in the bed sediments of the Colville, Kettle, and Sanpoil Rivers were considerably smaller than those in Lake Roosevelt sediment (table 8). Trace-element concentrations in tributary bed sediments were commonly at least three to five times smaller than in reservoir sediments (table 8 and fig. 16). Trace-element concentrations in local soils from nearby Okanagon, Stevens, and Spokane Counties (pl. 1) also were substantially smaller than in Lake Roosevelt sediment (table 8). The trace-element concentrations of these soils probably represent eroded soil carried to the reservoir by tributaries. Because of both smaller concentrations of these constituents in tributary sediments and smaller flows than in the main stem of the Columbia River, the trace-element discharges from these three major tributaries are smaller than that of the main stem of the Columbia River. Thus, these rivers probably do not contribute to the elevated constituent concentrations found in Lake Roosevelt.

Spokane River

Zinc concentrations in Spokane River bed sediments were particularly large (median concentration, 1,000 mg/kg) and exceeded sediment-quality guidelines (table 10). The median zinc concentration in bed sediment was larger than that in the lower reach of Lake Roosevelt (570 mg/kg) and approached the concentrations in the upper reach of the reservoir (table 8 and fig. 16). Because of the relatively large concentrations of zinc in depositional areas of the Spokane River bed sediment, the Spokane River could contribute to elevated concentrations of zinc in bed sediment of the lower reach of the reservoir.

Concentrations of total arsenic (median, 19 mg/kg) and cadmium (median, 6.0 mg/kg) in Spokane River bed sediment were slightly larger than those in the lower reach of the reservoir (table 8 and fig. 17). Consequently, the Spokane River could also be a contributor to the enriched concentrations of arsenic and cadmium in reservoir sediments. Lead and copper concentrations in the Spokane River bed sediment were larger than those detected at other major tributaries but not as large as concentrations in the lower reach of the reservoir. The sources of elevated concentrations of trace elements, and particularly zinc in the Spokane River are believed to be associated with mineralized deposits, urbanization in the Spokane River drainage, or upstream mine drainage from Lake Coeur d'Alene. Johnson and others (1989) suggested upstream mining as a possible source of the elevated concentration of 1,500 mg/kg zinc found in Spokane River bed sediments.

Pend D'Oreille River

Elevated concentrations of cadmium (8.7 mg/kg), lead (220 mg/kg), and zinc (1,600 mg/kg) were found in the bed sediment of the Pend D'Oreille River (fig. 17). The Pend D'Oreille River bed-sediment samples, which were obtained upstream of Waneta Dam, near the confluence of the Pend D'Oreille and Columbia Rivers (see fig. 1), were predominantly sand size. As in the Spokane River, bed sediment in the Pend D'Oreille River exceeded sediment-quality guidelines for zinc (1,600 mg/kg, table 10), and lead concentration nearly exceeded guidelines. The cadmium concentration was also elevated. The source of elevated trace-element concentrations in the Pend D'Oreille River may be the Metaline mining district (see fig. 5), and in turn transport of suspended sediments of the Pend D'Oreille River could be a source of these trace elements to Lake Roosevelt; however, the Waneta Dam (fig. 1) and other upstream dams impede transport of sediment during most flows.

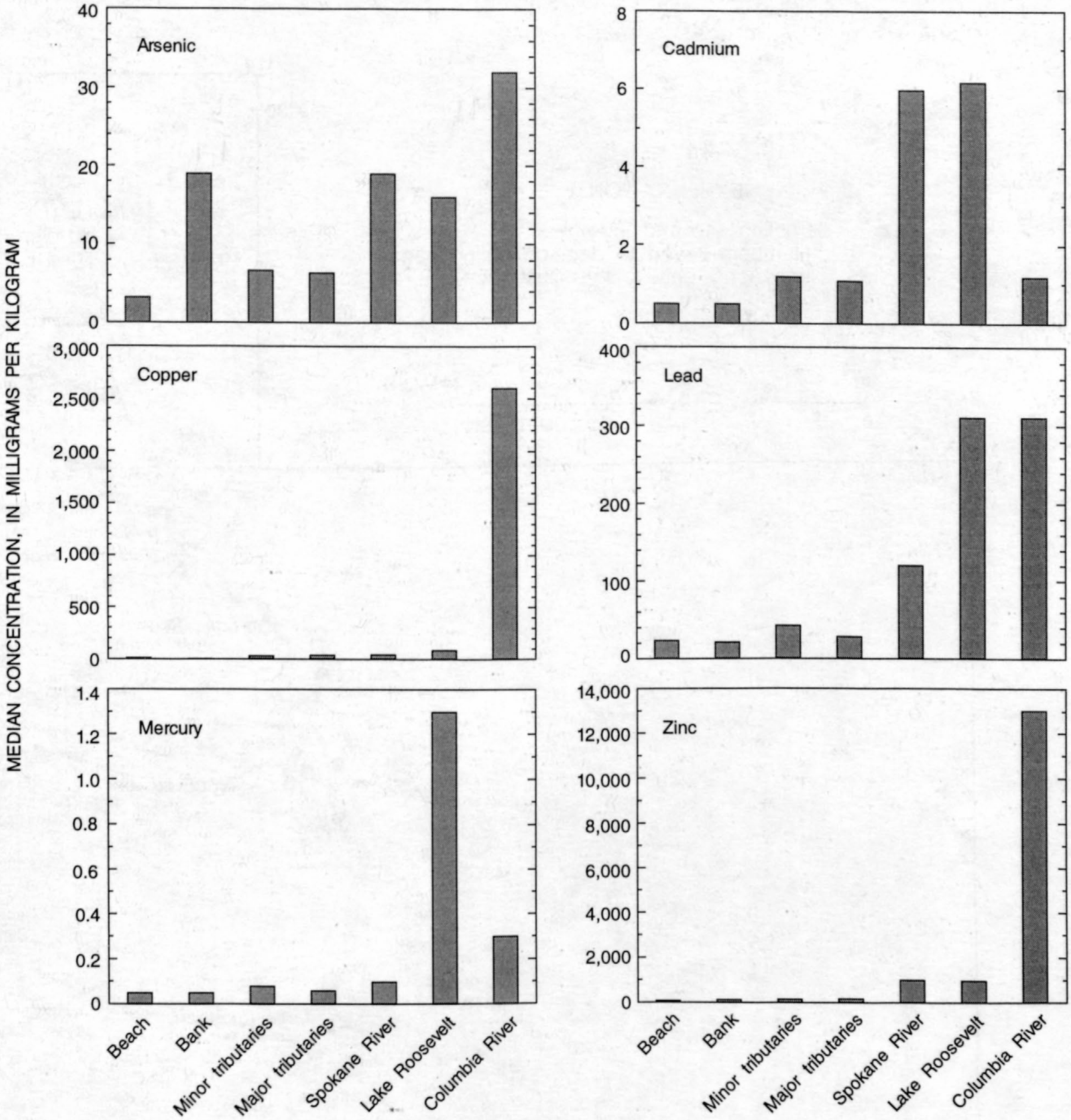


Figure 16.--Median concentrations of total arsenic, cadmium, copper, lead, mercury, and zinc in bed sediments at sites on the Northport reach of the Columbia River, Lake Roosevelt, major and minor tributaries, banks, and beaches.

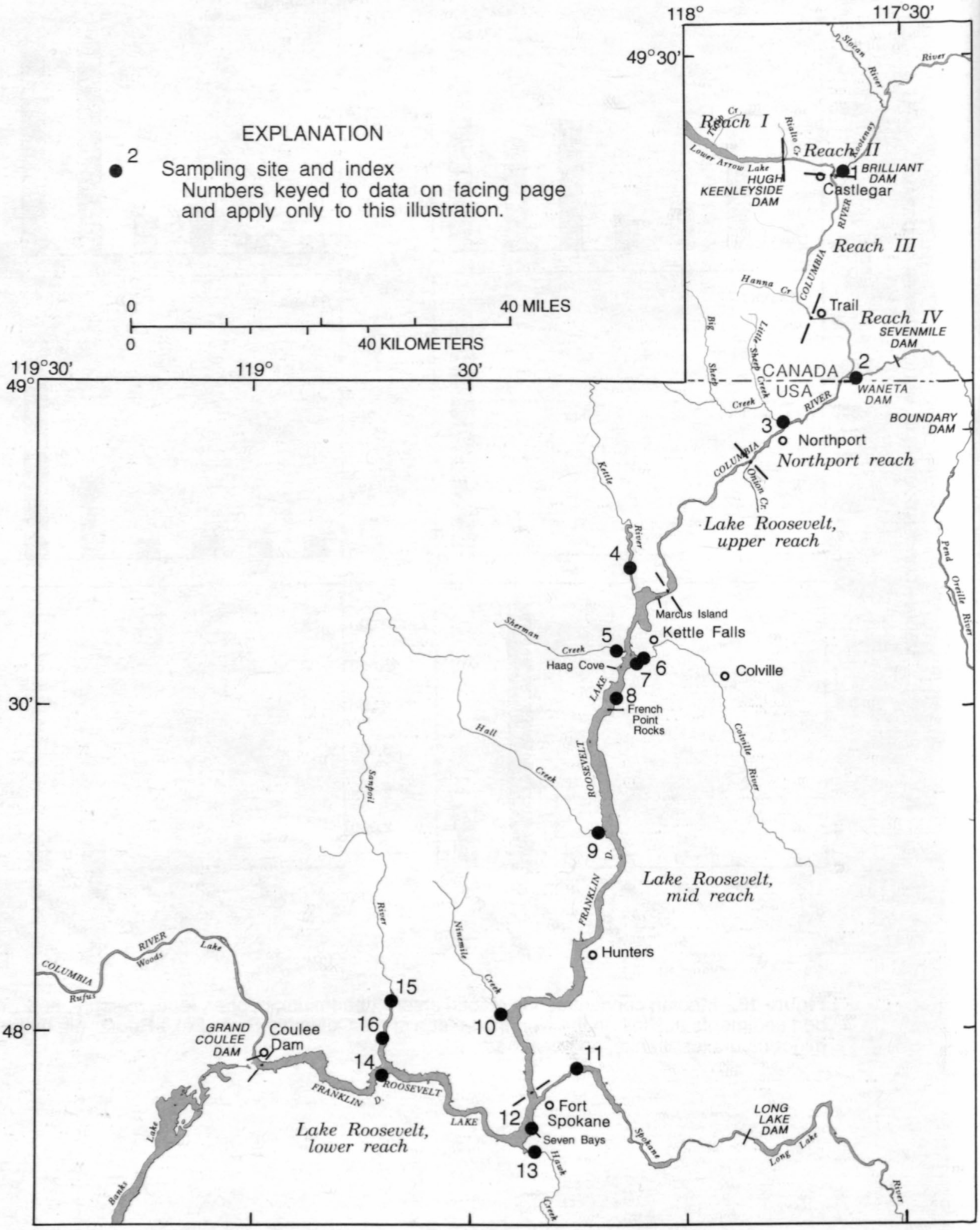


Figure 17.--Concentrations of total arsenic, cadmium, copper, lead, mercury, and zinc in bed sediments of major and minor tributaries of Lake Roosevelt and tributaries of the Columbia River.

[Concentrations in milligrams per kilogram; <, less than--, no data available; As, total arsenic; Cd, total cadmium; Cu, total copper; Pb, total lead; Hg, total mercury; Zn, total zinc; LB, RB, and MS indicate samples were collected on right side (toward the "right bank" from mid channel), left side (toward the "left bank" fron mid channel), and near the mid-section channel, respectively, numbers 1 and 2 denote different sites toward the same bank]

Major Tributaries Sites

1 Kootenay River

	LB	MS
As	<7.0	4.6
Cd	.5	2.0
Cu	20	48
Pb	27	76
Hg	<.05	<0.05
Zn	120	290

2 Pend D'Oreille River

	LB
As	13
Cd	8.7
Cu	18
Pb	220
Hg	0.1
Zn	1,600

4 Kettle River

	LB	RB1	RB2
As	2.4	<4.0	<2.0
Cd	<0.5	0.5	<0.5
Cu	10	23	28
Pb	20	20	17
Hg	<0.05	<0.05	<0.05
Zn	40	70	44

6 Colville River

	LB	MS	RB
As	6.0	3.6	6.6
Cd	3.3	0.7	3.4
Cu	41	21	39
Pb	74	28	68
Hg	0.3	0.06	0.2
Zn	260	110	260

11 Spokane River

	LB	MS	RB
As	19	30	15
Cd	6.0	11	4.9
Cu	42	49	40
Pb	120	150	80
Hg	0.1	0.1	0.06
Zn	1,000	1,800	980

15 Sanpoil River

	LB	MS	RB
As	6.3	7.3	7.3
Cd	0.9	1.4	0.8
Cu	24	36	43
Pb	21	23	29
Hg	<0.05	0.06	0.05
Zn	110	160	170

Minor Tributaries Sites

5 Sherman Creek

	MS
As	1.4
Cd	1.8
Cu	9.0
Pb	49
Hg	0.1
Zn	140

9 Hall Creek

	LB	MS
As	8.0	5.5
Cd	1.2	1.3
Cu	30	30
Pb	50	28
Hg	0.1	0.07
Zn	150	140

13 Hawk Creek

	RB
As	20
Cd	1.0
Cu	29
Pb	35
Hg	<0.05
Zn	170

Bank Sites

10 Ninemile Creek

	RB
As	22
Cd	<0.5
Cu	--
Pb	26
Hg	<0.05
Zn	140

12 Seven Bays

	LB1	LB2
As	18	20
Cd	<0.5	<0.5
Cu	--	--
Pb	21	21
Hg	<0.05	<0.05
Zn	93	88

16 Sanpoil River Embayment

	RB
As	16
Cd	<0.5
Cu	--
Pb	28
Hg	<0.05
Zn	200

Delta Deposits

3 Mouth of Sheep Creek

	RB
As	11
Cd	2.5
Cu	--
Pb	180
Hg	0.3
Zn	1,600

Beach Sites

7 Colville River Embayment

	LB
As	3.2
Cd	<0.5
Cu	9.0
Pb	23
Hg	<0.05
Zn	75

8 Bradbury

	LB
As	3.2
Cd	<0.5
Cu	9.0
Pb	23
Hg	<0.05
Zn	75

14 Keller Ferry

	LB
As	9.1
Cd	<0.5
Cu	11
Pb	15
Hg	<0.05
Zn	61

Figure 17.--Continued

Kootenay River

Elevated concentrations of trace elements were not found in bed sediments in the Kootenay River about 11 mi upstream from the mouth (fig. 17). Bed-sediment samples, which were obtained about 12 mi upstream of Brilliant Dam (see fig. 1), contained predominantly sand-size material. However, slightly elevated concentrations of cadmium (4.5 mg/kg), lead (180 mg/kg), and zinc (540 mg/kg) were found by CRIEMP in bed sediments of Kootenay Lake located upstream from a series of dams on the Kootenay River (Julia Beatty Spence, British Columbia Ministry of Environment, written commun., 1992). The source of elevated trace-element concentrations in Kootenay Lake may be the Sullivan mining district (fig. 5). Transport of suspended sediments containing elevated trace-element concentrations in Kootenay Lake could in turn be a source to Columbia River and Lake Roosevelt, but the dams on the Kootenay River impede transport of sediment during most flows.

Hall, Hawk, and Sherman Creeks

With the exception of arsenic, trace-element concentrations in Hall, Hawk, and Sherman Creeks were considerably smaller than those in the bed sediments of Lake Roosevelt (table 8; figs. 16 and 17). The bed sediment at Hawk Creek RB had an enriched concentration of arsenic (20 mg/kg). Despite a relatively large arsenic concentration at Hawk Creek RB, the annual quantities of trace elements discharging from these minor tributaries were small compared to those of the main stem of the Columbia River because the discharges of these tributaries are much less than that of the main stem.

Bank, Beach, and Delta

Bank erosion is a source of sediment to the reservoir because of past and present sliding and slumping of sediments along the reservoir banks (Jones and others, 1961). Concentrations of total cadmium, lead, and zinc in bank-derived sediment were smaller than those in the bed sediment of the Columbia River at Northport and all reaches of Lake Roosevelt. However, total arsenic concentrations in bank sediment were about the same as arsenic concentrations in the bed sediment of Lake Roosevelt, but not as large as those in the Northport reach of the Columbia River. Based on data from only four bank samples obtained in the mid and lower reaches of the reservoir, bank sediment may be a source of arsenic to reservoir bed sediments, but probably is not a source of other elevated trace elements.

Surficial sediment from three public beaches were sampled primarily because of public health concerns. Beach sediment is not derived from a single source, but rather it is a mixture of eroded bank material and riverine deposits. Much of the fine material has been removed from the beach deposits by wave action, leaving mostly sand-size sediment. Each beach sample represented a composite from 10 to 20 locations over the public beach area. Trace-element concentrations in mostly sand-size sediments from three public beaches along the mid and lower banks of the reservoir (Colville River embayment, Bradbury, and Keller Ferry; pl. 1) were smaller than those in reservoir bed sediment (table 8; figs. 16 and 17). Adjacent reservoir sediments in the mid and lower reaches contained largely silt- and clay-size material.

Total lead and zinc concentrations were elevated in a composite sample taken from 8 to 10 locations on delta deposits near the mouth of Big Sheep Creek (fig. 17). Limited data suggest that Big Sheep Creek, which drains a mineralized area, may be a source of lead and zinc enrichment to Columbia River sediment, but annual discharge from this tributary is small compared to the main stem of the Columbia River and other major tributaries. Nevertheless, a localized discharge of sediment containing elevated trace elements may contribute to the enriched trace-element concentrations observed in the bed sediments in the vicinity of Northport.

DISTRIBUTION OF TRACE ELEMENTS IN SUSPENDED SEDIMENTS AND WATER IN THE COLUMBIA RIVER ENTERING LAKE ROOSEVELT

In river systems such as the Columbia, trace elements in river flow are distributed between sediment and water. Although trace elements occur in both sediment and water, most trace elements associate more strongly with sediment. However, in the Northport reach of the Columbia River, the concentrations of suspended sediment tend to be small for the river's range of discharge, thereby substantially enhancing the importance of the water phase in the transport of trace elements. The partitioning of trace elements between sediment and water is governed in large part by water composition, sorptive partitioning, pH, and the solubility of mineral phases suspended in the water. These processes operate simultaneously; consequently, it is extremely difficult to determine the distribution of trace elements between sediment and water without concentration data from both phases.

The study addressed these objectives:

1. To determine the distribution of trace elements between the suspended sediment and water phases of the Columbia River flowing into Lake Roosevelt; and

2. To compare the discharge (for a 10-hour duration) of trace elements in the suspended sediment and water phases of the Columbia River flowing into Lake Roosevelt.

Data from this section of the report will show the following.

- Concentrations of total arsenic, cadmium, copper, lead, and zinc in whole water (water plus suspended-sediment phases) were smaller than the maximum and continuous criteria for freshwater established by the USEPA.

- The total discharge (for a 10-hour duration) of trace elements was generally larger in the water phase than in the suspended-sediment phase.

Methods

The collection of suspended-sediment and water samples from the Columbia River at Northport for analysis of trace elements was complex. Two procedures were used to collect river water samples, which were subsequently separated into suspended-sediment and water phases by centrifugation. Separation of water and suspended sediment by a continuous-flow centrifuge has been described by Horowitz, Elrick, and others (1989b). Depth-width integrated samples were collected at a Columbia River cross section following the sampling and processing methods described by Meade and Stevens (1990) to obtain representative and noncontaminated samples from a large river. Concurrent with the depth-width integrated sampling, point-source pumping samples of river water were also collected from a fixed point location by Ecology personnel using a peristaltic pump according to procedures outlined by Serdar and others (1993). The sampling plan is shown schematically on figure 18; sampling locations are shown on figure 1. Samples collected by both agencies were processed similarly and analyzed by the same laboratory in the same analytical batch. Some additional trace-element concentration data for the Columbia River at Northport were also available from Ecology; since December 1990, Ecology had been monitoring trace elements in whole- water samples obtained monthly by single-surface grabs taken near the center of flow.

The river water samples collected at the cross section were depth and width integrated, providing a discharge-weighted sample, by the equal-width-increment method (Edwards and Glysson, 1988). The cross section was 750 ft wide and divided into 10 sections. Depth integrated samples were collected at the center of each section by use of an isokinetic sampler (one designed to collect water at the same velocity as the flow velocity of the river). An 8-liter collapsible Teflon-bag sampler was used according to the procedures outlined by C.F. Nordin (U.S. Geological Survey, written commun., 1981).

The sample water collected at the cross section was transferred from the collapsible bag sampler to 6-gallon plastic buckets lined with Teflon bags. The 6-gallon plastic buckets were used to transfer water samples from the RV *Estero* to the processing facility on shore where the samples were transferred to a large plastic drum for temporary holding until they could be centrifuged. Prior to use, the plastic containers and the Teflon liners were washed, then thoroughly rinsed, first with tap water, then with 5-percent nitric acid, and finally with deionized water. In addition, the Teflon liners were rinsed with clarified river water at the time of sampling.

Serdar and others (1993) describe Ecology's procedure for collecting the point-source pumping sample. River water was collected by a peristaltic pump with the pump intake placed in the river flow about 50 ft from the left bank. At the sampling point, the river channel was about 800 ft wide. Water depth in the vicinity of pump intake was about 10 ft, and the pump intake was positioned at depths of 2, 5, or 9 ft, being changed about every 20 hours. The duration of sampling totaled 60 hours between September 29 and October 2, and 2,700 gallons of water were sampled.

The river water samples were separated with two types of continuous flow centrifuges into water and suspended-sediment phases. The centrifuge used with the depth-width integrated samples was a Westphalia®-MK-2; and for the point-source sample an Alfa-Laval® Sedisamp II was used. Both models of centrifuges were included in evaluations conducted by Horowitz, Elrick, and others (1989b), who found that sediment and water separated with the Alfa-Laval® Sedisamp II had consistently larger copper and lead concentrations that they attributed to contamination by the centrifuge. The contamination observed by Horowitz, Elrick, and others (1989b), which was in the range of 6 to 20 µg/L for copper and 13 to 40 µg/L for lead, was not apparent in the sediment and water data collected for this study. Contamination of water and suspended sediment was not apparent in this study because the concentrations of trace elements in water and suspended sediment from the Westphalia®-MK-2 and the Alfa-Laval® Sedisamp II were similar, and for water, substantially smaller than concentrations attributed to contamination reported by Horowitz, Elrick, and others (1989b). Suspended sediment, composed mostly of silt-size material, was removed from both centrifuges, placed in sample containers, stored at 4°C, and shipped to the appropriate laboratory.

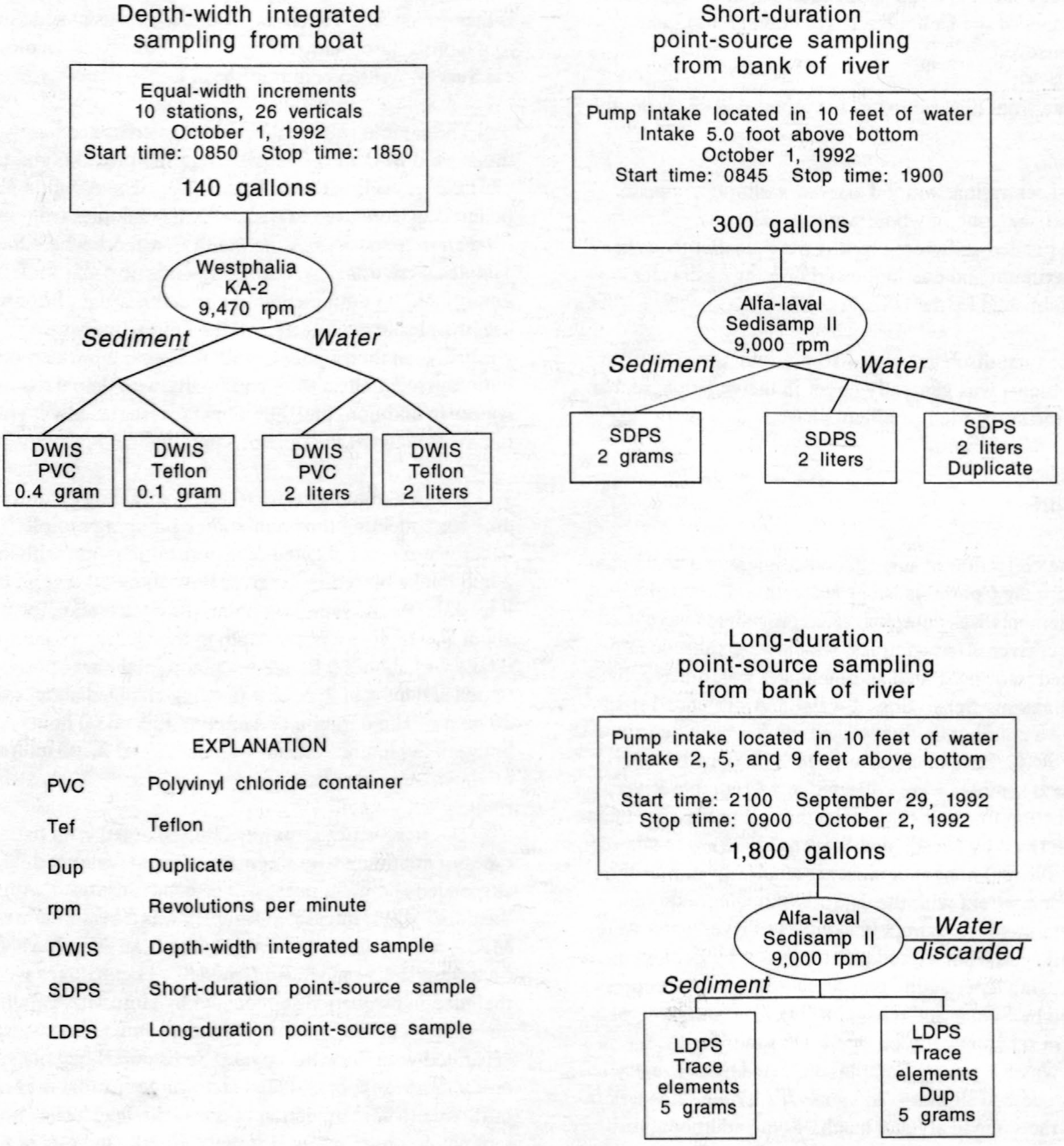


Figure 18.--Schematic of sample collection and processing of trace elements sampled in the Columbia River at Northport, Washington.

The depth-width integrated samples were collected on October 1, 1992, and designated DWIS. A long-duration point-source sample was also collected by Ecology for 3 days and designated LDPS. A part of the 3-day continuous suspended-sediment sample, collected concurrently with the DWIS, was isolated and designated a short-duration point-source sample or SDPS. Approximately 300 gallons were processed for the SDPS sample. Because of difficulties in collecting the DWIS sample, only 140 gallons were processed for it. The liners in two of the four large plastic drums split, so the DWIS sample was divided and processed as two samples (two drums), each one containing about 70 gallons of river water. During sample handling, the sample that contacted only Teflon was designated DWIS (tef), and the sample that contacted Teflon and the polyvinyl-chloride drum was designated DWIS (pvc) (see table 13). During the centrifuge processing, samples were in contact with the stainless steel bowls of the centrifuge. Sample flow through the centrifuge was about 2 liters (0.53 gallon) per minute.

Discharge of trace elements in the water and suspended-sediment phases was calculated from the following data: trace-element concentrations in Columbia River water (data from table 13, converted to pounds), an average discharge of 81,300 ft^3/s for the 10-hour sampling period, and suspended-sediment concentrations of 2 mg/L (1.25×10^{-4} lb/ft^3) for the DWIS samples and 1 mg/L (6.25×10^{-5} lb/ft^3) for the SDPS sample. Equations for discharge of water and suspended-sediment phases are provided in a later section on the distribution of dioxins and furans in water and suspended sediment. The trace-element discharge data were generated from samples that integrated river discharge over a 10-hour period during low flow; however, the trace-element discharge data presented in the section "Trace-Element Discharge" have been converted to a daily discharge (24 hours) for ease of comparison to trace-element discharge data from other river systems. Because trace-element discharge will vary with total trace-element concentration and discharge, the daily discharges of trace elements calculated for a short sampling period at low flow should not be extrapolated to annual discharge.

Trace-Element Concentrations

Concentrations of the trace elements arsenic, cadmium, copper, lead, mercury, and zinc in the Northport reach were much larger in the suspended-sediment phase than in the water phase, and the concentrations of all but mercury in suspended sediment were significantly larger than the estimated world average of trace-element concentrations in suspended sediment from large rivers representing 15 percent of global river discharge (table 13; Martin and Meybeck, 1979). No data were reported for mercury, and only three cadmium concentrations were reported by Martin and Meybeck (1979). The reported cadmium concentrations ranged from 0.8 to 2 mg/kg, values that are substantially less than the concentrations observed in suspended sediments from the Columbia River at Northport.

By contrast, concentrations of arsenic, copper, lead, and zinc in the water phase in the Columbia River at Northport (table 13) were generally smaller than the world-average river concentrations reported by Martin and Meybeck (1979). The small trace-element concentrations in the Columbia River probably reflect the large water-diluting capacity of this river even at low flows. The concentrations of dissolved arsenic, cadmium, lead, mercury, and zinc were similar to those reported in surface waters of the continental United States (Durum and others, 1971). However, dissolved lead, cadmium, arsenic, mercury, and zinc data collected before 1990 may be invalid because they were collected by techniques that may have introduced contamination. Thus, many trace-element analyses reported before 1990 may have indicated larger concentrations than actually existed (Meybeck and Helmer, 1989; Windom and others, 1991).

With two exceptions, the different procedures used to collect river water samples for this study generally produced similar trace-element concentrations in both suspended-sediment and water samples. Mercury concentrations showed differences in suspended sediment from all samples, and the DWIS-Teflon sample had larger copper, iron, manganese, and zinc concentrations (table 13). The concentration of mercury in suspended sediment of the LDPS sample was about seven times the concentration in either the DWIS sample or the SDPS sample. A likely explanation of the large concentration of mercury involves a 132-pound mercury spill that is alleged to have occurred near Trail, British Columbia, and that is currently (1993) under investigation by the British Columbia Ministry of Environment. The date of the alleged spill was October 1, 1992, the same day that the DWIS and the SDPS samples were collected. Because the travel time between Trail, British Columbia, and Northport, Wash., is approximately 5 hours at 81,300 ft^3/s, most of the alleged mercury slug in the river flow was probably missed by the DWIS and the SDPS samples but captured by the LDPS sample being collected continuously from September 29 until October 2.

Table 13.--*Total trace-element concentrations in suspended-sediment and water samples collected from the Columbia River at Northport, Wash., and world average concentrations of trace elements*

[DWIS, depth-width integrated sample October 1, 1992, 8:50 a.m-6:50 p.m.; DWIS (tef), sample held only in Teflon container; DWIS (pvc), sample held in Teflon and polyvinyl chloride container; SDPS, short-duration point-source sample October 1, 1992, 8:45 a.m.-7:00 p.m.; LDPS, long-duration point-source sample September 29 to October 2, 1992; --, no data; <, less than]

	Suspended-sediment phase							Water phase					
Trace elements	World average[1]	DWIS (tef)	DWIS (pvc)	SDPS	LDPS	LDPS duplicate	Median	World average[1]	DWIS (tef)	DWIS (pvc)	SDPS	SDPS duplicate	Median
	milligrams per kilogram[2]							micrograms per liter					
Aluminum	--	5.4	4.0	4.3	4.1	4.9	4.5	--	--	--	--	--	--
Arsenic	5	37	28	40	45	44	40	1.7	0.1	0.5	0.6	0.4	0.4
Barium	--	--	--	--	--	--	--	--	32	33	33	33	33
Cadmium	[3]0.8-2.0	8.0	9.8	13	16	16	13	--	.1	.1	.06	.07	.08
Chromium	--	--	--	--	--	--	--	--	.2	.3	.3	.1	.2
Copper	100	1,000	350	280	350	360	360	10	1.9	1.5	1.6	1.6	1.6
Iron	--	7.6	3.3	3.2	3.5	3.5	3.5	--	4.1	5.6	4.5	3.8	4.5
Lead	150	430	530	490	560	550	490	1.0	1.2	.6	.5	.6	.8
Manganese	--	2,300	1,100	2,000	1,800	1,800	1,800	--	--	--	--	--	--
Mercury	--	0.7	2.6	1.7	14	14	1.7	--	<.1	<.1	<.1	<.1	<.1
Selenium	--	--	--	--	--	--	--	--	<1.0	<1.0	<1.0	<1.0	<1.0
Thallium	--	--	--	--	--	--	--	--	.1	.2	.04	.1	.1
Zinc	350	5,100	1,800	1,100	1,500	1,500	1,500	30	6.2	6.0	2.6	3.5	4.6

[1] Martin and Meybeck (1979).

[2] Except concentrations of aluminum and iron, which are given in percent by weight.

[3] Only three values reported for cadmium.

The other major difference among the trace-element concentration data is the analysis of suspended trace elements from the DWIS-Teflon sample, which showed significantly larger concentrations of copper, iron, manganese, and zinc than were observed in the other suspended-sediment samples (table 13). A probable explanation involves the small sample size (0.1 gram, see fig. 18) that was available for this sample. The smaller sample increases the range of analytical uncertainty and, as in this case, increases the chances that the particles making up the sample will not be present in the same proportions as in a well-mixed sample and therefore will not be representative. A disproportionate amount of slag particles in the DWIS-Teflon sample could cause the larger concentrations of these elements, all of which are present in large concentrations in slag material from the smelter at Trail, British Columbia (Nener, 1992).

Suspended sediment from the DWIS samples may contain larger proportions of slag material than are found in the point-source pumping samples. Although concentrations of arsenic and cadmium are generally larger in the point-source pumping samples than in the DWIS samples and lead concentrations are fairly uniform in all suspended-sediment samples, nevertheless, the DWIS samples generally have larger concentrations of copper, iron, manganese, and zinc, which are found in slag from the smelter at Trail, British Columbia (Nener, 1992). Slag material discharged by the smelter at Trail enters the Columbia River along the right bank, whereas the intake for the point-source pumping samples is near the left bank. Transverse mixing of sediment requires larger reaches of the river than is required for water phase constituents; consequently, suspended-sediment samples collected by depth-width integrating techniques across the entire river channel are likely to contain more slag than samples obtained near the river bank opposite the source of the slag.

The concentrations of copper and lead were similar in water samples processed with either the Westphalia®-MK-2 or the Alfa-Laval® Sedisamp II centrifuge and were well below the contaminated concentrations that Horowitz, Elrick, and others (1989b) found in water processed with a similar Alfa-Laval® Sedisamp II centrifuge. Although the field blank water sample that was passed through the centrifuge was inadvertently destroyed, trace-element concentrations in water samples did not show obvious evidence of field contamination because environmental samples contained trace-element concentrations near the minimum values measured by Ecology in its monthly grab samples (table 14), which were collected by noncontaminating procedures.

Trace-element concentrations in Columbia River samples collected for the present study can be compared with samples collected by CRIEMP and with monitoring samples collected by Ecology. Ecology collected samples on a monthly basis at Northport that provided data on temporal variations in trace-element concentrations for that site. CRIEMP collected trace-element concentration data in raw river water and suspended sediment at several locations upstream from the international boundary. Both Ecology and CRIEMP analyzed whole-water samples. Because water samples from the present study were centrifuged to remove suspended sediment, the trace-element concentration in suspended sediment was multiplied by the concentration of suspended sediment and added to the concentration in the centrifuged water to give a whole-water concentration (see equation below) comparable to data of Ecology and CRIEMP.

$$C_{TE,\,WW} = C_{TE,\,aq} + (\ C_{TE,\,SS} \times SS \times 10^{-3}\ ) \qquad (1)$$

where

$C_{TE,\,WW}$ = trace-element concentration in whole water, in micrograms per liter;

$C_{TE,\,aq}$ = trace-element concentration in water phase, in micrograms per liter;

$C_{TE,\,SS}$ = trace-element concentration in suspended sediment, in milligrams per kilogram;

SS = suspended-sediment concentration in river water, in milligrams per liter; and

10^{-3} = unit conversion factor

Whole-water concentrations (water plus suspended-sediment phases) of trace elements were generally small and ranged from 0.4 to 0.6 µg/L for arsenic, 0.08 to 0.1 µg/L for cadmium, 2.0 to 3.0 µg/L for copper, 1.2 to 1.9 µg/L for lead, and 4.6 to 13 µg/L for zinc (table 14). Total concentrations for mercury were not applicable because the mercury concentrations in the water phase were less than the minimum detection limits. Whole-water concentrations of trace elements sampled by the USGS from the Columbia River at Northport were below USEPA maximum and continuous concentration criteria for fresh-water organisms as shown in table 15 (U.S. Environmental Protection Agency, Region 4, Atlanta, Ga., written commun., December 1992). However, median mercury concentrations from whole-water samples collected by Ecology were larger than continuous concentration criteria for fresh-water organisms, but smaller than maximum criteria (table 15).

Table 14.--*Trace-element concentrations in Columbia River water*

[CRIEMP, Columbia River Integrated Environmental Monitoring Program; USGS, U.S. Geological Survey; Ecology, Washington State Department of Ecology; µg/L, micrograms per liter; --, no data; N, number of analyses; na, not applicable because mercury concentrations in the water phase were less than the minimum detection limit]

	USGS			USGS			Ecology			CRIEMP		
	Columbia River at Northport, Wash., October 1992, water phase			Columbia River at Northport, Wash., October 1992, total[2]			Columbia River at Northport, Wash., 1991—1992, total[1]			Columbia River, above Hugh Keenleyside Dam 1990—1991, total[1]		
Trace elements	Median µg/L	Range µg/L	N	Median µg/L	Range µg/L	N	Median µg/L	Range µg/L	N	Median µg/L	Range µg/L	N
Arsenic	0.4	0.3 - 0.5	2	0.5	0.4 - 0.6	2	--	-- - --	--	0.2	0.1 - 0.3	17
Cadmium	.08	.06- .1	2	.10	.08 - .1	2	0.2	<.1 - 0.4	12	<.1	<.1 - .1	17
Copper	1.6	1.6 - 1.7	2	2.5	2.0 - 3.0	2	3.0	<2.0 - 12	18	.4	.3 - .8	17
Lead	.8	.6 - .9	2	1.6	1.2 - 1.9	2	2.2	1.3 - 5.7	16	<.2	<.2 - .8	17
Mercury	<.1	<.1 - <.1	2	na	na - na	--	.05	<.04 - .3	19	<.01	<.01- .02	17
Zinc	4.6	3.0 - 6.2	2	8.8	4.6 -13	2	12	7.0 -45	13	.4	<.2 - 1.1	17

[1] Total is analysis of raw water from a non-depth-width integrated sample.

[2] Total is computed concentration from water and suspended-sediment phases from depth-width integrated and short-duration point source samples (see table 13).

Table 15.--*Criteria for trace-element concentrations for freshwater organisms and observed median concentrations in the Columbia River at Northport, Wash.*

[--, no data]

Total trace element	Criterion maximum concentration for freshwater organisms[1]	Criterion continuous for freshwater organisms[1]	Columbia River at Northport, Wash., October 1992 total[2]	Columbia River at Northport, Wash., 1991-1992, total[3]
	micrograms per liter			
Arsenic	360	190	0.5	--
Cadmium[4]	2.7	.88	.1	0.2
Copper[4]	13	8.9	2.5	3.0
Lead[4]	54	2.1	1.6	2.2
Mercury	2.4	.012	--	.05
Zinc[4]	89	80	8.8	12

[1] U.S. Environmental Protection Agency, Region 4, Atlanta, Georgia, written commun., 1992.

[2] Total is computed concentration from water and suspended-sediment phases (collected by U.S. Geological Survey).

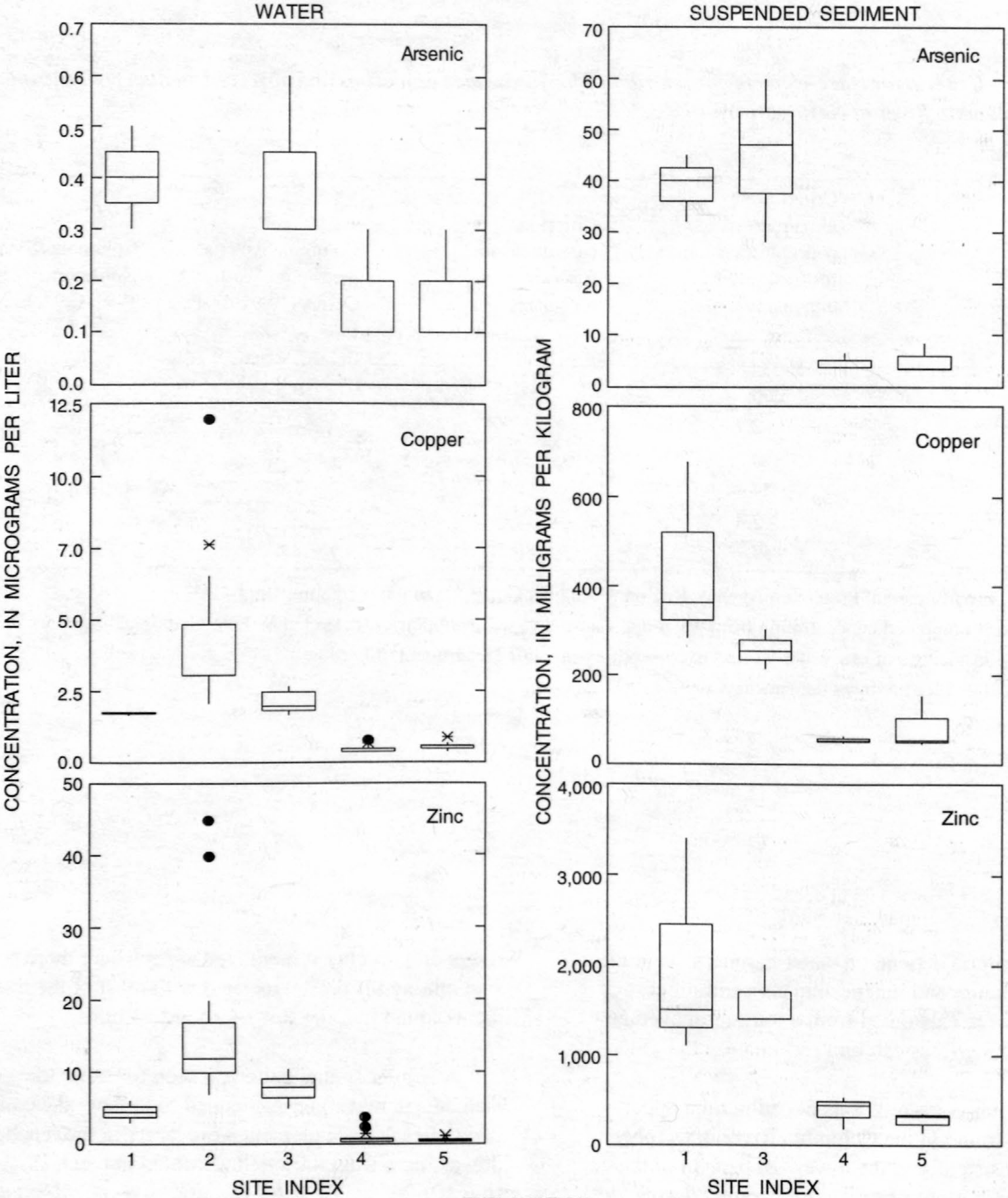
[3] Total is analysis of raw water (collected by Washington State Department of Ecology).

[4] Calculated for hardness dependency.

Some of the criteria depend on water hardness, which is a function of calcium and magnesium concentrations, and these criteria were calculated from a long-term average hardness of 72 mg/L, as calcium carbonate.

Whole-water concentrations of cadmium, copper, lead, and zinc found in the Columbia River in October 1992 were consistently in the lowest 10 percent of the range of concentrations observed by Ecology during 1991 and 1992 (table 14). However, even the small concentrations of copper, lead, and zinc observed during the USGS October sampling of the Columbia River at Northport were larger than concentrations observed by CRIEMP in samples upstream from Hugh Keenleyside Dam in Lower Arrow Lake. The Lower Arrow Lake sampling area is upstream of the influence of the smelter at Trail and of the mouths of the Kootenay and Pend D'Oreille Rivers. Both rivers drain highly mineralized areas where there is extensive mining for ores associated with most of the trace elements found in Lake Roosevelt sediments.

A similar spatial pattern is seen for other trace elements in water and suspended sediment: the concentrations of each trace element were larger in the reaches downstream from the smelter located in reach IV (figs. 19-20; see fig. 1 for location of reach). No pattern was discernible from data on mercury concentrations in the water phase because mercury was at or near the minimum reporting level (0.1 µg/L) in all reaches. Of the trace elements studied, mercury has the least affinity for the water phase and is usually found almost exclusively associated with sediment (Meybeck and Helmer, 1989; Horowitz, 1991).



EXPLANATION

SITE INDEX	SITE DESCRIPTION AND DATA SOURCE
1	Columbia River, Northport reach, USGS
2	Columbia River, Northport reach, Ecology
3	Columbia River, reach IV, CRIEMP
4	Columbia River, reach II, CRIEMP
5	Lower Arrow Lake, reach I, CRIEMP

● — Far outside value
× — Outside value
— Whisker
— Third quartile
— Median
— First quartile

Figure 19.--Concentrations of arsenic, copper, and zinc in whole water and suspended sediment at sites on the Columbia River. Concentrations determined were either total concentration in whole water (suspended sediment and water phases) or water phase concentration collected by the USGS (centrifuged water with suspended sediment removed). Samples were collected by the U.S. Geological Survey (USGS), the Columbia River Environmental Monitoring Program (CRIEMP), or the Washington State Department of Ecology (Ecology).

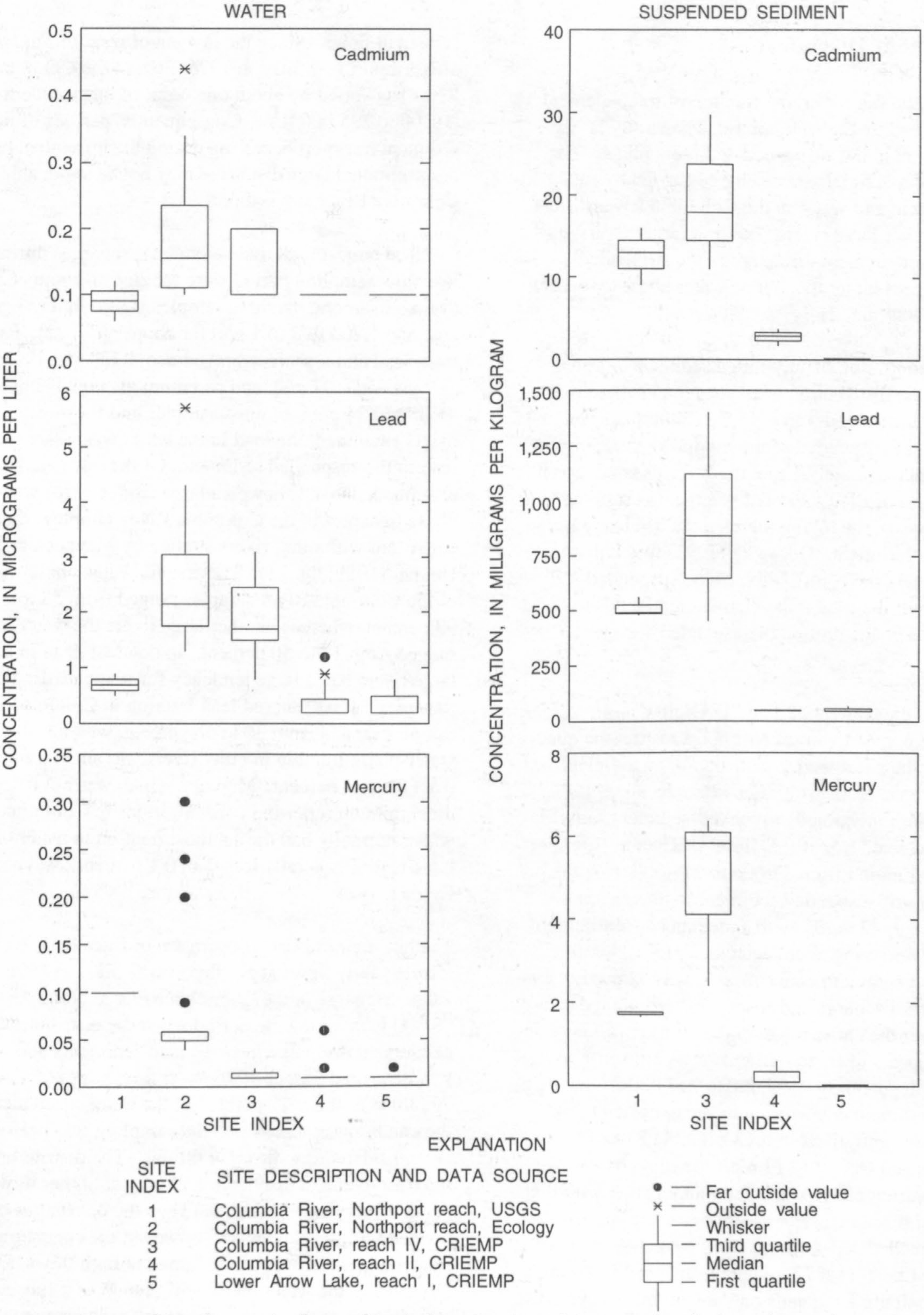


Figure 20.--Concentrations of cadmium, lead, and mercury in whole water and suspended sediment at sites on the Columbia River. Concentrations determined were either total concentration in whole water (suspended sediment and water phases) or water phase concentration collected by the USGS (centrifuged water with suspended sediment removed). Samples were collected by the U.S. Geological Survey (USGS), the Columbia River Environmental Monitoring Program (CRIEMP), or the Washington State Department of Ecology (Ecology).

Trace-Element Discharge

In the Columbia River, the fraction of trace-element discharge carried by the water phase is generally larger than the fraction in the suspended-sediment phase. The distribution of trace-element discharge carried by suspended sediment and water in the Columbia River differs from that of other large rivers. In other larger rivers, the fraction of trace-element discharge in the suspended-sediment phase is larger than in the water phase (Meybeck and Helmer 1989; fig. 21).

The concentration of suspended sediment substantially affects the distribution of trace elements between suspended sediment and water. In the Columbia River, the concentration of suspended sediment during the sampling period was approximately 1 to 2 mg/L. This small concentration of suspended sediment in large part resulted in a smaller fraction of the total trace-element discharge borne by suspended sediment. Horowitz (1991) found that for unpolluted rivers the contribution of the suspended-sediment fraction of the total trace-element load tends to increase as the concentration of suspended sediment increases.

Dams on the Columbia, Pend D'Oreille, and Kootenay Rivers upstream of Northport restrict the quantity and alter the particle-size distribution of sediment flowing into Lake Roosevelt. For example, since 1973, 142 depth-width integrated suspended-sediment samples have been collected from the Columbia River at Northport at discharges ranging from 37,000 to 217,000 ft^3/s; the concentrations of suspended sediment in these samples ranged from 0 to 42 mg/L, with a median concentration of 5 mg/L. For one sample, collected at about 105,000 ft^3/s, the suspended-sediment concentration was 42 mg/L; however, when the discharge and suspended-sediment data are compared over the entire range of data, this particular concentration appears to be an outlier. At high discharges, above the 95th percentile (175,000 to 217,000 ft^3/s), when suspended-sediment concentrations are expected to be largest, the concentrations in the Columbia River at Northport ranged from 2 to 19 mg/L (median of 13). These concentrations are small for a major river with this magnitude of discharge. For comparison, the concentrations of suspended sediment reported for major rivers of the world by Lisitzin (1972) ranged from 7 to 15,000 mg/L (median of 340 mg/L). Dams on the Columbia River system are also used for storage and subsequent release of water, which has virtually eliminated exceptionally large and small flows. Since the last major reservoir upstream of Northport was filled in 1976, flow in the Columbia River has varied by about one order of magnitude from 20,400 to 235,000 ft^3/s. Consequently, periods of major sediment transport occurring during the infrequent periods of exceptional large discharge may not be applicable to the Columbia River at Northport.

The largest total trace-element discharges during the low-flow sampling period were for zinc and copper, which averaged, among the three samples, 4,400 lb/d (23 g/s) for zinc and 1,200 lb/d (6.1 g/s) for copper (fig. 22). By contrast, lead and arsenic averaged about 700 and 190 lb/d (3.7 g/s and 0.97 g/s), and cadmium averaged about 45 lb/d (0.24 g/s). In most samples and for most trace elements examined, the load in the water was larger than the load in the suspended sediment. Of the trace elements examined, arsenic showed a large tendency for water-phase transport in the Columbia River samples which is consistent with other rivers studied by Meybeck and Helmer (1989; fig. 21). The arsenic water-phase fraction of the Columbia River samples ranged from 58 to 93 percent, whereas in other large rivers the water fraction ranged from 10 to 50 percent. In contrast, lead in other large rivers had a large tendency for suspended-phase transport. The observed lead fraction in Columbia River samples ranged from 36 to 58 percent, whereas the lead water-phase fraction in other rivers was small, ranging from 0.5 to 1 percent. Mercury, which was not detected at the minimum reporting concentrations in Columbia River water, normally had the smallest fraction in water of other large rivers, generally less than 0.1 percent (Meybeck and Helmer, 1989).

The last major reservoir upstream of Lake Roosevelt that affects yearly flows at Northport was filled in 1976. The mean discharge in the Columbia River at Northport was 78,300 ft^3/s during the period when the distribution of trace-element discharge in suspended sediments and water was measured. Since 1976, river flow has exceeded 78,300 ft^3/s about 70 percent of the time; consequently, the conditions under which the sampling was performed are considered low-flow conditions. The distribution of the trace-element discharge will vary at higher flows as a result of varying relations between the discharges of suspended sediment and water; however, the concentration of suspended sediment remains small at high flows, and the transport in the water phase will remain as a substantial contribution to the total transport of trace elements.

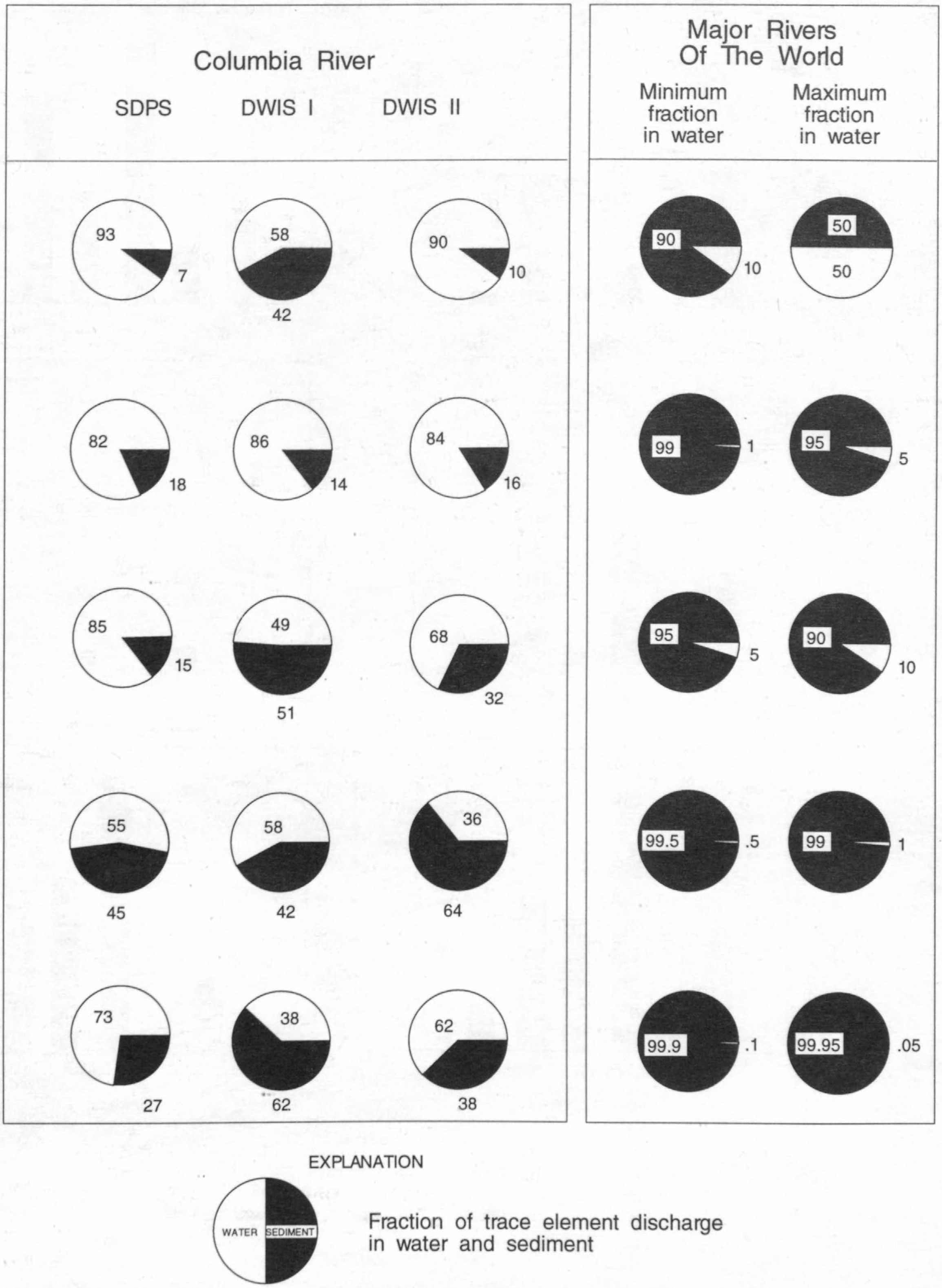


Figure 21.--Distribution of total trace-element discharge observed in the Columbia River in short-duration point-source samples (SDPS) and depth-width integrated samples (DWIS) and distribution reported for other major rivers of the world (Meybeck and Helmer, 1989).

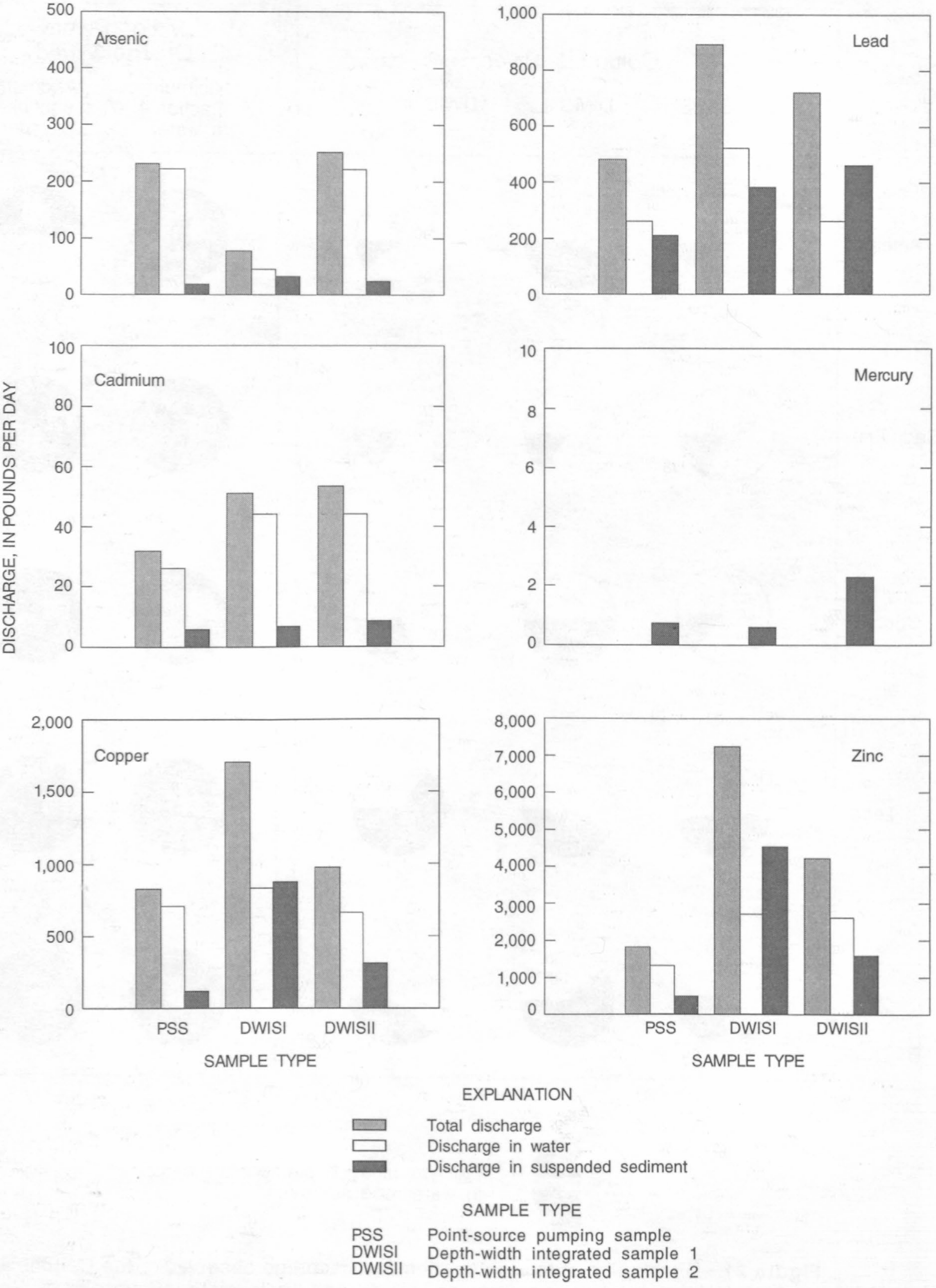


Figure 22.--Discharge of arsenic, cadmium, copper, lead, mercury, and zinc in the Columbia River at Northport, Washington, October 1992.

For example, for the sake of argument, if it is assumed that the trace-element concentrations determined at 81,300 ft^3/s (table 13) are applicable at high flow, the distribution of trace elements can be calculated for high-flow conditions (median values of data above the 95th percentile), with a river discharge of 200,000 ft^3/s and a suspended-sediment concentration of 13 mg/L. Water-quality concentration data collected over the range of low to high discharges indicate that this is a reasonable assumption. The resulting distribution of total transport for copper at this high flow would result in about 74 percent of the load in suspended-sediment fraction and the remaining fraction in water. Even though under these conditions the fraction of total discharge in the suspended-sediment phase is larger than the water phase, the fraction in the water phase is still substantially larger than those fractions reported by Meybeck and Helmer, 1989). Even though the fraction of trace-element discharge is larger for the water phases than for the suspended-sediment phase, deposition of trace-element-enriched suspended sediments can increase trace-element concentrations in the bed sediments of Lake Roosevelt.

OCCURRENCE AND DISTRIBUTION OF DIOXINS AND FURANS IN SUSPENDED SEDIMENT AND WATER IN THE COLUMBIA RIVER ENTERING LAKE ROOSEVELT

In aquatic environments like Lake Roosevelt and the Columbia River, dioxins and furans will be distributed into different environmental compartments of water, sediment, and biota. Dioxins and furans have been found in sediment and fish from Lake Roosevelt, and in suspended sediment of the Columbia River flowing into Lake Roosevelt (Johnson, Serdar, and Magoon, 1991; and Arthur Johnson, Washington State Department of Ecology, written commun., 1991). Most of the input of dioxins and furans to Lake Roosevelt is from the sediment and water compartments of the Columbia River flow.

Water and dioxins and furans have quite different chemical properties (water is polar; dioxins and furans are nonpolar), so dioxins and furans tend to associate (sorb) more strongly with sediments that are less polar than water. Thus, because of their hydrophobic nature, most of the dioxins and furans carried in sediment-ladened rivers will be sorbed to suspended sediment. However, because concentrations of suspended sediment in the Northport reach of the Columbia River are small for a river of its size, the water phase is uncommonly important in the transport and distribution of dioxins and furans in the river.

This part of the study addressed the following objectives:

1. To determine concentrations and types of dioxins and furans in the water and suspended-sediment phases of samples obtained from the Columbia River at Northport;
2. To compare concentrations of dioxins and furans observed in suspended sediment with existing data on dioxin and furan concentrations in bed sediment from Lake Roosevelt and the adjacent reaches of the Columbia River system;
3. To determine dioxin and furan discharges in suspended sediment and water; and
4. To estimate the discharge of 2,3,7,8- tetrachlorodibenzo-*p*-dioxin (2,3,7,8-TCDD) entering Lake Roosevelt and compare this discharge to USEPA's total maximum daily loading (TMDL) for 2,3,7,8-TCDD.

Data in this section of the report will show the following results.

- Dioxins and furans were found in water and suspended sediment collected in the Columbia River at Northport, but only a few of the targeted congeners and isomers were detected. Concentrations of some dioxins and furans detected in samples varied depending on the sampling regime used. The isomer 2,3,7,8-TCDD was not found in water or suspended sediment.
- Hepta- and octachlorodibenzo-*p*-dioxin (HpCDD and OCDD) were detected in suspended sediment and water in proportions that agree with existing equilibrium chemistry data.
- 2,3,7,8-tetrachlorodibenzofuran (2,3,7,8-TCDF) was detected in suspended sediment. Concentrations of 2,3,7,8-TCDF in suspended-sediment samples collected in 1992 were substantially smaller than those in 1990 samples from the Columbia River collected at the same location by Serdar and others (1993).

- For dioxin isomers detected in suspended-sediment and water phases, the calculated fraction of the discharge in the water phase ranged from 32 to 84 percent of the total discharge.

- 2,3,7,8-TCDD was not found above the detection limits of 0.01 pg/L and 1.5 pg/g in water and suspended sediment, respectively. These detection limits were not low enough to assure that the total maximum daily load established by USEPA was not exceeded during the sampling period.

Methods

Collecting and field processing dioxin and furan samples was complex. Dioxin and furan concentrations in whole-water samples from the Columbia River at Northport were small, necessitating procedures to concentrate dioxin and furan analytes. Furthermore, river-water samples were separated into water and suspended phases. Finally, samples were collected for comparison of sample collection procedures using depth-width integrating and point-source sampling techniques. The sampling plan is shown schematically on figure 23. Raw river water was centrifuged to separate it into suspended-sediment and water phases. Depending on the density of the sediment particles, the centrifuge was able to remove particles from about 0.5 to about 1 micrometer (μm) in size. In this study, the water phase included very fine particles in the range of colloidal material (less than 1 μm) not readily separated from large volumes of river water by the continuous centrifuge.

As much as possible, the present study employed a sampling strategy developed to complement the Lake Roosevelt water-quality trend-monitoring program initiated by Ecology in October of 1990 and continued in 1992 and 1993. The field work for this study was scheduled to coincide with Ecology's 1992 sampling period of September 29 to October 2. Arrangements had previously been made to assure that the upstream pulp mill was scheduled for routine operation during the sampling period and to collect a 1-liter, 24-hour composite sample of pulp-mill effluent discharged to the Columbia River (Serdar and others, 1993). The composite effluent sample was collected by the pulp mill on the day before sampling at Northport. Samples collected by Ecology were obtained as described in the previous section on trace elements in suspended sediment and water. The point-source pumping sample procedure could process the large volumes of river water needed to obtain optimum quantities of suspended sediment for analysis. However, point samples in this reach of the river may be subject to incomplete lateral mixing. For this study, river water was collected concurrently from the point-source location used by Ecology and from a nearby cross section used by the USGS to obtain DWIS samples.

Altogether, dioxin and furan samples were collected by three sampling regimes. In the first regime, USGS personnel on September 30, 1992, collected the DWIS sample by the equal-width-increment technique for collecting discharge-weighted samples (Edwards and Glysson, 1988). In the second regime, Ecology personnel sampled from the same point-source sampling location from September 29 to October 2 for trace elements to collect sufficient suspended sediment for analysis and quality-control samples. A portion of the Ecology sample collected on September 30 concurrently with the DWIS sample was isolated and designated SDPS. A total of about 0.5 gram (dry weight) of suspended sediment was available for dioxin and furan analysis from the DWIS and SDPS samples. In the third regime, a 1.1-gram (dry weight) subsample of the composite suspended-sediment sample collected over the 3-day period by Ecology was isolated for similar analysis and designated LDPS-92 in the data tables; the year was included to avoid confusion with the 3-day composite sample collected by Ecology in 1990. The DWIS and SDPS water samples were analyzed for dioxins and furans in both suspended-sediment and water phases, whereas only the suspended sediment was analyzed from the LPDS-92 sample.

The collection of river water samples followed procedures similar to those described in the section on trace-element distribution. The primary difference was that dioxin and furan samples were stored and transferred in stainless steel containers. The stainless steel containers were prepared by a washing with a non-phosphate soap, a thorough rinsing with deionized water, and a final rinsing with methanol. On the day before sample collection, all stainless steel containers were rinsed with raw river water. Containers used to hold clarified (centrifuged) river water before solid-phase extraction were rinsed with clarified river water. Samples were transferred from the RV *Estero* to the shore facility in 10-gallon seamless stainless steel milk containers with tight-fitting lids. Two 250-gallon covered stainless steel tanks held the clarified water from the SDPS prior to use with the solid-phase extraction columns.

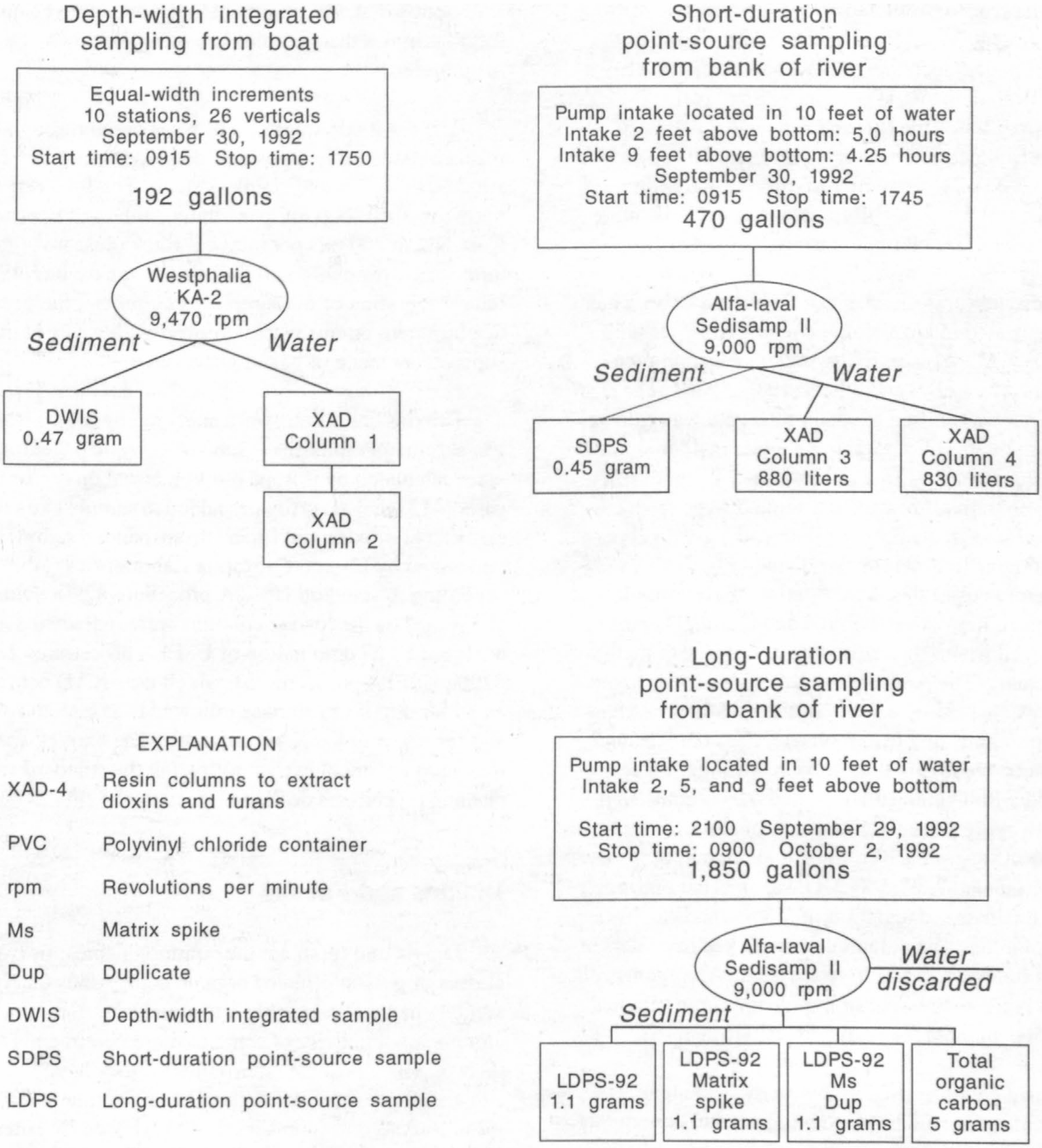


Figure 23.--Schematic of sample collection and processing of dioxins and furans sampled in the Columbia River at Northport, Washington.

Solid-phase extraction using Amberlite® XAD-2 resin was used to concentrate dioxins and furans in the water phase. The resin is a hydrophobic styrene-divinylbenzene copolymer; when water is passed through the resin, hydrophobic compounds like dioxin and furans that are in the water find a more favorable environment on the resin than in the water and consequently sorb to the resin and accumulate there. The analytes can then be removed from the resin with an appropriate non-polar solvent. Solid-phase sorbents have been used extensively to accumulate a wide variety of trace-organic compounds in water (Liska and others, 1989; Dressler, 1979). Amberlite® XAD resins, and in particular XAD-2, are efficient sorbents for concentrating trace-organic compounds at the parts per billion and parts per trillion level (Daignault and others, 1988; Van Rossum and Webb, 1978).

Although the recovery efficiency of the sorbent to sorb organic compounds decreases as the concentration of the organic compound decreases, LeBel and others (1986) found that even at the parts per quadrillion level (picograms per liter), dioxins and furans that had been quantitatively added to drinking water could be trapped for analysis on XAD-2 resin, with recoveries ranging from about 26 percent for octa-chlorinated isomers to about 52 percent for tetra- chlorinated isomers.

Dioxins and furans in clarified Columbia River water were concentrated in large-volume resin cartridges with Amberlite® XAD-2 resin, following the general procedures outlined by LeBel and others (1987, 1986). The size of the column was chosen to accommodate a water-flow rate of as much as a liter per minute while maintaining a resin-water-contact flow rate of less than 3 volumes of the XAD resin column pore space per minute. The resin cartridges were made from 330 milliliter (mL) glass gel permeation columns (3.8-centimeter diameter by 39-centimeter length) that were fitted with Teflon end pieces. The columns were washed and thoroughly rinsed with deionized water, then rinsed three times with methanol and hexane. The Amberlite® XAD-2 was purchased new and was cleaned by a series of three 16-hour soxhlet-solvent extractions, first using toluene, then acetone, and then methanol. After the final solvent washing, the resin was washed with deionized water, and the columns were packed with approximately 150 grams of resin. Prior to capping the inflow of each column, 1 nanogram of chlorine-37 labeled 2,3,7,8-TCDD was injected onto each column to evaluate the retention of dioxins and furans on the resin columns. The columns were packed in coolers at 4°C during transport to and from the field. All organic solvents used in the processing of dioxin and furan samples were certified suitable for pesticide residue analysis.

The resin columns used in this study held about 150 grams of resin, which, based on direct and continuous dioxin spiking trials conducted by LeBel and others (1987), would be sufficient to retain in excess of 5,000 picograms per gram (pg/g) of dioxins and furans. These same tests also showed that the XAD resin columns were not 100-percent effective in recovering dioxins and furans added to the sample water and that the inefficiencies were also related to small sample concentrations. Consequently, to quantify the retention characteristics of the XAD resin cartridges used in this study, the clarified water from the DWIS sample was passed through a second column that was arranged in series with the first column. Column efficiency was estimated from the concentration data from the two-column sample (see table 18), with the assumption that the column inefficiency would be constant for all samples that had dioxin concentrations of similar magnitudes.

The clarified sample water was passed through the resin columns using a positive-displacement pump constructed of Teflon and stainless steel. The flow rate was normally about 600 mL per minute, although it varied from 500 to 700 mL per minute. Back pressure at the column varied from 20 to 40 pounds per square inch. To reduce vibration of the sampling equipment, the positive-displacement pumps were equipped with water-hammer suppressors made of baked glass.

Dioxins and furans were analyzed by high-resolution gas chromatography-mass spectroscopy. Concentrations were calculated by isotope dilution based on recoveries of carbon-13 labeled surrogates added to sample extract. The analysis of dioxins and furans on suspended sediment was performed by Enseco California Laboratories (table 2) according to standard USEPA procedure 8290. Dioxins and furans on the loaded columns were extracted and then analyzed by a combination of USEPA procedures 23 and 8290. USEPA procedure 23, which uses XAD columns to assay for dioxins in air, was followed to extract the dioxins and furans from the XAD columns. The extract was then treated as sediment extract following the standard sample cleanup procedures described in method 8290.

Dioxins and Furans

Dioxin and furan are the common names for two classes of polychlorinated organic compounds that have similar chemical properties and structures. Because of the extreme high toxicity of some of these compounds and their presence in some environments, they have been the subject of extensive research. The environmental behavior of dioxins and furans has been reviewed by Hites (1990) and Rappe and others (1987). Dioxins and furans are hydrophobic and extremely persistent in the environment. They are primarily the byproducts of the manufacture of chlorinated organic compounds and the combustion products formed during incineration of municipal or chemical waste. Other industrial processes can also produce dioxins and furans, including pulp and paper mill processes that use chlorine in bleaching (Swanson and others, 1988; Amendola, Handy, and others, 1989; and Berry and others, 1989) and copper smelter processes that recycle scrap copper-containing wires coated with polyvinylchloride (Rappe and others, 1987; and Marklund and others, 1986).

Dioxins and furans associated with pulp and paper mills have been studied extensively. The bleaching of wood pulp during the production of certain types of paper products has been shown to produce many dioxin and furan isomers, but primarily the TCDF's and TCDD's (U.S.Environmental Protection Agency, 1988; Swanson and others, 1988). In an analysis of six samples from five pulp mills, Amendola and seven others (1989) found that 2,3,7,8-TCDD and 2,3,7,8-TCDF made up 93 to 99 percent of the total toxicity related to dioxins and furans. The formation of these dioxins and furans is mainly during the initial bleaching process, which employs elemental chlorine to breakdown lignins in pulp (Kringstad and others, 1989). Dioxins and furans have been found in fish and sediment samples collected downstream of pulp and paper mills (U.S. Environmental Protection Agency, 1987), including the pulp mill at Castlegar, British Columbia (Mah and others, 1989).

Dioxins and furans have been reported in pulp-mill effluents discharged into the environment (Amendola and seven others, 1989; Clement and others, 1989). From 25 to 40 percent of dioxins and furans in the pulp-mill effluent was reported by Amendola, Handy, and others (1989) to be in the water phase, which was defined as the material passing through a paper filter with a nominal pore size of 2.5 μm. The general pattern of dioxins and furans present in pulp-mill effluent is characteristically dominated by TCDF's and smaller amounts of TCDD and OCDD.

Dioxin and furan molecules have a similar basic ring structure (fig. 24). From 1 to 8 chlorine atoms can be attached to the basic ring structure, resulting in 75 possible dioxin isomers and 135 possible furan isomers (Rappe, 1984; Environment Canada, 1990). Individual compounds, or isomers, are identified by the number and position of chlorine atoms attached to the ring structure. Isomers with the same number of chlorine atoms are referred to as "congeners." The congeners with 4 to 8 chlorine atoms attached to the ring structure are listed below with their respective abbreviations.

Tetrachlorodibenzo-*p*-dioxin	(TCDD)
Pentachlorodibenzo-*p*-dioxin	(PeCDD)
Hexachlorodibenzo-*p*-dioxin	(HeCDD)
Heptachlorodibenzo-*p*-dioxin	(HpCDD)
Octachlorodibenzo-*p*-dioxin	(OCDD)

Tetrachlorodibenzofuran	(TCDF)
Pentachlorodibenzofuran	(PeCDF)
Hexachlorodibenzofuran	(HeCDF)
Heptachlorodibenzofuran	(HpCDF)
Octachlorodibenzofuran	(OCDF)

Designations of specific isomers are noted by the position of the chlorine atoms before the congener designation; for example, see 2,3,7,8-TCDD and 2,3,7,8-TCDF on figure 24. The dioxin and furan isomers that are highly toxic to some laboratory animals have chlorine atoms in the 2,3,7, and 8 positions. There are 7 possible dioxin and 10 possible furan isomers that have chlorine atoms in the 2,3,7, and 8 positions, and these 17 isomers make up the group of isomers that are routinely analyzed in environmental samples, including this study. Many analyses also report the sum of all isomers within the congener group for tetra- through octachlorinated dioxins and furans.

The overall toxicity of the mixture of dioxins and furans can be compared with other samples by using the toxicity equivalent concentration (TEC). TEC represents a toxicity-weighted total dioxin and furan concentration based on the weighted sum of all isomers that have chlorine atoms in the 2,3,7,8 positions. TEC methodology was developed as an international comparison and is advocated by the U.S. Environmental Protection Agency (1992). TEC values are determined using 2,3,7,8-TCDD as a reference compound, and all other isomers are compared to the reference by toxicity equivalent factors (TEF). TEC's are computed as the sum of individual isomer concentrations after they have been multiplied by their respective TEF's. In general, tetrachlorinated isomers have the highest toxicity factors, and octachlorinated isomers have the lowest. TEC's are calculated only for the isomer detected in a sample. Differences between the toxicity equivalent values of two samples may be because of the differences in the total dioxin and furan concentrations or differences in the proportions of the more toxic isomers.

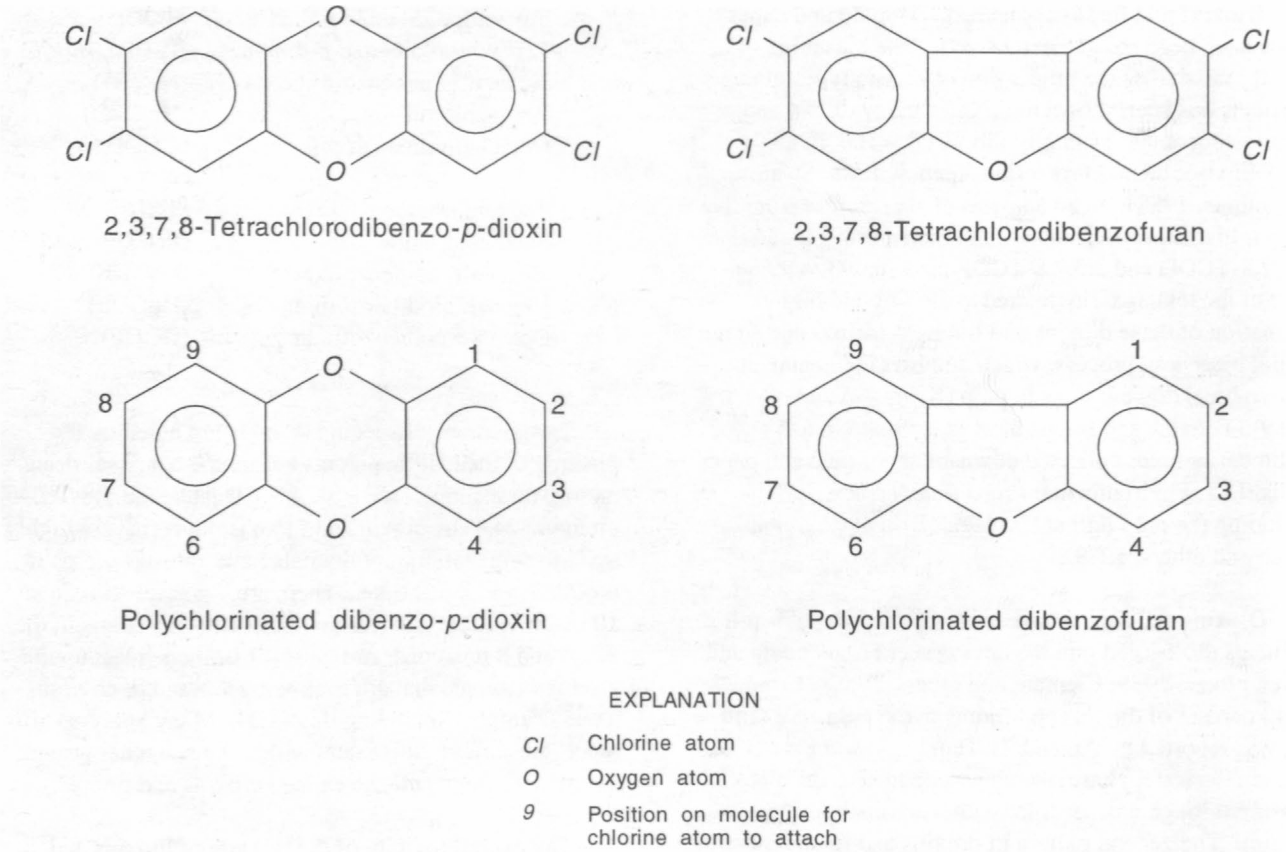


Figure 24.--Chemical structures of dioxins and furans.

Observed Concentrations and Toxicity

Data from the analyses of dioxins and furans collected on XAD resin columns from the DWIS and SDPS water samples and from suspended sediment from the DWIS, SDPS, and LDPS samples are shown in table 16. Included with the data collected for this study are data from the analysis of a 1-liter composite sample of pulp-mill effluent collected on the day before sampling at Northport (James McLaren, Celgar Pulp Company, written commun., 1992) and from the average of the duplicate analyses of suspended sediment collected at Northport in 1990 by Ecology (Arthur Johnson, Washington State Department of Ecology, written commun., 1991).

Data from samples collected for quality-control purposes for this study indicate good overall data quality; however, some aspects of sampling conditions do limit the interpretation of the results. Dioxins and furans were not detected in the field blank resin column or in the laboratory methods blank samples used with sediment and XAD samples extract, indicating that the samples were not contaminated during the collection and analyzation process. Detection-level concentrations for spike samples are shown in table 17. Spike recoveries of known quantities of unlabeled dioxins and furans added to sediment sample material ranged from 82 to 111 percent (table 17), indicating good analytical recovery of dioxin and furans from suspended sediment. The recoveries of the chlorine-37 pre-spike placed on the XAD resin column range from 77 to 91 percent (table 16), indicating that nearly all the dioxins and furans sorbed to the resin trap were retained. Dioxin and furan concentrations of replicate suspended-sediment samples were within 40 percent for LDPS-1992 samples (table 16) and 7.5 percent for the matrix spike and matrix spike duplicate (table 17), indicating adequate analytical precision.

Several factors related to sample collection and processing and to analytical procedures influence interpretation of dioxin and furan data collected for this study. First, there was a small and variable amount of suspended sediment available for analysis from the different sampling regimes. Samples consisting of smaller quantities of suspended sediment had larger detection-level concentrations, which could result in an isomer that was present at low concentrations being reported as a non-detection. A possible example of this is seen in the observed concentration of 2,3,7,8-TCDF in suspended sediment (table 16). The LDPS-1992 samples (analyzed in replicate) consisted of more than two and one-half times as much sediment as either the SDPS or the DWIS sample; the detection-level concentrations for SDPS and DWIS samples were larger than the reported concentration of the LDPS-1992 sample. With few exceptions, the minimum detection-level concentrations for isomers shown on table 16 are smaller for suspended-sediment samples with larger sample weights.

A second factor that influences interpretation of dioxin and furan concentrations in water is that there are limited data on the recovery efficiency of dioxins and furans on XAD resin columns in the 1 pg/L concentration range for isomers found on both columns. The recovery efficiency determined from the DWIS sample, which was passed through two columns in series, ranged from 50 to 61 percent (table 18). These recoveries were nearly two times greater than recoveries reported by LeBel and others (1987) in their direct and continuous spiking trials at the 1 pg/L level. The efficiency of XAD resin columns estimated for this study was twice as large as the efficiency reported by LeBel and others (1987) for their direct and continuous spiking trials, indicating that two-column method may overestimate recoveries. In this case, the actual dioxin and furan concentrations in the water phase of the Columbia River may be twice as large as those reported in table 16. It is possible that dioxins and furans associated with dissolved organic matter and colloidal particles could escape detection because these materials would be too small to be retained by the centrifuge and dioxin and furans sorbed to fine colloidal material might not remain hydrophobic enough to be retained on the XAD resin. Hydrophobic organic compounds have shown an apparent increase in solubility in the presence of dissolved organic matter or colloidal material (Carter and Suffett, 1982, and Baker and others, 1986). Rostad and Monsterleet (1993) reported that in the Mississippi River more than 50 percent of the suspended organic carbon was associated with colloidal material. The effect of dioxins and furans associated with dissolved organic matter and with colloidal material on the distribution between sediment and water was beyond the scope of this investigation.

Dioxins and furans were found in water and suspended sediment collected at Northport in 1992, but few of the 17 targeted isomers were detected (table 16). In the samples collected at Northport, more dioxin congeners were detected than furan congeners. TCDD's, including the isomer 2,3,7,8-TCDD, which is the most toxic of the isomers to some laboratory animals (Schwetz and others, 1973; Poland and Knutson, 1982), were not detected in any of the Northport samples, but TCDD's were found in the composite sample of pulp-mill effluent that had been collected on the day prior to sampling at Northport. For 2,3,7,8-TCDD, the minimum detection level ranged from 1.5 to 3.7 pg/g in suspended sediment and from 0.01 to 0.02 pg/g in water (table 16). PeCDD's were not detected in any of the Northport samples or the pulp-mill effluent. The HxCDD congener group was detected in the effluent, and a HxCDD isomer was detected in the DWIS suspended- sediment sample. HpCDD's and OCDD were present in all samples; concentrations of the higher chlorinated dioxin congeners varied among suspended-sediment samples as follows: from 57 to 380 pg/g for total HpCDD, from 25 to 210 pg/g for 1,2,3,4,6,7,8-HpCDD and from 180 to 1,300 pg/g for OCDD. However, the analysis of pulp-mill effluent detected both congeners as contaminants in the laboratory method blank at about 76 and 78 percent of reported concentration, indicating that those detections are questionable.

TCDF's were detected in water and suspended sediment and in the analysis of pulp-mill effluent (table 16). Concentrations of total TCDF's ranged from 24 to 49 pg/g in suspended sediment and from 0.05 to 1.6 pg/L in water. Concentrations of 2,3,7,8-TCDF were detected in suspended sediment; the average concentration of replicate sample was 6.1 pg/g. The 2,3,7,8-TCDF isomer, which was detected in the pulp-mill effluent (20 pg/L), was detected in suspended sediment from the LDPS-1992 sample. PeCDF's and HxCDF's were not detected in any of the 1992 Northport samples, although both congeners were detected in the pulp-mill effluent. The DWIS suspended-sediment sample was the only 1992 Northport sample that had detected HpCDF's, which were present in small concentrations in the pulp-mill effluent. OCDF was not detected in any of the water samples or in suspended sediment from the LDPS sample, but was found in suspended sediment of the DWIS and SDPS samples as well as in the pulp-mill effluent.

Table 16.--*Dioxin and furan concentrations collected on XAD resin columns and in suspended sediment in the Columbia River at Northport*

[<, less than minimum detectable concentration; SDPS, short-duration point-source sample; DWIS, depth-width integrated sample; LDPS, long-duration point-source sample; LDPS-90, collected in 1992; LDPS-92, collected in 1992; TCDF's (total), all tetrachlorinated dibenzofuran congeners; 2, 3, 7, 8-TCDF, 2, 3, 7, 8-tetrachlorodibenzofuran; Pe—, penta; Hx—, hexa; Hp—,hepta; O—, octa; —CDF, chlorodibenzofuran; —CDD, chlorodibenzo-*p*-dioxin; TEC: 4-7, toxicity equivalent concentration using tetra- through heptachlorinated dioxin and furan congeners for calculation of toxicity equivalent concentrations; L, liters of sample river water or effluent; g, grams of sediment (dry weight); --, not applicable]

		Concentrations in picograms per liter					Concentrations in picograms per gram				
		XAD columns					Suspended-sediment phase				
Compound	Toxicity equivalence factor	SDPS (882 L)	SDPS duplicate (834 L)	DWIS column 1 (720 L)	DWIS column 2 (720 L)	Pulp-mill effluent[1] (1 L)	DWIS (0.47 g)	SDPS (0.45 g)	LDPS-92 (1.2 g)	LDPS-92 duplicate (1.2 g)	LDPS-90[2] (10 g)
						Furans					
TCDF's (total)	--	1.6	1.2	0.05	<0.01	140	<7.8	49	[3]33	[3]24	200
2, 3, 7, 8-TCDF	0.1	<.01	<.01	<.02	<.01	20	<7.4	<9.4	6.6	5.6	99
PeCDF's (total)	--	<.02	<.02	<.03	<.02	16	<17	<4.5	<2.6	<2.5	4.3
1, 2, 3, 7, 8-PeCDF	.05	<.01	<.01	<.02	<.01	<4.0	<4.6	<3.3	<1.8	<1.7	1.0
2, 3, 4, 7, 8-PeCDF	.5	<.02	<.02	<.03	<.02	<4.0	<6.7	<4.5	<2.6	<2.5	1.4
HxCDF's (total)	--	<.01	<.02	<.02	<.02	4.3	[3]<25	<6.3	<5.6	<2.4	<0.29
1,2,3,4, 7, 8-HxCDF	.1	<.01	<.02	<.02	<.02	<4.0	<7.4	<5.8	<2.6	<2.2	<0.25
1, 2, 3, 6, 7, 8-HxCDF	.1	<.01	<.02	<.02	<.02	<4.0	<4.4	<6.3	<2.8	<2.4	<0.19
2, 3, 4, 6, 7, 8-HxCDF	.1	<.01	<.02	<.02	<.02	<4.0	<8.0	<5.8	<2.5	<2.2	<0.29
1, 2, 3, 7, 8, 9-HxCDF	.1	<.01	<.02	<.02	<.02	<4.0	<1.7	<6.3	<2.6	<2.2	<0.29
HpCDF's (total)	--	<.01	<.02	<.03	<.01	6.3	300	<18	<10	<10	4.2
1, 2, 3, 4, 6, 7, 8-HpCDF	.01	<.01	<.01	<.01	<.01	<6.0	130	<18	<10	<1.2	<1.1
1, 2, 3, 4, 7, 8, 9-HpCDF	.01	<.01	<.01	<.03	<.01	<6.0	<6.1	<3.0	<.99	<10	<0.52
OCDF	.001	<.04	<.03	<.04	<.07	8.6	230	130	<14	<11	4.6
						Dioxins					
TCDD's (total)	--	<.01	<.02	<.02	<.02	7.6	<3.6	<3.7	<1.5	<1.7	<0.77
2, 3, 7, 8-TCDD	1.0	<.01	<.02	<.02	<.02	7.6	<3.6	<3.7	<1.5	<1.7	<0.77
PeCDD's (total)	--	<.02	<.03	<.04	<.02	<4.0	<12	<16	<4.7	<6.6	<0.51
1, 2, 3, 7, 8-PeCDD	.5	<.02	<.03	<.04	<.02	<4.0	<4.4	<3.7	<1.5	<1.0	<0.51
HxCDD's (total)	--	<.02	<.02	<.03	<.02	16	<18	<5.8	<6.1	<4.5	<2.0
1, 2, 3, 4, 7, 8-HxCDD	.1	<.01	<.01	<.01	<.02	<4.0	<2.5	<4.9	<2.5	<2.6	<0.67
1, 2, 3, 6, 7, 8-HxCDD	.1	<.02	<.02	<.01	<.02	<4.0	<8.6	<6.3	<3.2	<3.2	<0.68
1, 2, 3, 7, 8, 9-HxCDD	.1	<.01	<.02	<.01	<.02	<4.0	<3.4	<5.4	<2.7	<2.7	<0.75
HpCDD's (total)	--	.16	.19	.22	.09	108	380	[3]<85	80	57	24
1, 2, 3, 4, 6, 7, 8-HpCDD	.01	.09	.12	.12	.06	[4]33	210	<37	37	25	11
OCDD	.001	.85	.72	.71	.28	[4]450	1,300	240	240	180	74

Table 16.--*Dioxin and furan concentrations collected on XAD resin columns and in suspended sediment in the Columbia River at Northport--Continued*

Compound	Toxicity equivalence factor	Concentrations in picograms per liter					Concentrations in picograms per gram				
		XAD columns				Pulp-mill effluent[1]	Suspended-sediment phase				
		SDPS (882 L)	SDPS duplicate (834 L)	DWIS column 1 (720 L)	DWIS column 2 (720 L)	(1 L)	DWIS (0.47 g)	SDPS (0.45 g)	LDPS-92 (1.2 g)	LDPS-92 duplicate (1.2 g)	LDPS-90[2] (10 g)
Sample toxicity equivalent concentration											
Toxicity equivalent concentration	--	--	--	--	--	--	4.9	0.37	1.3	.99	11
TEC: 4-7	--	--	--	--	--	--	3.4	0.0	1.0	.81	11
Recovery of carbon-13 (13C) and chlorine-37 (37Cl) labeled dioxin and furan surrogates, in percent											
13C-2, 3, 7, 8-TCDF	--	92	76	86	98	76	101	101	102	92	80
13C-2, 3, 7, 8-TCDD	--	114	92	110	110	68	105	101	107	95	90
13C-1, 2, 3, 7, 8-PeCDF	--	90	84	88	100	91	102	103	102	91	84
13C-1, 2, 3, 7, 8-PeCDD	--	98	94	100	109	106	87	88	95	84	100
13C-1, 2, 3, 4, 7, 8-HxCDF	--	98	70	94	81	74	85	88	90	78	70
13C-1, 2, 3, 6, 7, 8-HxCDD	--	114	92	106	111	82	98	103	96	84	80
13C-1, 2, 3, 4, 6, 7, 8-HpCDD	--	96	72	98	83	65	123	124	110	99	80
13C-1,2,3,4,6,7,8-HpCDF	--	104	92	90	83	64	124	132	110	99	59
13C-OCDD	--	112	96	100	101	37	131	117	109	98	64
37Cl-2, 3, 7, 8-TCDD	--	82	91	77	86	--	--	--	--	--	--

[1] Jim McClaren, Celgar Pulp Company, written commun., 1992.

[2] Arthur Johnson, Washington Department of Ecology, written commun., 1991.

[3] Estimate concentration.

[4] Isomer detection in method blank (HpCDD, 25 picograms per gram; OCDD, 350 picograms per gram).

Table 17.--*Concentration and percentage recovery of dioxins and furans in spike samples*

[pg/g, picogram per gram; nd, not detected; --, not applicable; TCDF, tetrachlorinated dibenzofuran congeners; 2, 3, 7, 8-TCDF, 2, 3, 7, 8-tetrachlorinated dibenzofuran; Pe—, pentachlorinated; Hx—, hexachlorinated; Hp—, heptachlorinated; O—, octachlorinated; —CDF, chlorinated dibenzofuran; —CDD, chlorinated dibenzodioxin]

Isomer	Concentration in environmental sample	Spike concentration	Concentration found in spike sample	Percentage recovery found in spike sample	Concentration found in spike duplicate	Percentage recovery in spike duplicate
		(pg/g)			(pg/g)	
			Furans			
2,3,7,8-TCDF	1.4	40	41	99	41	99
1,2,3,7,8-PeCDF	nd	100	100	100	101	101
2,3,4,7,8-PeCDF	nd	100	85	85	84	84
1,2,3,4,7,8-HxCDF	nd	100	100	100	102	102
1,2,3,6,7,8-HxCDF	nd	100	101	101	102	102
1,2,3,7,8,9-HxCDF	nd	100	106	106	108	108
2,3,4,6,7,8-HxCDF	nd	100	105	105	103	103
1,2,3,4,6,7,8-HpCDF	nd	100	103	103	106	106
1,2,3,4,7,8,9-HpCDF	nd	100	102	102	110	111
OCDF	nd	200	180	90	190	93
			Dioxins			
2,3,7,8-TCDD	nd	40	37	92	38	95
1,2,3,7,8-PeCDD	nd	100	92	92	94	94
1,2,3,4,7,8-HxCDD	nd	100	88	88	87	87
1,2,3,6,7,8-HxCDD	nd	100	95	95	95	95
1,2,3,7,8,9-HxCDD	nd	100	97	97	94	94
1,2,3,4,6,7,8-HpCDD	7.8	100	102	94	99	92
OCDD	52	200	230	91	220	82
			Recovery of carbon-13 labeled surrogate			
13C-2,3,7,8-TCDF	--	--	--	93	--	104
13C-2,3,7,8-TCDD	--	--	--	76	--	107
13C-1,2,3,7,8-PeCDF	--	--	--	94	--	104
13C-1,2,3,7,8-PeCDD	--	--	--	83	--	93
13C-1,2,3,4,7,8-HxCDF	--	--	--	92	--	90
13C-1,2,3,4,7,8-HxCDD	--	--	--	88	--	103
13C-1,2,3,4,6,7,8-HpCDF	--	--	--	83	--	120
13C-1,2,3,4,6,7,8-HpCDD	--	--	--	97	--	123
13C-OCDD	--	--	--	100	--	125

Concentrations of dioxins and furans in suspended sediment from the different sampling regimes varied. A measure of the analytical variation is shown in the duplicate analysis of suspended sediment from the LDPS sample. For the five isomers or congeners detected in the LDPS sample, the relative percent differences between the samples were less than 40 percent and averaged about 30 percent (table 16). The variation between isomer and congener concentrations from the different sampling regimes generally showed much larger relative percent differences, indicative of concentration differences between the samples. A consistent pattern of variation between sampling regimes was not discernible, and with only a single set of data for comparison, there are obvious limitations to interpretation. Most notable is the limited information on short-term variability of dioxin and furan concentrations with respect to river flow, which has been shown to be large in the case of trace-element constituents that are also strongly associated with suspended sediment (Horowitz, Rinella, and others, 1989). However, concentration data from the SDPS and the LDPS samples did not show large differences where sampling procedures differed only in the duration of the sampling period, 9 hours for the SDPS and 60 hours for the LDPS. Variations between HpCDD and OCDD concentrations from these two sampling regimes are within the range observed for analytical variation of the replicate samples. TCDF concentrations in the SDPS and LDPS samples showed a relative difference of about 53 percent, which is slightly larger than observed for the replicate analysis. However, the analysis of the SDPS sample also detected OCDF, which was not detected in either analysis of the LDPS sample.

Differences between the DWIS sample and the SDPS and LDPS-1992 samples were more apparent. Most notable was the absence of TCDF's from the DWIS samples, whereas other congeners (HpCDF and HxCDD) detected in the DWIS sample were not detected in the SDPS or LDPS-1992 samples. Also, the HpCDD and OCDD concentrations were much larger in the DWIS samples than in the SDPS and LDPS-1992 samples.

The toxicity equivalent concentrations (TEC's) of the suspended-sediment samples ranged by almost an order of magnitude (0.37-4.9 pg/g), depending on the sampling regime used (table 16). The TEC of the DWIS sample (4.9 pg/g) was larger than either of the point-source samples. All of the toxicity in the DWIS sample was due to large concentrations of the less toxic hepta- and octachlorinated isomers, whereas the TEC's of the SDPS and the LDPS-1992 samples were much smaller, primarily because they contained much smaller concentrations of the higher chlorinated dioxins and furans. The LDPS sample also included toxicity from 2,3,7,8-TCDF and 1,2,3,4,6,7,8-HpCDD, which increased the sample TEC's from 0.37 for the SDPS to 0.99 to 1.3 for the LDPS-1992.

Concentrations of 2,3,7,8-TCDF in suspended sediment in 1992 were substantially smaller than concentrations observed in 1990 by Ecology in similar samples designated LDPS-1990 (table 16). From the beginning of operation of the pulp-mill plant near Castlegar in 1961 until plant modernization in 1991 and 1992, the chlorine bleach process was used. This process is known to produce dioxins and furans, which were reported in all available effluent analyses prior to 1993, the earliest available analysis being dated 1987. Dioxins and furans were probably a component of pulp effluent during that entire period of operation prior to modernization. Modernization of the pulp-mill operation was designed in part to reduce the level of discharge of dioxins and furans. The volume of effluent discharged by the pulp mill was about 43 ft^3/s before modernization and about 45 ft^3/s after modernization; however, the average concentration of 2,3,7,8-TCDF in 1990 was reported to be 660 pg/L, which declined to 13 pg/L in 1992 (Celgar Pulp Company, 1992). The decline of TCDF in effluent samples from 1990 to 1992 is a likely explanation for decrease in concentration observed in suspended sediment at Northport in 1990 and 1992; however, other variables such as plant operations, sample collection procedures, and river mixing are also plausible explanations for changes in observed concentrations at Northport. Additional collections of representative samples over time will be needed to establish statistical trends.

The TEC's of the LDPS-1992 samples (0.99 and 1.3 pg/g) were about an order of magnitude smaller than the TEC of the LDPS-1990 sample (11 pg/g). The smaller TEC in the 1992 sample resulted from an order of magnitude decline in the concentration of 2,3,7,8-TCDF (table 16). The concentration of OCDD was larger in the 1992 sample; however, the TEF of OCDD is much smaller than that of 2,3,7,8-TCDF; thus the larger concentration of OCDD had little effect on the sample TEC. The sample TEC of the pulp-mill effluent also declined; the isomer 2,3,7,8-TCDD, which was not detected in 1990, was detected in four of six samples in 1992 (James McClaren, Celgar Pulp Company, written commun., 1993). The isomer 2,3,7,8-TCDD was not detected in the suspended-sediment sample collected at Northport by Ecology in either 1990 or 1992.

Suspended sediment and most of the sorbed dioxins and furans in the Columbia River at Northport will settle out in the slower moving waters of Lake Roosevelt. There the dioxins and furans are incorporated into bed sediment or are taken up by biota. When dioxins and furans were measured in bed sediments of Lake Roosevelt by Johnson, Serdar, and Norton (1991), they noted a trend of decreasing TCDF concentration from near French Point Rocks downstream to Grand Coulee Dam. A comparison of the pattern of concentrations of dioxin and furan congeners found in suspended sediments at Northport with the pattern of concentrations in bed sediments of Lake Roosevelt (Johnson, Serdar, and Norton, 1991) and the Columbia River upstream of Northport (Julia Beatty-Spence, CRIEMP, written commun., 1993) is shown on figure 25. Additional dioxin and furan data for the Columbia River in Canada were reported by Mah and others (1989) and by Celgar Pulp Company (1990). Dioxin and furan concentrations are compared primarily by use of bar charts to plot the pattern of relative concentrations of the different dioxin and furan congeners, although information regarding TEC's, grain size, and organic carbon content is also included. Bed-sediment samples from Lake Roosevelt obtained by Johnson, Serdar, and Norton (1991) for analysis of dioxins and furans were not analyzed for OCDF and OCDD; consequently the TEC's shown on figure 25 are the sums of the isomer toxicity equivalent concentrations for the tetra- through hepta- isomers and are designated TEC:4-7. The dioxin and furan concentrations shown on figure 25 are from both suspended sediment and bed sediments. Because the grain size distributions and total organic carbon content of these phases are different, the data should only be compared in a conceptual manner.

The two most prominent congener groups in the congener patterns are TCDF and OCDD. The source of the TCDF observed in sediment samples is likely related to pulp-mill operations. TCDF's, along with smaller quantities of TCDD's, have been reported to be the major congeners present in pulp-mill effluent (Clement and others, 1989; Amendola and seven others, 1989) and in sediments associated with pulp mills (Mah and others, 1989; Rappe and others, 1989). TCDF's and smaller amounts of TCDD's were consistently detected in samples of pulp-mill effluent discharged to the Columbia River at Castlegar between 1987 and 1992 (Celgar Pulp Company, 1992). With the exception of pulp mills using chlorine in the bleaching process, TCDF's are minor congeners in other processes that release dioxins and furans into the environment (Rappe and others, 1987).

TCDF was the predominant furan congener detected in bed sediment in many of the samples downstream of the pulp mill (fig. 25), although for sediment samples from Lake Roosevelt, OCDF and OCDD were not analyzed. TCDF concentrations were much smaller at the two reservoir sites upstream of the pulp mill and at the Long Lake reservoir site on the Spokane River, which is also upstream of Lake Roosevelt. TCDF's were found in all of the Lake Roosevelt bed sediment samples where dioxins and furans were detected and in the one sample downstream of Grand Coulee Dam. Dioxins and furans were not detected at three locations in the upstream reach of Lake Roosevelt, which has relatively coarse sediment devoid of organic carbon. As noted by Johnson and others (1991), concentrations of TCDF's in Lake Roosevelt sediments were smaller at the sampling locations further downstream. The source of the TCDF's observed in sediment samples from Lake Roosevelt and the upstream reaches of the Columbia River is most likely related to pulp-mill effluent discharge to the Columbia River.

OCDD was present in all samples for which it was analyzed, and in many samples it was the predominant isomer and congener class. OCDD is generally present only as a minor congener in reported analyses of dioxins and furans in effluent and sediment associated with pulp mills (Clement and others, 1989, and Rappe and others, 1989) and in the analysis from the pulp mill at Castlegar (James McLaren, Celgar Pulp Company, written commun., 1992). OCDD has been shown to be a major congener produced by incineration of municipal solid waste (Czuczwa and Hites, 1986; Miyata and others, 1988), transported by prevailing winds in the atmosphere (Eitzer and Hites, 1989) and widely deposited in lake, stream, and marine sediments (Hites, 1990; MacDonald and Cretney, 1992; and Borman and others, 1989). Although other environmental sources produce dioxins and furans in which OCDD is the prominent congener, its extreme widespread occurrence and presence in remote locations (Czuczwa and Hites, 1986; Frank Rinella, U.S. Geological Survey, written commun., 1992) attest to atmospheric transport being a major transport mechanism. Aside from the fact that OCDD is produced by nearly all of the common processes that release dioxins and furans, its widespread occurrence in the environment may in part reflect some of its chemical properties that make it more resistant to environmental degradation and more strongly associated with sediments than other dioxins and furans. The widespread occurrence of OCDD, particularly in reservoirs upstream of Lake Roosevelt, and the relative prominence of OCDD in the DWIS Columbia River suspended-sediment sample indicate that sources other than pulp-mill effluent contribute to the dioxins and furans in these sediments.

Distribution of Dioxins and Furans Between Sediment and Water

Total discharge of dioxins and furans in river flow will be the combined discharge of dioxins and furans associated with both the suspended-sediment and the water phases. Even though dioxins and furans are hydrophobic compounds and associate much more strongly with the sediment phase, the discharge of suspended sediment in the Northport reach of the Columbia River is small in comparison to the discharge of water, so the smaller concentration of dioxins and furans in the water phase contributes a larger fraction of the total discharge of dioxins and furans.

In this study, the dioxin and furan concentrations measured in the suspended-sediment and water phases were used in three ways: first, to compare the distribution of dioxin and furan concentrations measured in the suspended-sediment and water phases to distributions in other aquatic environments; second, to determine the relative importance of the dioxins and furans associated with the water phases to the total discharge of dioxins and furans in the Northport reach of the Columbia River; and third, to use the equilibrium distribution as part of an evaluation of the total discharge of 2,3,7,8-TCDD in this reach of the river and to compare this discharge to the TMDL of 2,3,7,8-TCDD established by USEPA for this reach of the river.

Calculation of Sorption Partition Coefficient

The distribution of dioxins and furans between water and suspended sediment, which is governed by the physical and chemical conditions in the river, is said to be in equilibrium when the relative proportions of the compound present in each phase are constant with respect to time. This equilibrium distribution can be used to make estimates of the total amount of dioxin and furan present when concentration information is available for only one of the phases.

The equilibrium distribution of hydrophobic compounds between suspended sediment and water is described by the sorption partition coefficient, K_{oc}, defined as the ratio of the concentration in suspended sediment to the concentration in water and normalized to the organic carbon content of the suspended sediment (Chiou and others, 1986; Smith and others, 1988). K_{oc} is defined as follows:

$$K_{oc} = \left(\frac{\mathrm{C}_{\mathrm{ss}} \times 10^3}{\mathrm{C}_{\mathrm{aq}} \times \frac{1}{\rho}}\right)\left(\frac{1}{f_{oc}}\right), \qquad (2)$$

where

C_{ss} = concentration of dioxin in suspended sediments, in picograms per gram;

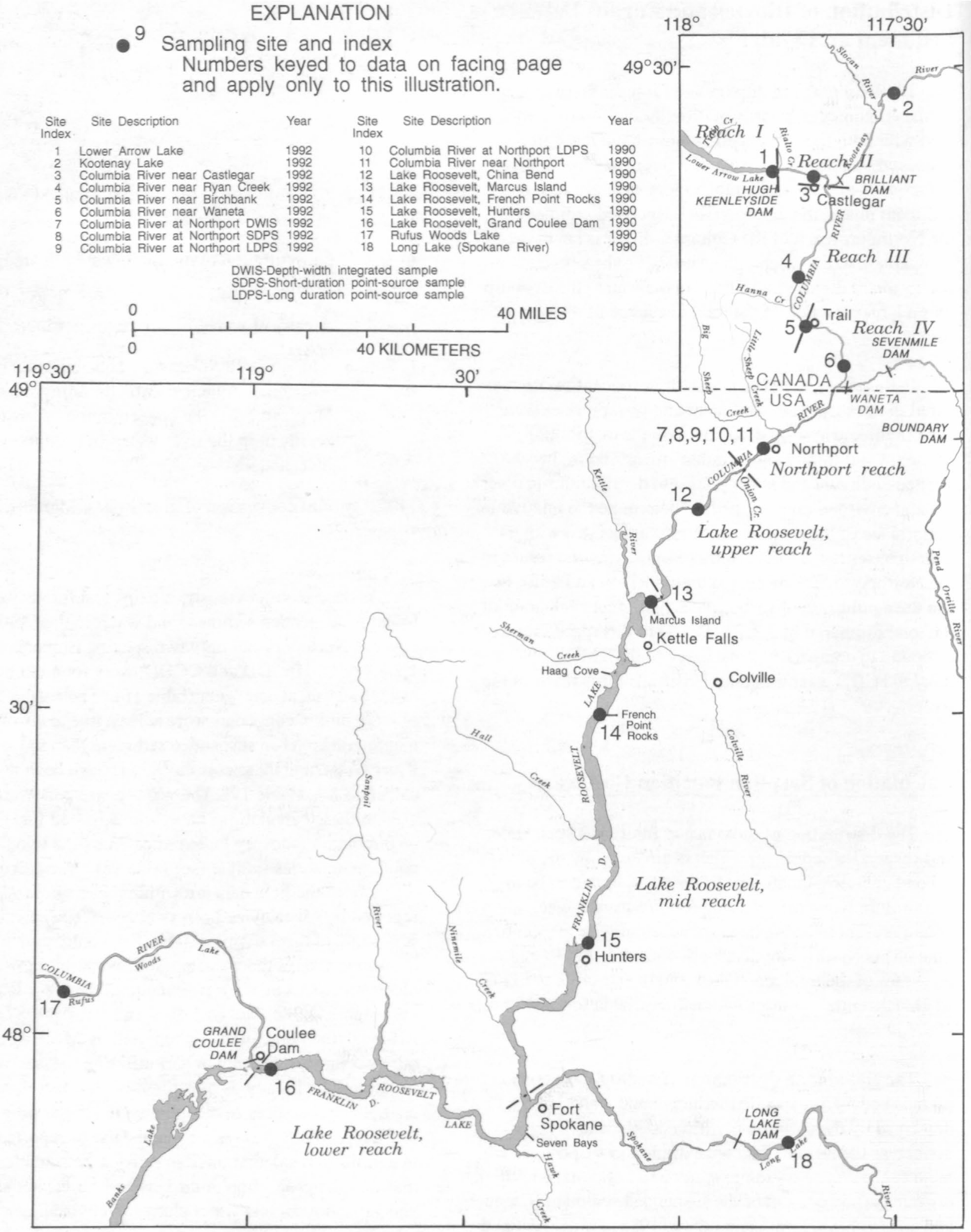
C_{aq} = concentration of dioxin in water, in picograms per liter;

ρ = density of water, in kilograms per liter;

f_{oc} = $\frac{SOC}{SS}$, where SOC is the concentration of suspended organic carbon, in milligrams per liter, and SS is the concentration of suspended sediment in the river water, in milligrams per liter; and

10^3 = unit conversion of grams per kilograms.

As described previously, dioxins and furans were found in suspended sediment and water in the Columbia River at Northport, but only two specific isomers, 1,2,3,4,6,7,8-HpCDD and OCDD, were found in both suspended sediment and water (table 16). The concentrations of these dioxin congeners were at least five to six orders of magnitude larger in suspended sediment than in Columbia River water, and these concentrations have been used to calculate K_{oc} (table 19). The water phase concentrations used in these calculations have been adjusted for the resin-column recovery loses indicated by the two-columns-in-series sample (see table 18). The calculated K_{oc}'s from the field data are within the range of K_{oc}'s reported by MacKay and others (1992). The calculated K_{oc}'s of 2 of the 3 samples (table 19) would remain within this range even if the water phase concentration were doubled again to account for resin column recovery loses of the magnitude reported by LeBel and others (1987). Although the range of K_{oc}'s reported by MacKay and others is large, reflecting in part differing measurement techniques and methods of estimation, the fact that concentrations measured in the field are in similar proportions to the reported K_{oc} suggests that the use of reported K_{oc}'s in equilibrium calculations can provide reasonable estimates of the proportion of dioxins and furans in the suspended-sediment and water phases of environmental samples.

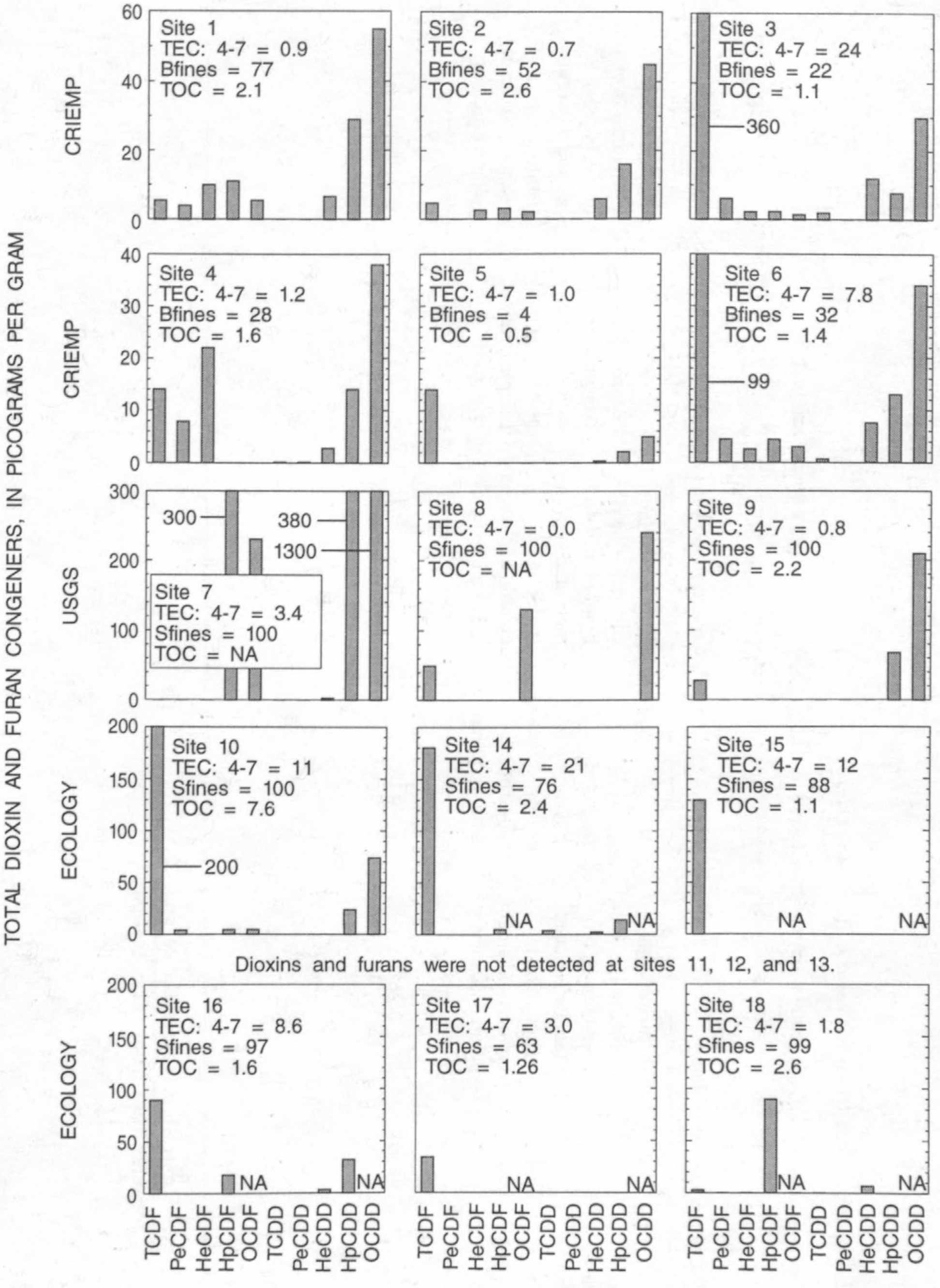

EXPLANATION

● 9 Sampling site and index
Numbers keyed to data on facing page and apply only to this illustration.

Site Index	Site Description	Year	Site Index	Site Description	Year
1	Lower Arrow Lake	1992	10	Columbia River at Northport LDPS	1990
2	Kootenay Lake	1992	11	Columbia River near Northport	1990
3	Columbia River near Castlegar	1992	12	Lake Roosevelt, China Bend	1990
4	Columbia River near Ryan Creek	1992	13	Lake Roosevelt, Marcus Island	1990
5	Columbia River near Birchbank	1992	14	Lake Roosevelt, French Point Rocks	1990
6	Columbia River near Waneta	1992	15	Lake Roosevelt, Hunters	1990
7	Columbia River at Northport DWIS	1992	16	Lake Roosevelt, Grand Coulee Dam	1990
8	Columbia River at Northport SDPS	1992	17	Rufus Woods Lake	1990
9	Columbia River at Northport LDPS	1992	18	Long Lake (Spokane River)	1990

DWIS-Depth-width integrated sample
SDPS-Short-duration point-source sample
LDPS-Long duration point-source sample

Figure 25.--Congener patterns of dioxins and furans in suspended and bed sediment from sites on the Columbia River and Lake Roosevelt. (Dioxins and furans were not detected at sites 11, 12, and 13.) Data were collected by the U.S. Geological Survey (USGS), the Columbia River Environmental Monitoring Program (CRIEMP), or the Washington State Department of Ecology (Ecology).



EXPLANATION

TCDF	Tetrachlorodibenzofuran	TCDD	Tetrachlorodibenzo-*p*-dioxin
PeCDF	Pentachlorodibenzofuran	PeCDD	Pentachlorodibenzo-*p*-dioxin
HeCDF	Hexachlorodibenzofuran	HeCDD	Hexachlorodibenzo-*p*-dioxin
HpCDF	Heptachlorodibenzofuran	HpCDD	Heptachlorodibenzo-*p*-dioxin
OCDF	Octachlorodibenzofuran	OCDD	Octachlorodibenzo-*p*-dioxin

TEC: 4-7	Sum of toxicity equivalent concentrations for tetra- through hepta-chlorinated dioxin and furan congeners
Bfines	Percentage of silt and clay in bed sediments
Sfines	Percentage of silt and clay in suspended sediments
TOC	Percentage total organic carbon
NA	Not analyzed
—100	Bar value exceeds graph.

Figure 25.--Continued

Table 18.--*Total concentrations of dioxins recovered from two resin columns in series*

[Hp—, hepta; O—, octa;—CDD, chlorodibenzo-*p*-dioxin; DWIS, depth-width integrated sample; SDPS, short-duration point-source sample]

	DWIS Concentrations, in picograms per liter				SDPS Concentrations, in picograms per liter			
Isomers	Concentration in depth-width integrated sample, resin column 1	Concentration in depth-width integrated sample, resin column 2	Single column efficiency[1]	Estimated total concentration of dioxin based on measured concentration in one column and single column efficiency	Measured concentration in short-duration point-source sample column	Estimated total concentration of dioxin based on measured concentration in one column and single column efficiency	Measured concentration in short-duration point-source sample column, duplicate	Estimated total concentration of dioxin based on measured concentration in one column and single column efficiency
1,2,3,4,6,7,8-HpCDD	0.12	0.06	0.50	0.24	0.09	0.18	0.12	0.24
Total-HpCDD	.22	.09	.59	.37	.16	.27	.19	.32
OCDD	.71	.28	.61	1.2	.85	1.4	.72	1.2

[1] Column efficiency calculated as $\left(1-\frac{\text{concentration from resin column 2}}{\text{concentration from resin column 1}}\right)$.

Table 19.--*Calculated and published sorption partition coefficients* K_{oc} *for hepta- and octachlorodibenzo*-p-*dioxin*

[DWIS, depth-width integrated sample; SDPS, short-duration point-source sample; pg/L, picograms per liter; pg/g, picograms per gram; mg/L, milligrams per liter; <, less than; --, not applicable]

		Concentrations					
Congener	Sample method	Dioxin in water (pg/L)[1]	Dioxin in suspended sediment (pg/g)	Suspended organic carbon (mg/L)	Suspended sediment (mg/L)	Calculated log K_{oc}	Published range of log K_{oc}[2]
1,2,3,4,6,7,8-Heptachlorodibenzo-*p*-dioxin	DWIS[2]	0.24	210	0.2	2	6.94	5.47 - 7.80
	SDPS	.21	<37	.2	1	--	--
Octachlorinated dioxin	DWIS[2]	1.2	1,300	.2	2	7.03	5.92 - 7.90
	SDPS	1.3	240	.2	1	5.97	5.92 - 7.90

[1] Concentrations estimated on the basis of single resin column efficiency (see table 18).

[2] MacKay and others, 1992.

Phases of Dioxins and Furans Discharge

The discharge (or load) of dioxins and furans is distributed between the suspended-sediment and water phases, and as such, the total discharge is the sum of the discharge associated with each phase. For 1,2,3,4,6,7,8-HpCDD and OCDD, which were present in both phases, the total discharge and the discharge for each phase can be determined directly, as shown below. At the time of sampling, the flow in the Columbia River was 83,800 ft^3/s (2,370,000 L/s), with a mean suspended-sediment concentration of 1 to 2 mg/L.

Discharge of dioxins and furans in the water phase is determined for the general case by

$$Q_{D/F,aq} = C_{D/F,aq} \times Q_R \ , \tag{3}$$

where

$Q_{D/F,aq}$ = discharge of dioxins or furans in water phase, in picograms per second;

$C_{D/F,aq}$ = concentration of dioxins or furans in the water phase, in picograms per liter; and

Q_R = discharge of river water, in liters per second.

Discharge of dioxins and furans associated with suspended sediment is determined by

$$Q_{D/F,\mathrm{ss}} = C_{D/F,\mathrm{ss}} \times SS \times Q_R \times 10^{-3} \ , \tag{4}$$

where

$Q_{D/F,\mathrm{ss}}$ = discharge of dioxins or furans in suspended sediment, in picograms per second;

$C_{D/F,\mathrm{ss}}$ = concentration of dioxins or furans in suspended sediment, in picograms per gram;

SS = concentration of suspended sediment in river water, in milligrams per liter;

Q_R = discharge of river water, in liters per second; and

10^{-3} = unit conversion for grams to milligrams.

The total discharge for the isomer is the sum of the results of equations 3 and 4, and the fraction of the total discharge of dioxins and furans in the water phase can be determined as

$$\frac{Q_{D/F,aq}}{Q_{D/F,aq} + Q_{D/F,ss}} \quad . \qquad (5)$$

The resulting total discharge and fraction of the total discharge in the water phase for the 1,2,3,4,6,7,8-HpCDD and OCDD isomers are shown in table 20. In the DWIS sample, the resulting fraction of the total discharge of 1,2,3,4,6,7,8-HpCDD in the water phase was 36 percent, and the water fraction of OCDD discharge was 32 percent; and in the SDPS sample, which did not include HpCDD, the water fraction of the OCDD discharge approached 84 percent. These data show directly that if dioxins are present in the river flow, the dioxins in the water phase (dissolved and associated with colloidal material) account for a substantial portion of the total discharge of these dioxin isomers. The fact that these isomers are among the most hydrophobic of dioxin isomers indicates that the discharge in the water phase may be significant for other dioxins and furans that have greater solubilities and that were not detected in these samples.

The equilibrium distribution of dioxins and furans between suspended-sediment and water phases can be estimated for any isomer when the appropriate K_{oc}, the concentrations of suspended-sediment, and the organic carbon fraction in suspended sediment are known. The fraction of dioxins and furans in the water phase can be determined from equation 5 as shown below.

$$\frac{Q_{D/F,aq}}{Q_{D/F,aq} + Q_{D/F,ss}} = \frac{C_{D/F,aq} \times Q_R}{(C_{D/F,aq} \times Q_R) + (C_{D/F,ss} \times Q_R \times SS \times 10^{-3})}$$

$$= \frac{C_{D/F,aq}}{C_{D/F,aq} + (C_{D/F,ss} \times SS \times 10^{-3})}$$

$$= \frac{1}{1 + \left(\left(\frac{C_{D/F,ss}}{C_{D/F,aq}}\right) \times SS \times 10^{-3}\right)} \quad .$$

Equation 2 can be rearranged with the ratio of concentrations of dioxins in suspended-sediment and water phases on the left side:

$$\left(\frac{C_{D/F,ss}}{C_{D/F,aq}}\right) = \frac{K_{oc} \times f_{oc}}{\rho \times 10^3} \quad .$$

Substituting this rearranged expression in the equation for the water fraction gives

$$\frac{Q_{D/F,aq}}{Q_{D/F,aq} + Q_{D/F,ss}} = \frac{1}{1 + \left(\frac{K_{oc} \times f_{oc} \times SS \times 10^{-3}}{\rho \times 10^3}\right)}$$

$$= \frac{1}{1 + \left(\frac{K_{oc} \times f_{oc} \times SS \times 10^{-6}}{\rho}\right)} \quad .$$

And finally, because the density of dilute river water is very close to 1 for ambient river conditions, the general case for calculating the dioxin or furan fraction in water is

$$\text{Fraction in water} \approx \frac{1}{1 + (K_{oc} \times f_{oc} \times SS \times 10^{-6})} \quad . \qquad (6)$$

For isomers of interest, such as 2,3,7,8-TCDD, that were not detected in the analysis of suspended sediment and water, the distribution between the suspended-sediment and water phases can be estimated by equation 6 with the K_{oc}, SS, and f_{oc} (SOC/SS). A K_{oc} of 3.3 x 10^6 has been reported for 2,3,7,8-TCDD (Mabey and others, 1982). By use of SS and SOC determined for the DWIS and the SDPS samples (table 19), 60 percent of the 2,3,7,8-TCDD load would be in the water phase and the remainder in the suspended-sediment phase. The solubility of hydrophobic organic compounds is reported to be increased by the presence of colloidal matter (Baker and others, 1986) and dissolved organic matter (Carter and Suffet, 1982), which would increase the fraction and in effect lower the K_{oc}. A K_{oc} of one-half or one-tenth of the value reported by Mabey and others (1982) would increase the fraction in the water phase of the DWIS sample from 60 percent to 75 and 94 percent, respectively. Measurements of the fraction of hydrophobic organic compounds found in water and particulate phases in waters of the Great Lakes have shown similar relations. In their study of radioactive labeled organic compounds added to natural lake waters, Eadie and others (1992) found that for benzo[a]pyrene, a hydrophobic compound with a K_{oc} similar to 2,3,7,8-TCDD, the distribution between sediment and water phases was about equal under conditions similar to those in the Columbia River at Northport, where there are small suspended-sediment concentrations and the fraction of organic carbon is also small. Less-hydrophobic compounds such as 4-monochlorobiphenyl or pyrene had even larger fractions in the water phase.

As shown in equation 6, the two environmental factors that govern the distribution of dioxins and furans between suspended-sediment and water phases are the concentration of suspended sediment (SS) and the fraction of organic carbon in suspended sediment. In the Columbia River at Northport, the concentration of suspended sediment and the fraction of organic carbon that normally occur in the range would result in about one-half of the discharge of 2,3,7,8-TCDD ($K_{oc} = 3.3 \times 10^6$) occurring in the water phase. This relation is shown on figure 26, where equation 6 was used to calculate values of SS and f_{oc} that result in different percentages of the total 2,3,7,8-TCDD discharge in the water phases. Historical data for SS and f_{oc} in the Columbia River at Northport and data from the DWIS and SDPS are plotted on figure 26; they show that the fraction of the total 2,3,7,8-TCDD discharge in the water phase in the Columbia River at Northport is usually greater than 50 percent.

Table 20.--*Percentage of water and suspended-sediment contribution to dioxin discharge in the Columbia River at Northport, Wash., on September 30, 1992*

[g/d, grams per day; pg/L, picograms per liter; mg/d, milligrams per day; mg/L, milligrams per liter; ft^3/s, cubic feet per second; HpCDD, 1,2,3,4,6,7,8-heptachlorodibenzo-*p*-dioxin; OCDD, octachlorodibenzo-*p*-dioxin; DWIS, depth-width integrated sample; SDPS, short-duration point-source sample]

Isomer and sample type	Concentration in water[1] (pg/L)	Daily load dioxin in water (mg/d)	Concentration in suspended sediment (pg/g)	Daily load dioxin in suspended sediment (mg/d)	Total daily load (mg/d)	Percentage suspended-sediment contribution to daily load	Percentage water phase contribution to daily load
HpCDD (DWIS)	0.24 (2.4×10^{-10} mg/L)[2]	49.2	210 (2.1×10^{-7} mg/g)[2]	86.1	135	64	36
OCDD (DWIS)	1.2 (1.2×10^{-9} mg/L)[2]	246	1,300 (1.3×10^{-6} mg/g)[2]	533	779	68	32
OCDD (SDPS)	1.3 (1.3×10^{-9} mg/L)[2]	266	240 (2.4×10^{-7} mg/g)[2]	49.2	315	16	84

[1] The concentrations of dioxins in water used to calculate discharge are the adjusted concentrations based on column efficiency determined from the sample using two resin columns in series; see table 18.

[2] Concentration in parentheses are equivalent concentration used in conjunction with water and sediment discharge for calculating daily loads. Mean daily discharge is 83,800 ft^3/s or 1.81×10^{11} liters per day; suspended sediment concentrations is 2 mg/L for the DWIS sample and 1 mg/L for the SDPS sample.

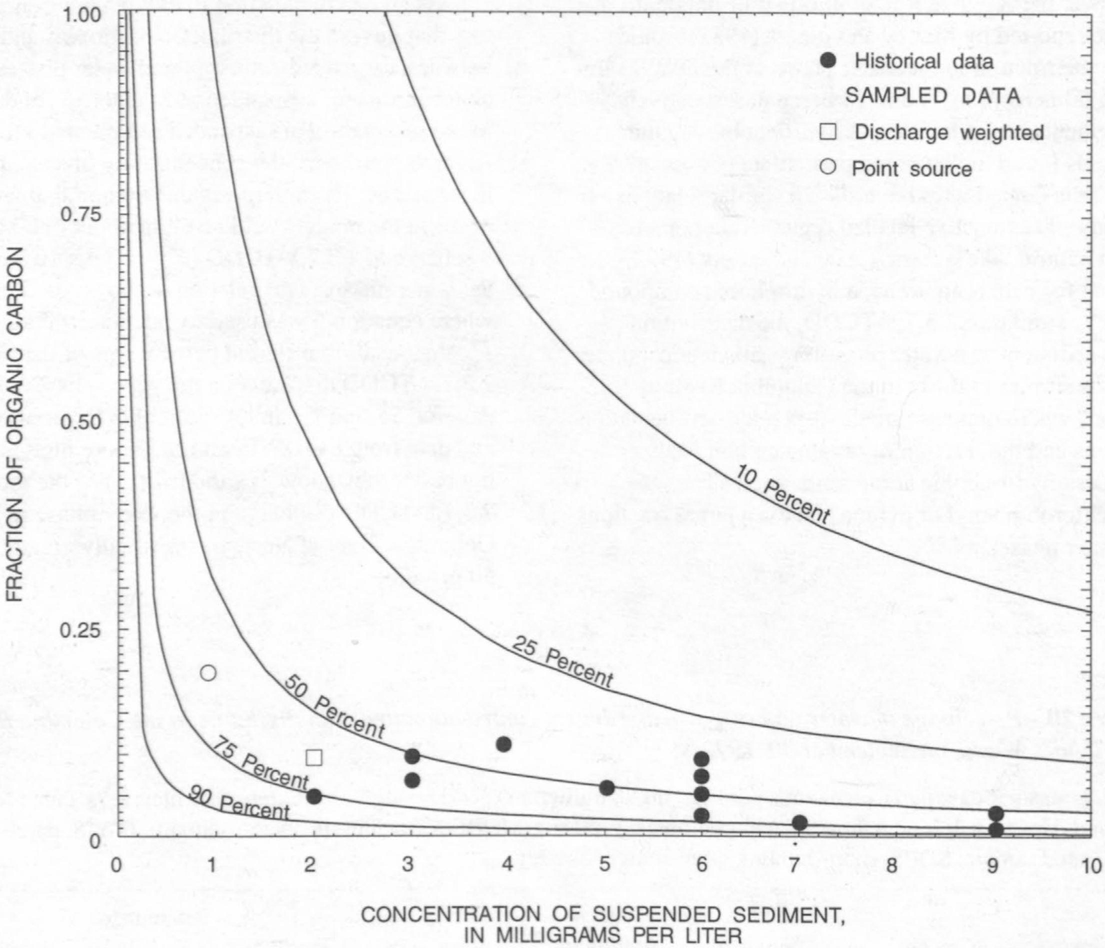


Figure 26.--Relation of suspended-sediment concentration and fraction of organic carbon that results in different percentages of the total discharge of 2,3,7,8-tetrachlorodibenzo-*p*-dioxin occurring in the water phase.

Total Maximum Daily Load of 2,3,7,8-Tetrachlorodibenzo-*p*-dioxin

The TMDL guideline for 2,3,7,8-TCDD in the Columbia River at the international boundary is 2.3 mg/d. This guideline was established in response to impaired water-quality conditions found in parts of the Columbia River resulting from the presence of 2,3,7,8-TCDD in the river's fish and sediments. TMDL's were developed to serve as a set of guidelines for the maximum amount of a pollutant that can be safely accommodated by parts of the Columbia River system. Because 2,3,7,8-TCDD was not detected in any of the suspended-sediment or water samples, the load of 2,3,7,8-TCDD could not be determined and then compared with the TMDL for this isomer (U.S. Environmental Protection Agency, 1991). 2,3,7,8-TCDD was also not detected in the 1990 suspended-sediment sample collected by Ecology. In that case, Ecology used only suspended-sediment data to estimate a maximum possible discharge of 2,3,7,8-TCDD from the analytical detection-limit data and existing river conditions (flow and concentrations of suspended sediment and suspended organic carbon). The maximum possible load calculated by Ecology was less than the TMDL of 2.3 mg/d and did not account for transport in the water phase.

In this study, the river discharge, suspended-sediment concentration, and suspended organic carbon concentrations were used to calculate the concentration of 2,3,7,8-TCDD in suspended sediments and water that would yield a total daily load equivalent to the TMDL of

2.3 mg/d. The calculation is based on the sediment and water phase distribution shown in equation 6, coupled with a discharge of 83,800 ft^3/s. The calculated 2,3,7,8-TCDD concentrations in the suspended sediment and water needed to yield the TMDL are shown in table 21. For the DWIS and suspended-sediment samples and for both of the water samples, the analytical detection-limit concentrations were larger than the calculated concentration needed to yield the TMDL. The analytical detection levels for the analysis of the SDPS and LDPS suspended sediment samples were smaller than the calculated concentrations necessary to yield the TMDL. Thus, calculations of a TMDL are possible in some instances; however, for these point-source pumping samples to be representative of the entire flow of the river, dioxins must be evenly distributed across the river flow, a condition that has not been demonstrated and would be a questionable assumption. Thus, the data are inconclusive in determining whether the TMDL was exceeded during the sampling period.

Table 21.--*Calculated concentrations of 2,3,7,8-tetrachlorodibenzo*-p-*dioxin (2,3,7,8-TCDD) in suspended sediment and water from the Columbia River at Northport that yield the equilibrium fraction of the total maximum daily load of 2.3 milligrams per day (U.S. Environmental Protection Agency, 1991)*

[DWIS, depth-width integrated sample; SDPS, short-duration point-source sample; LDPS, long-duration point-source sample; TMDL, total maximum daily load; mg/d, milligrams per day; ft^3/s, cubic feet per second; g, grams; L/d, liters per day; mg/L, milligrams per liter; pg/g, picograms per gram; pg/L, picograms per liter; --, not applicable]

Sample method	Fraction of 2,3,7,8-TCDD load in sample phase	Calculated 2,3,7,8-TCDD load associated with sample phase (mg/d)	Mean river discharge (ft^3/s)	Dry weight of sample (g)	Suspended-sediment concentration (mg/L)	Calculated 2,3,7,8-TCDD concentration needed to yield the equilibrium fraction of the TMDL	Analytical detection limit of 2,3,7,8-TCDD
			Suspended-sediment phase				
DWIS	0.40	0.92	83,800 (2.05 x 10^{11} L/d)[1]	0.47	2	2.2 pg/g	3.6 pg/g
SDPS	.40	0.92	83,800 (2.05 x 10^{11} L/d)[1]	0.45	1	4.5 pg/g	3.7 pg/g
LDPS	.40	0.92	78,300 (1.92 x 10^{11} L/d)[1]	1.06	1	4.8 pg/g	1.5 pg/g
			Water phase				
DWIS	0.60	1.38	83,800 (2.05 x 10^{11} L/d)[1]	--	--	.0067 pg/L	0.02 pg/L
SDPS	.60	1.38	83,800 (2.05 x 10^{11} L/d)[1]	--	--	.0067 pg/L	.01 pg/L
LDPS	.60	1.38	78,300 (1.92 x 10^{11} L/d)[1]	--	--	.072 pg/L	--

[1] Numbers in parentheses are mean river discharge in liters per day.

OCCURRENCE OF TRACE-ORGANIC COMPOUNDS IN BED SEDIMENT

Bed sediments of Lake Roosevelt and the Northport reach of the Columbia River were analyzed for this study for two main groups of trace-organic compounds: methylene-chloride extractable compounds and wood-pulp-related compounds other than dioxins and furans.

Methylene-chloride extractable compounds were analyzed to assess the extent to which the bed sediments of the reservoir or major tributaries may be contaminated by compounds that mostly originate from urban and industrial sources. Of the tributaries draining to Lake Roosevelt, those of the Spokane River Basin are the most urbanized and as such are the most likely to contain detectable quantities of organic compounds related to urban runoff. Wood-pulp-related organic compounds, most likely originating at a wood-pulp mill in Canada, are carried by the Columbia River. A limited number of bed-sediment samples were collected on a reconnaissance level to assess whether wood-pulp-related organic compounds, such as unchlorinated phenols that degrade fairly readily in the environment (Smith and others, 1988), reside in the upper part of the reservoir to a large extent.

Specifically, this part of the study addressed the following objectives:

1. To determine from a limited number of samples, the occurrence of methylene-chloride extractable compounds in the bed sediment of the mid and lower reaches of the reservoir and major tributaries to assess the extent of contamination from the urban and industrial sources; and

2. To determine the occurrence of wood-pulp-related organic compounds in the bed sediment of the upper part of the mid reach of the reservoir to assess the extent of contamination from a pulp mill at Castlegar, British Columbia.

Data in this section of the report will show the following results.

- Bed sediments collected from the reservoir and tributaries of Lake Roosevelt generally were not contaminated with methylene-chloride extractable compounds, which are usually associated with urban and industrial activities (Smith and others, 1988).
- Bed sediments collected from the mid reach of Lake Roosevelt near Marcus Island and French Point Rocks generally was not contaminated with common wood-pulp-related compounds (except dioxins and furans). A few of the non-dioxin and non-furan compounds, however, were found in small concentrations as far as 52 mi downstream of the international boundary.

Methods

All trace-organic compounds analyzed in bed sediment were from a composite sample that was wet sieved through a 2-mm stainless steel screen and dispensed into baked-glass sample containers. Sieves and other processing equipment were methanol rinsed between trace-organic compound sampling sites. Samples were packed on ice and sent to the respective laboratories for analyses (table 2).

Methylene-Chloride Extractable Compounds

Fifty-four methylene-chloride extractable compounds were analyzed in bed sediments collected from three sites in the mid reach of the reservoir and two sites in the lower reach. These compounds also were analyzed in bed sediments of major tributaries to Lake Roosevelt, the Kootenay and Pend D'Oreille Rivers, and Lower Arrow Lake. The compounds and the laboratory reporting levels are listed on table 22.

Lake Roosevelt and its major tributaries generally were not contaminated with methylene-chloride extractable compounds. Fifty-two of the methylene-chloride extractable compounds analyzed either were not detected or were below the minimum reporting level.

However, 15 compounds that were detected during the present study, but at concentrations that were not quantified because they were less than the minimum reporting level, are shown in table 23. These 15 compounds were detected at small concentrations, usually less than 50 µg/kg. Of the 15 methylene-chloride extractable compounds detected, 11 were polycyclic aromatic hydrocarbons (PAH's), and two were phenolic compounds.

Table 22.--*Methylene-chloride extractable compounds analyzed for in bed sediment from the Lake Roosevelt study area, and laboratory reporting level*

[USEPA, U.S. Environmental Protection Agency; STORET, Storage and Retrieval System; µg/kg, micrograms per kilogram]

Compound	USEPA STORET code	Reporting level, µg/kg (dry weight)
4-Chloro-3-methylphenol	34455	600
2-Chlorophenol	34589	200
2,4-Dichlorophenol	34604	200
2,4-Dimethylphenol	34609	200
4,6-Dinitro-2-methylphenol	34660	600
2,4-Dinitrophenol	34619	600
2-Nitrophenol	34594	200
4-Nitrophenol	34649	600
Pentachlorophenol	39061	600
Phenol	34695	200
2,4,6-Trichlorophenol	34624	600
Acenaphthene	34208	200
Acenaphthylene	34203	200
Anthracene	34223	200
Benzo (a) anthracene	34529	400
Benzo (b) fluoranthene	34233	400
Benzo (k) fluoranthene	34245	400
Benzo (g,h,i) perylene	34524	400
Benzo (a) pyrene	34250	400
4-Bromophenyl phenyl ether	34639	200
Butyl benzyl phthalate	34295	200
bis (2-Chloroethoxy) methane	34281	200
bis (2-Chloroethyl) ether	34276	200
bis (2-Chloroisopropyl) ether	34286	200
2-Chloronaphthalene	34584	200
4-Chlorophenyl phenyl ether	34641	200
Chrysene	34323	400
Dibenzo (a,h) anthracene	34559	400
1,2-Dichlorobenzene	34539	200
1,3-Dichlorobenzene	34569	200
1,4-Dichlorobenzene	34574	200
Diethyl phthalate	34339	200
Dimethyl phthalate	34344	200
Di-n-butyl phthalate	39112	200
2,4-Dinitrotoluene	34614	200
2,6-Dinitrotoluene	34629	200
Di-n-octylphthalate	34599	200
bis (2-Ethylhexyl) phthalate	39102	200
Fluoranthene	34379	200
Fluorene	34384	200
Hexachlorobenzene	39701	200
Hexachlorobutadiene	39705	200
Hexachlorocyclopentadiene	34389	200
Hexachloroethane	34399	200
Indeno (1,2,3-c, d) pyrene	34406	400
Isophorone	34411	200
Naphthalene	34445	200
Nitrobenzene	34450	200
n-Nitrosodimethylamine	34441	200
n-Nitrosodi-n-propylamine	34431	200
n-Nitrosodiphenylamine	34436	200
Phenanthrene	34464	200
Pyrene	34472	200
1,2,4-Trichlorobenzene	34554	200

In the bed sediments of both the reservoir and tributaries, PAH's were detected less frequently in the southern part of the study area than in the northern part. For example, in the northern part 9 PAH's were detected at Marcus Island MS, and 11 PAH's were detected at Kootenay River MS. At the reference site, Lower Arrow Lake LB1, 6 PAH's were detected. In contrast, in the southern part of the study area, downstream of French Point Rocks (RM 691), 2 to 5 PAH's were detected per site. The widespread presence of PAH's may be due to atmospheric deposition from combustion. Forest fires and wood burning are frequent in the forested northern part of the study area. PAH's found in Lake Roosevelt sediment were several orders of magnitude less than criteria concentrations developed by USEPA for some of these compounds (Bennett and Cubbage, 1991).

The occurrence of small concentrations of organic compounds in addition to methylene-chloride extractable compounds in bed sediment of Lake Roosevelt generally agrees with findings by Ecology. Ecology had previously analyzed eight bed sediment sites in Lake Roosevelt, one site in Rufus Woods Lake, and one site in Long Lake of the Spokane River for bioaccumulative organic chemicals, including several chlorobenzenes, and PCB's (Arthur Johnson, Washington State Department of Ecology, written commun., July 1991). Ecology detected PCB's and DDE (a metabolite of DDT) together at a single site near Grand Coulee Dam. The largest concentrations of total PCB's occurred at one site in the lower reach of the reservoir and in Long Lake. Ecology also detected DDE at one site in the lower reach of the reservoir.

Table 23.--*Methylene-chloride extractable compounds detected in bed sediment at concentrations below the reporting level and therefore not quantified*

[LB, RB, and MS indicate samples were collected on right side (toward the "right bank" from mid channel), left side (toward the "left bank" from mid channel), and near the mid-section channel, respectively, numbers 1 and 2 denote different sites toward the same bank; PAH, polycyclic aromatic hydrocarbons; --, not detected]

	Concentrations, in micrograms per kilogram												
Compound	Lower Arrow Lake LB1^1	Kootenay River MS^1	Pend D'Oreille River LB^1	Marcus Island MS^1	Marcus Island MS^1 (duplicate)	Kettle River RB1^1	West Kettle Falls LB^1	Colville River MS^1	French Point Rocks MS^1	Spokane River LB^1	Seven Bays MS^1	Sanpoil River MS^1	Swawilla Basin MS^1
Acenaphthylene (PAH)	20	29	--	30	36	17	35	18	51	--	--	--	--
Acenaphthene (PAH)	--	8.3	--	--	2.5	--	5.1	--	--	--	--	--	--
Anthracene (PAH)	10	48	--	21	26	--	19	18	41	--	--	--	--
Chrysene (PAH)	--	120	--	53	84	--	55	49	140	--	--	--	--
Fluoranthene (PAH)	20	130	5.1	49	53	13	44	12	71	20	8.2	6.9	12
Fluorene (PAH)	--	28	--	17	19	--	17	--	31	--	--	--	--
Isophorone (PAH)	--	55	--	--	--	41	25	41	--	--	--	--	--
Naphthalene (PAH)	150	42	6.0	120	120	15	180	7.5	140	6.9	5.5	--	8.3
Phenanthrene (PAH)	54	150	9.3	110	120	23	110	19	150	21	15	13	24
Pyrene (PAH)	11	90	--	28	29	7.5	27	7.5	38	16	4.7	--	6.5
Benzo (a) anthracene (PAH)	--	110	--	36	56	--	35	38	88	--	--	--	--
2,4-Dimethylphenol	--	--	52	14	18	--	18	--	--	--	--	--	--
Phenol	44	71	61	57	74	98	84	50	95	--	--	49	--
bis (2-Ethylhexyl) phthalate	--	--	--	84	--	--	--	--	--	--	--	^{2}980	--
Di-n-butyl phthalate	36	98	70	--	--	96	--	--	--	--	--	^{2}590	--

[1] See plate 1 for complete name.

[2] Quantifiable concentration above reporting level.

Chlorinated Phenols and Other Wood-Pulp-Related Compounds

Targeted chlorinated phenols and wood-pulp-related compounds of veratroles, anisoles, and vanillins were not detected during the present study in bed sediment at Marcus Island MS, 37 mi downstream from the international boundary, nor at French Point Rocks MS, 52 mi downstream from the international boundary (table 24). Previous studies had shown that pulp-mill effluent and Columbia River water and bed sediment contain chlorinated phenols and chlorinated guaiacols (Celgar Pulp Company, 1990). Previously, these compounds were seldom detected in Columbia River sediments upstream from the international boundary, except in sediments just downstream of the pulp mill in Castlegar, British Columbia (Celgar Pulp Company, 1990). However, a few targeted chlorinated guaiacols and catechols were found during the present study in the bed sediment of Lake Roosevelt. Three of six chlorinated catechols and one of seven chlorinated guaiacols were detected at concentrations above the minimum reporting level at Marcus Island MS; two of these six chlorinated catechols were also found downstream at French Point Rocks MS. Concentrations of catechols and guaiacols found in the reservoir ranged from 2.2 to 6.2 μg/kg.

Chlorinated resin acids, found in pulp-mill effluent, had not been found previously in sediment of the Columbia River (Celgar Pulp Company, 1990), nor were they found in Lake Roosevelt sediment (table 25). However, a few unchlorinated resin and fatty acids were detected by this study in bed sediment of Lake Roosevelt. Unchlorinated resin and fatty acids are a component of pulp-mill effluent, and also occur naturally. This study found 8 of 15 unchlorinated resin and fatty acids in bed sediment of Lake Roosevelt.

Extractable organic halides, which provide a gross indicator of chlorinated organic compounds, were not found during the present study above the minimum reporting levels of 10 mg/kg in Lake Roosevelt bed sediments at Marcus Island and French Point Rocks (table 24). Extractable organic halides have been found in previous studies in relatively large concentrations downstream of the pulp mill at Castlegar. Even though the extractable organic halides procedure does not measure individual chlorinated organic compounds, the limited data do indicate that total concentrations of chlorinated compounds in Lake Roosevelt bed sediments are small.

TOXICITY OF BED SEDIMENT

Many synthetic organic compounds and trace elements sorb to bed sediment; in other words, they attach to the surfaces of sediment particles or are taken into the particles themselves. These sorbed organic compounds and elements may remain in place, unavailable to overlying water and aquatic organisms, or they may be released to the water overlying the bed sediment, where they pose a more immediate toxic risk to water-dwelling or consuming organisms. Organisms that reside in or consume sediments rich in synthetic organic compounds are also at risk. To evaluate the effects of contaminants in Lake Roosevelt sediments on aquatic organisms, the present study applied selected sediment bioassays to measure toxicity from samples collected at specific sites (see table 3). Three species of aquatic organisms were exposed to bed sediment under laboratory conditions as described by Burton (1992), Sasson-Brickson and Burton (1991), and the American Society for Testing and Materials (1991b), and the organisms' survival and reproductive rates were observed. The bioassay results from study site sediment were compared with the bioassay results from reference site sediment to determine the significance of bed-sediment toxicity.

This study used three species of aquatic organisms for the sediment toxicity tests. *Hyalella azteca*, an amphipod that spends time in both the water column and the upper layer of bed sediment, was exposed to bed sediment for 7 days, and then its mortality rate was measured. *Ceriodaphnia dubia*, a water flea that primarily resides in the water column but is commonly observed on the sediment surface, was exposed to sediment for 7 days; then its mortality and reproductive rates were measured. Its mortality rate determined lethal sediment toxicity, and its reduced reproduction rate determined sublethal sediment toxicity. *Photobacterium phosphoreum,* a bioluminescent marine bacterium, was exposed to both sediment and pore water, which is the interstitial (pore) water in contact with sediments. Then the reduction of the bacteria's output of light (which resulted when some of them died) was measured.

Table 24.--*Concentrations of chlorinated phenols and other wood-pulp-related compounds in bed sediment*

[LB, RB, and MS indicate samples were collected on right side (toward the "right bank" from mid channel), left side (toward the "left bank" from mid channel), and near the mid section channel, respectively, numbers 1 and 2 denote different sites toward the same bank; <, less than minimum detectable concentration; µg/kg, micrograms per kilogram (dry weight); mg/kg, milligrams per kilogram; 13C6, carbon-13 labeled compound on carbon 6 ring]

	Concentrations					
Compound	French Point Rocks MS[1]	Marcus Island MS[1]	Marcus Island MS[1] (duplicate)	Lower Arrow Lake LB1[1]	Lower Arrow Lake LB1[1] (duplicate)	Laboratory blank
			Chlorinated phenols, in µg/kg			
Pentachlorophenol	<0.2	<0.2	<0.2	<0.2	<0.2	<0.2
2, 3, 4, 6+2, 3, 5, 6-Tetrachlorophenol	<0.2	<0.2	<0.2	<0.2	<0.2	<0.2
2, 3, 4, 5-Tetrachlorophenol	<0.2	<0.2	<0.2	<0.2	<0.2	<0.2
2, 3, 4-Trichlorophenol	<0.2	<0.2	<0.2	<0.2	<0.2	<0.2
2, 3, 5-Trichlorophenol	<0.2	<0.2	<0.2	<0.2	<0.2	<0.2
2, 3, 6-Trichlorophenol	<0.2	<0.2	<0.2	<0.2	<0.2	<0.2
2, 4, 5-Trichlorophenol	<0.2	<0.2	<0.2	<0.2	<0.2	<0.2
2, 4, 6-Trichlorophenol	<0.2	<0.2	<0.2	<0.2	<0.2	<0.2
2, 4-Dichlorophenol	<0.2	<0.2	<0.2	<0.2	<0.2	<0.2
2, 6-Dichlorophenol	<0.2	<0.2	<0.2	<0.2	<0.2	<0.2
			Chlorinated guaiacols, in µg/kg			
Tetrachloroguaiacol	2.5	<0.4	<0.4	<0.4	<0.4	<0.4
3, 4, 5-Trichloroguaiacol	4.6	3.4	3.7	<0.4	<0.4	<0.4
3, 4, 6-Trichloroguaiacol	<0.4	<0.4	<0.4	<0.4	<0.4	<0.4
4, 5, 6-Trichloroguaiacol	<0.4	<0.4	<0.4	<0.4	<0.4	<0.4
4, 5-Trichloroguaiacol	<0.4	<0.4	<0.4	<0.4	<0.4	<0.4
4, 6-Dichloroguaiacol	<0.4	<0.4	<0.4	<0.4	<0.4	<0.4
4-Chloroguaiacol	<0.4	<0.4	<0.4	<0.4	<0.4	<0.4
			Chlorinated catechols, in µg/kg			
Tetrachlorocatechol	5.1	5.8	5.4	<0.4	<0.4	<0.4
3, 4, 5-Trichlorocatechol	<0.4	<0.4	<0.4	<0.4	<0.4	<0.4
3, 4-Dichlorocatechol	<0.4	2.4	2.2	<0.4	<0.4	<0.4
3, 5-Dichlororocatechol	<0.4	<0.4	<0.4	<0.4	<0.4	<0.4
4, 5-Dichlororocatechol	4.7	6.2	5.2	<0.4	<0.4	<0.4
4-Chlorocatechol	<0.4	<0.4	<0.4	<0.4	<0.4	<0.4
			Chlorinated veratroles, in µg/kg			
Tetrachloroveratrole	<0.4	<0.4	<0.4	<0.4	<0.4	<0.4
3, 4, 5-Trichloroveratrole	<0.4	<0.4	<0.4	<0.4	<0.4	<0.4
4, 5-Dichloroveratrole	<0.4	<0.4	<0.4	<0.4	<0.4	<0.4

Table 24.--*Concentrations of chlorinated phenols and other wood-pulp-related compounds in bed sediment--Continued*

Compound	Concentrations					
	French Point Rocks MS[1]	Marcus Island MS[1]	Marcus Island MS[1] (duplicate)	Lower Arrow Lake LB1[1]	Lower Arrow Lake LB1[1] (duplicate)	Laboratory blank
Chlorinated anisoles, in µg/kg						
Pentachloroanisole	<0.2	<0.2	<0.2	<0.2	<0.2	<0.2
2, 3, 4, 6+2, 3, 5, 6-Tetrachloroanisole	<0.4	<0.4	<0.4	<0.4	<0.4	<0.4
2, 3, 4, 5-Tetrachloroanisole	<0.4	<0.4	<0.4	<0.4	<0.4	<0.4
2, 3, 4-Trichloroanisole	<0.4	<0.4	<0.4	<0.4	<0.4	<0.4
2, 3, 5-Trichloroanisole	<0.4	<0.4	<0.4	<0.4	<0.4	<0.4
2, 3, 6-Trichloroanisole	<0.4	<0.4	<0.4	<0.4	<0.4	<0.4
2, 4, 5-Trichloroanisole	<0.4	<0.4	<0.4	<0.4	<0.4	<0.4
2, 4, 6-Trichloroanisole	<0.4	<0.4	<0.4	<0.4	<0.4	<0.4
2, 4-Dichloroanisole	<0.2	<0.2	<0.2	<0.2	<0.2	<0.2
2, 6-Dichloroanisole	<0.2	<0.2	<0.2	<0.2	<0.2	<0.2
Other organic compounds, in µg/kg						
3, 4, 5-Trichlorosyringol	<0.4	<0.4	<0.4	<0.4	<0.4	<0.4
5, 6-Dichlorovanillin	<0.4	<0.4	<0.4	<0.4	<0.4	<0.4
6-Chlorovanillin	<0.4	<0.4	<0.4	<0.4	<0.4	<0.4
Extractable organic halide, in mg/kg						
Extractable organic halide	<10	<10	<10	<10	<10	<10
Surrogate recovery for quality control, in percent						
Dichlorophenol	119	113	96	107	118	99
13C6-Pentachlorophenol	95	96	88	96	93	100
13C6-Chloroguaiacol	116	108	98	104	112	97
13C6-Trichloroguaiacol	101	98	97	97	100	100
13C6-Tetrachloroguaiacol	98	96	93	97	97	100
13C6-Dichlorocatechol	103	92	73	99	101	81
13C6-Tetrachlorocatechol	56	50	40	52	58	77
13C6-Chlorovanillin	106	103	67	102	103	100

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[1] See plate 1 for complete site name.

Table 25.--*Concentrations of resin and fatty acids in bed sediment*

[<, less than minimum detectable concentrations; mg/kg, milligrams per kilogram; LB, RB, and MS indicate samples were collected on right side (toward the "right bank" from mid channel), left side (toward the "left bank" from mid channel), and near the mid-section channel, respectively, numbers 1 and 2 denote different sites toward the same bank]

Compound	Concentrations, in milligrams per kilogram					Laboratory spike (1 mg/kg), percent recovery
	French Point Rocks MS[1]	Marcus Island MS[1]	Marcus Island MS duplicate[1]	Lower Arrow Lake LB1[1]	Laboratory blank	
Resin acids						
Arachidic	0.99	0.64	0.56	0.21	<0.05	77
Behemic	2.8	2.5	1.6	0.60	<0.05	168
Chloroabietic no. 1[2]	<0.05	<0.05	<0.05	<0.05	<0.05	79
Chloroabietic no. 2[2]	<0.05	<0.05	<0.05	<0.05	<0.05	81
Dehydroabietic	<0.05	0.28	<0.05	0.15	<0.05	125
Dichloroabietic[2]	<0.05	<0.05	<0.05	<0.05	<0.05	78
Isopimaric+Pallustric	<0.20	<0.20	<0.20	<0.20	<0.20	55
Lignoceric	3.2	3.0	1.8	1.2	<0.05	86
Pimaric	<0.05	<0.05	<0.05	<0.05	<0.05	71
Sandaraco Pimaric	<0.05	<0.05	<0.05	<0.05	<0.05	74
Fatty acids						
Lauric	0.47	2.0	0.54	0.73	<0.05	75
Myristic	0.90	1.0	0.57	0.49	<0.05	72
Palmitic	2.1	2.1	1.2	1.0	<0.05	110
Oleic+Linoleic+Linolenic	<0.20	<0.20	<0.20	<0.20	<0.20	37
Octadecanoic	1.1	1.4	0.61	0.40	<0.05	110

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[1] See plate 1 for complete site name.

[2] Chlorinated resin acids.

The following section presents results in the context of four specific objectives that the study's testing sought to determine:

- The lethal response as the percent survival of *H. azteca* and *C. dubia* by exposure to sediment;
- The sublethal response of *C. dubia* by exposure to sediment;
- The toxicity response of *P. phosphoreum* (Microtox® test) by exposure to sediment and pore water; and
- The potential toxicity of bed sediment as indicated by patterns of toxicity response among the three test organisms.

Data in this section of the report will show the following results.

- *H. azteca* and *C. dubia* showed low survival rates when exposed to bed sediment from sites in the Columbia River near the international boundary and downstream 7 mi.
- *C. dubia* reproduction rates declined when the organisms were exposed to bed sediment from sites in the Columbia River near the international boundary and from two of three sites in the lower reach of the reservoir.
- *P. phosphoreum* showed high toxicity response when exposed to sandy bed sediment from the lower sites in the Northport reach of the Columbia River and when exposed to fine-grained bed sediment from about one-third of the sites in the mid and lower reaches of Lake Roosevelt.

Methods

Sediment subsamples for toxicity testing with *H. azteca*, *C. dubia*, and *P. phosphoreum* was taken from the composite samples obtained at each site. Sediment samples were kept at or below 4°C until testing began. After all the sediment had been wet-sieved through a 2-mm nylon screen, sediment for *H. azteca* and *C. dubia* testing was placed in cleaned high-density polyethylene containers for shipment, and sediment for *P. phosphoreum* testing was placed in sealed, clean glass jars and tested in the field.

Dunnett's test (Dunnett, 1964; Rand and Petrocelli, 1985) was used to test for differences in the responses of the organisms to the sampling sites and to the reference sites and laboratory controls. For testing the significant differences between the sampling sites and the reference sites and laboratory controls, the sites for *H. azteca* and *C. dubia* were grouped into the Northport reach of the Columbia River, the reaches of Lake Roosevelt, and the major tributaries (tables 26 and 27). Dunnett's test was performed on Toxstat software (Gulley and others, 1990) at the 5-percent level of significance, meaning there was a 5-percent risk of concluding that there was no difference in response when in fact there was a difference. The Bonferroni T-test (cited by Burton and others, 1987; Gulley and others, 1990; Burton and Jacher, 1992) was used when an unequal number of replicates was compared. In addition, *C. dubia* survival was tested by Fisher's Exact procedure, which is included in the Toxstat software (Gulley and others, 1990). For *C. dubia*, one set of control data was not used in the statistical tests because of abnormally low reproduction of only 15 young per female (table 27).

Hyalella azteca Bioassay

Bed sediment for the *H. azteca* bioassay was collected from five sites in the Columbia River, six sites in major tributaries, and nine sites in Lake Roosevelt (see table 3). Tests began an average of 6 days after collection; holding times before analysis began ranged from 4 to 11 days, with only one sample held for 11 days. Toxicity tests from each sampling site were performed in triplicate, using 10 organisms per beaker; the exposure period was 7 days. Organisms were fed on days 0, 3, and 5, and overlying water was gently aerated and dissolved oxygen was not allowed to drop below 5 mg/L. Replicate test controls containing no sediment were maintained throughout the test period.

H. azteca had low survival rates when exposed to samples from sites in the Northport reach of the Columbia River (table 26). The lowest survival rates ranged from 10 to 57 percent at three of five sites in the Northport reach of the Columbia River: Boundary LB, 30 percent; Auxiliary Gage LB, 10 percent; and Goodeve Creek RB, 57 percent (see plate 1 for site locations). Goodeve Creek RB, the most downstream site in this group, is 7 mi downstream from the international boundary. Samples causing low *H. azteca* survival contained predominantly sand-size sediment with large proportions of slag particles and elevated trace-element concentrations.

Table 26.-- *Percent survival of* Hyalella azteca *exposed to whole sediment*

[LB, RB, and MS indicate samples were collected on right side (toward the "right bank" from mid-channel), left side (toward the "left bank" from mid channel), and near the mid-section channel, respectively, numbers 1 and 2 denote different sites toward the same bank; D, significantly different from laboratory control samples and reference sites by use of Dunnett's test; *, indicates result also significant by use of Bonferroni-T test for unequal number of replicates; ns, not significantly different from laboratory control samples and reference sites; --, no site number or test]

		Hyalella azteca		Samples that are significantly different compared to controls and reference sites		
Site number	Site name (see plate 1 for complete name)	Percent survival	Standard deviation	Average of controls 1-3	Lower Arrow Lake LB1	Lower Arrow Lake LB2
	Control and reference sites					
--	Control 1	96.7	5.8	--	--	--
--	Control 2	86.6	5.8	--	--	--
--	Control 3	95.0	7.1	--	--	--
1	Lower Arrow Lake LB1	90.0	10.0	--	--	--
2	Lower Arrow Lake LB2	86.7	5.8	--	--	--
	Columbia River, Northport reach					
8	Boundary LB	30.0	10.0	D*	D	D
10	Auxiliary Gage LB	10.0	10.0	D*	D	D
11	Goodeve Creek RB	56.7	11.6	D*	ns	ns
14	Fivemile Creek LB	73.3	25.2	ns	ns	ns
15	Onion Creek LB	86.7	5.8	ns	ns	ns
	Major tributaries to Columbia River					
4	Kootenay River MS	76.7	25.2	ns	ns	ns
6	Pend D'Oreille River LB	96.7	5.8	ns	ns	ns
	Major tributaries to Lake Roosevelt					
25	Kettle River RB1	86.7	5.8	ns	ns	ns
29	Colville River MS	80.0	17.3	ns	ns	ns
53	Spokane River LB	100	0.0	ns	ns	ns
62	Sanpoil River MS	60.0	26.5	D*	ns	ns
	Lake Roosevelt, upper reach					
17	China Bend RB	86.7	5.8	ns	ns	ns
19	Bossborg RB	76.7	5.8	ns	ns	ns
20	Summer Island RB1	73.3	20.8	ns	ns	ns
	Lake Roosevelt, mid reach					
22	Marcus Island MS	80.0	10.0	ns	ns	ns
38	French Point Rocks MS	96.7	5.8	ns	ns	ns
46	Hunters LB	90.0	10.0	ns	ns	ns
	Lake Roosevelt, lower reach					
57	Seven Bays RB	93.3	11.6	ns	ns	ns
61	Whitestone Creek MS	96.7	5.8	ns	ns	ns
71	Grand Coulee Dam RB	83.3	5.8	ns	ns	ns

H. azteca bioassays conducted by the Canadian Department of Fisheries and Oceans (Nener, 1992) used slag obtained in March 1992 from smelter discharge at Trail (fig. 1). The mean survival of *H. azteca* was zero percent for three slag samples, compared to 94 percent for laboratory control samples. Copper and zinc concentrations in leachate water from toxicity tests were large compared to controls (Nener, 1992). For example, copper and zinc concentrations in leachate water were 2.9 to 26 and 13 to 168 times larger than concentrations in control samples, respectively.

Four other organisms exposed to slag showed lethal and sublethal responses (Nener, 1992). These organisms, which occupy different ecological niches, were *Selenastrum capricornutum*, a unicellular green alga; *Daphnia magna*, a species of zooplankton; *Chironomus tentans*, a benthic invertebrate; and *Oncorhynchus mykiss*, a rainbow trout fingerling.

H. azteca survival ranged from 73 to 97 percent for sites in Lake Roosevelt (table 26). The survival of *H. azteca* exposed to sediment from the mid and lower reaches of Lake Roosevelt, from most tributaries to Lake Roosevelt, and from tributaries to the Columbia River in Canada was not significantly different from the survival of *H. azteca* exposed to laboratory control samples or sediment from reference sites. *H. azteca* survival was 97 and 100 percent for sediment from Spokane River LB and Pend D'Oreille River LB, respectively.

The high survival of *H. azteca* exposed to sediment from the mid to lower reaches of the reservoir is corroborated by data from Ecology (Arthur Johnson, Washington State Department of Ecology, written commun., 1991). In bioassays reported by Johnson in 1989, the mean survival of *H. azteca* was 70 to 90 percent when exposed to sediment from three sites in the mid or lower reaches of the reservoir. Survival of *H. azteca* was 80 and 90 percent for the Spokane and Sanpoil Rivers, respectively.

Ceriodaphnia dubia Bioassay

Seven-day survival and three-brood reproduction toxicity tests for *C. dubia* were done on bed sediment from nine sites in Lake Roosevelt, five sites in the Columbia River, and six sites in major tributaries (table 27). Sediment samples were held an average of 9 days before testing began; holding times ranged from 7 to 14 days, but only three samples were held for 12 days or more. Toxicity tests were performed in replicates of 10, each replicate using one organism less than 24 hours of age. The survival tests ended after a 7-day exposure period, and reproductive tests, which measured the number of young per brood, terminated when 60 percent of the control organisms had their third brood (Burton and Jacher, 1992).

Low survival rates were found for *C. dubia* exposed to bed sediment from near and downstream of the international boundary. A *C. dubia* bioassay showed complete mortality (zero percent survival) at Boundary LB near the international boundary and a survival of 40 percent at Auxiliary LB, 2 mi downstream from the international boundary. Depressed reproduction of *C. dubia*, significantly different from laboratory controls and at reference sites, was observed at Boundary LB, Auxiliary Gage LB, and Goodeve Creek RB (pl. 1). Reproduction ranged from zero to 18 young per female exposed to sediment from these three sites (table 27).

In sediments from the upper and mid reaches of Lake Roosevelt, however, survival and reproductive rates were high and not significantly different from those of laboratory controls and reference sites. Even though the survival of *C. dubia* ranged from 80 to 100 percent in the lower reach of the reservoir, *C. dubia* reproduction was significantly depressed at Whitestone Creek MS and Grand Coulee Dam RB (14 to 17 young per female). Compared with rates for control sediment, a low *C. dubia* survival rate of 50 percent and a reproductive rate of 19 young per female were found at Kettle River RB1 (table 27).

Photobacterium phosphoreum Bioassay

P. phosphoreum was exposed to both whole sediment and pore water. Whole sediment from 42 sites and pore water from 27 of these sites were tested by this study for toxicity. Pore water availability in sediment samples depends on sediment grain size. For example, sandy sediment samples are well drained and retain only small amounts of pore water.

P. phosphoreum toxicity is measured by the EC_{50}, the percentage of sample sediment or water that causes a 50-percent reduction in light output from *P. phosphoreum*, as calculated from measurements of a dilution series. Lower EC_{50} values indicate greater toxicity. EC_{50} values of whole-sediment and pore-water tests cannot be directly compared with each other because the two tests use different dilution series to calculate EC_{50}. High, moderate, and low toxicity responses correspond to three data clusters of the lower, middle, and upper third of EC_{50} values, respectively (tables 28, 29, and 30). Thus, high toxicity responses are indicated at sites with responses well below the toxicity response of the reference sites.

Table 27.-- *Percent survival and reproduction rates of* Ceriodaphnia dubia *exposed to whole sediment*

[LB, RB, and MS indicate samples were collected on right side (toward the "right bank" from mid channel), left side (toward the "left bank" from mid-channel), and near the mid-section channel, respectively, numbers 1 and 2 denote different sites toward the same bank; D, significantly different from laboratory control samples and reference sites by use of Dunnett's test; F, significantly different from laboratory control samples and reference sites by use of Fisher's Exact procedure (only used to test survival); *, indicates result also significant using Bonferroni adjustment for unequal number of replicates; ns, not significantly different from laboratory control samples and reference sites; --, no site number or test]

			Significantly different survival compared to:			Reproduction		Samples that are significantly different compared to control and reference sites		
Site number	Site name (see plate 1 for complete name)	Percent survival	Laboratory control 2	Lower Arrow Lake LB1	Lower Arrow Lake LB2	Young per female	Standard deviation	Laboratory control 2	Lower Arrow Lake LB1	Lower Arrow Lake LB2
	Control and reference sites									
--	Control 1	90	--	--	--	14.8	10.2	--	--	--
--	Control 2	90	--	--	--	33.3	12.8	--	--	--
1	Lower Arrow Lake LB1	100	--	--	--	31.2	5.5	--	--	--
2	Lower Arrow Lake LB2	90	--	--	--	30.8	14.2	--	--	--
	Columbia River, Northport reach									
8	Boundary LB	0	F, D	F, D	F, D	0	0	D	D	D
10	Auxiliary Gage LB	40	F, D	F, D	F, D	1.8	3.0	D	D	D
11	Goodeve Creek RB	80	ns	ns	ns	18.4	8.7	D	D	D
14	Fivemile Creek LB	80	ns	ns	ns	29.0	10.2	ns	ns	ns
15	Onion Creek LB	90	ns	ns	ns	33.3	16.9	ns	ns	ns
	Major tributaries to Columbia River									
4	Kootenay River MS	80	ns	ns	ns	30.9	12.7	ns	ns	ns
6	Pend D'Oreille River LB	90	ns	ns	ns	36.0	12.6	ns	ns	ns
	Major tributaries to Lake Roosevelt									
25	Kettle River RB1	50	D	F, D	D	19.4	19.0	D	ns	ns
29	Colville River MS	70	ns	ns	ns	31.9	12.6	ns	ns	ns
53	Spokane River LB	100	ns	ns	ns	22.1	3.1	ns	ns	ns
62	Sanpoil River MS	90	ns	ns	ns	22.3	9.7	ns	ns	ns
	Lake Roosevelt, upper reach									
17	China Bend RB	100	ns	ns	ns	38.7	2.8	ns	ns	ns
19	Bossborg RB	90	ns	ns	ns	29.2	4.8	ns	ns	ns
20	Summer Island RB1	90	ns	ns	ns	33.2	5.0	ns	ns	ns
	Lake Roosevelt, mid reach									
22	Marcus Island MS	70	ns	ns	ns	23.2	18.2	ns	ns	ns
38	French Point Rocks MS	70	ns	ns	ns	27.7	15.5	ns	ns	ns
46	Hunters LB	100	ns	ns	ns	35.6	7.0	ns	ns	ns
	Lake Roosevelt, lower reach									
57	Seven Bays RB	100	ns	ns	ns	23.6	6.2	ns	ns	ns
61	Whitestone Creek MS	100	ns	ns	ns	17.3	6.9	D*	D*	D*
71	Grand Coulee Dam RB	80	ns	ns	ns	13.6	10.7	D*	D*	D*

Sediment samples settled for at least 20 hours before surface water and floating organic matter were decanted. A portion of the sample was then centrifuged to obtain a laboratory pore-water sample. Samples were held an average of 39 hours until testing; holding times ranged from 20 to 142 hours. Almost all samples (88 percent) were tested within 3 days of collection, and most (59 percent) were run the day after collection.

The sediment toxicity test required appropriate reference samples of similar grain-size distributions. The Sanpoil River MS was chosen as a reference site for fine-grained sediment, and Lower Arrow Lake LB1 and Lower Arrow Lake LB2 were used as reference sites for sandy sediment (see plate 1 for location).

Both the pore-water and whole-sediment tests were conducted following procedures of Microbics Corporation (1992). The pore-water toxicity test followed the procedure called "100-percent test" to obtain a laboratory pore water sample. The pore water was tested in the same manner for all samples. It used a dilution series of 90.1, 45.5, 22.7 and 11.4 percent of the sample, and it used one control containing no sample. Light output was measured at 5 and 15 minutes after bacterial exposure. The toxicity test for whole sediment followed the procedure called "solid-phase test"; however, the dilution series was modified. Distilled water was added to 0.30 gram of sediment (wet weight) to create a 10-percent solution and a dilution series of 10.0, 5.00, 2.50, 1.25, 0.63, 0.31, 0.17, and 0.08 percent of the sample. Two controls containing only water were used.

All sediment toxicity tests included paired controls. A 95-percent confidence range was calculated for each EC_{50} value (Microbics Corporation, 1992). The dilution series allows the statistical calculation of EC_{50} values. In tests of an identical sample, 95 of 100 EC_{50} values would fall within the 95-percent confidence range. As a guideline, if the upper and lower bounds of the 95-percent confidence range fell within ±30 percent of the EC_{50} value, the data were considered of acceptable quality. Data not meeting this guideline are noted in tables 28, 29, and 30 showing EC_{50} values. Further details of testing procedures are available from Block (1992).

Whole Sediment

Because *P. phosphoreum* showed low or no toxicity response for Lower Arrow Lake LB1 and Lower Arrow Lake LB2 sediments, these sites were appropriate reference sites for comparison with other sandy sediment sites (table 28). Sediments from the Fivemile Creek LB, Onion Creek RB, and Onion Creek LB sites in the Northport reach of the Columbia River caused elevated toxicity response (low EC_{50}). These sites contained slightly more silt- and clay-size material (see table 12) than the upstream sites near the international boundary, which were nearly all sandy. Thus, constituents associated with fine-grained sediment may be causing the elevated toxicity response at these lower sites in the Northport reach of the Columbia River.

The low toxicity response to Sanpoil River MS sediment made this site an appropriate reference site for comparison with other fine-grained sediment sites (table 29). All of the tributaries with fine-grained sediment showed greater toxicity responses than the reference site, with the exception of Hall Creek MS, where a low toxicity response was approximately equal to the reference site. There were high toxicity responses to sediments from the Kootenay River MS and Spokane River MS sites. The response to the Kootenay River MS site sediments was probably associated with a chemical interference because of the presence of natural organic compounds there. An elevated but false toxicity response can occur because of natural organic compounds in areas that support an abundance of plant and animal life (Microbics Corporation, 1992).

In the upper reach of Lake Roosevelt, low or no apparent toxicity responses were observed, but in the mid and lower reaches of Lake Roosevelt, most toxicity responses varied from moderate to high (table 29). The highest toxicity responses in fine-grained sediment were to sediments from Gifford MS, Hunters LB, Seven Bays RB, and Whitestone Creek MS sites in the mid and lower reaches of the reservoir.

Pore-Water Test

Most of the *P. phosphoreum* bioassays exposing the bacterium to sediment pore water showed low or no apparent toxicity response (table 30), possibly indicating that any toxic constituents were tightly bound to sediment under test conditions. Comparisons of pore-water toxicity between sites were limited because more than half of the samples showed no toxicity response. However, pore water from Kootenay River MS and Kettle River RB1 caused unusually high toxicity responses.

Measuring pore-water toxicity response at two times after exposure (5 and 15 minutes) can give some indication of the type of contaminant causing toxicity. Metals are the likely cause of toxicity when the toxicity response is greater at 15 than at 5 minutes for a particular sample (Microbics Corporation, 1992). Of 13 samples that showed a toxicity response at 5 minutes, 9 samples showed a higher toxicity response (lower EC_{50} value) at 15 minutes (table 30).

Table 28.-- *EC_{50} of* Photobacterium phosphoreum *exposed to sandy sediment*

[LB, RB, and MS indicate samples were collected on right side (toward the "right bank" from mid channel), left side (toward the "left bank" from mid channel), and near the mid-section channel, respectively, numbers 1 and 2 denote different sites toward the same bank; EC_{50} value, 50 percent reduction in light output of *Photobacterium phosphoreum*; lower EC_{50} values indicate higher toxicity response; values in parentheses are duplicate samples]

Site number	Site name (see plate 1 for complete name)	EC_{50} value (percent)	Toxicity response
		Reference sites	
1	Lower Arrow Lake LB1[1]	[2]10	Low
2	Lower Arrow Lake LB2[1]	No apparent toxicity	No apparent toxicity
		Major tributaries to Columbia River	
5	Kootenay River LB	2.6	High
6	Pend D'Oreille River LB	No apparent toxicity	No apparent toxicity
		Columbia River, Northport reach	
7	Boundary RB	[2]27	Low
8	Boundary LB	[2]11	Low
9	Auxiliary Gage RB	No apparent toxicity	No apparent toxicity
10	Auxiliary Gage LB	No apparent toxicity	No apparent toxicity
11	Goodeve Creek RB	No apparent toxicity	No apparent toxicity
14	Fivemile Creek LB	4.9	Moderate
15	Onion Creek LB	3.6	High
16	Onion Creek RB	5.9 (5.5)	Moderate (Moderate)
		Minor tributaries	
33	Sherman Creek MS	4.2	Moderate
		Columbia River	
3	Keenleyside Dam LB	[2]3.8	High
72	Rufus Woods Lake LB	[2]9.4	Low

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[1] Lower Arrow Lake LB1 and LB2 reference sites.

[2] 95-percent confidence range wider than ±30 percent of EC_{50} value.

Table 29.-- *EC_{50} of* Photobacterium phosphoreum *exposed to fine-grained sediment*

[LB, RB, and MS indicate samples were collected on right side (toward the "right bank" from mid channel), left side (toward the "left bank" from mid channel), and near the mid-section channel, respectively, numbers 1 and 2 denote different sites toward the same bank; EC_{50} value, 50 percent reduction in light output; lower EC_{50} values indicate higher toxicity response; values in parentheses are duplicate samples; N, no apparent toxicity]

Site number	Site name (see plate 1 for complete name)	EC_{50} value (percent)	Toxicity response
		Reference site	
62	Sanpoil River MS	2.6 (3.1)	Low (Low)
		Major tributaries to Columbia River	
4	Kootenay River MS	0.44	High
		Columbia River, Northport reach	
12	Goodeve Creek LB	[1]1.7 (3.6)	Moderate (Low)
		Major tributaries to Lake Roosevelt	
25	Kettle River RB1	[1]1.8	Moderate
29	Colville River MS	[1]1.2	Moderate
52	Spokane River MS	.18	High
53	Spokane River LB	.90	Moderate
		Lake Roosevelt, upper reach	
17	China Bend RB	[1]11	Low
19	Bossborg RB	2.1	Low
20	Summer Island RB1	[1]3.9	Low
21	Summer Island RB2	No apparent toxicity (N)	No apparent toxicity
		Lake Roosevelt, mid reach	
22	Marcus Island MS	[1]5.1	Low
28	West Kettle Falls LB	1.9	Moderate
35	Haag Cove RB	5.6	Low
38	French Point Rocks MS	.81	Moderate
40	Cheweka Creek LB	1.9	Moderate
41	Gifford MS	0.20	High
46	Hunters LB	.50	High
49	Ninemile Creek RB	1.2	Moderate
51	Fort Spokane RB	0.9 (1.0)	Moderate (Moderate)
		Lake Roosevelt, lower reach	
57	Seven Bays RB[2]	0.77 (0.18)	High (High)
61	Whitestone Creek MS	.18 (.17)	High (High)
66	Keller Ferry RB	1.9	Moderate
69	Swawilla Basin LB	.88	Moderate
71	Grand Coulee Dam RB	.63	High
		Minor tributaries	
45	Hall Creek MS	2.6	Low
55	Hawk Creek RB	.89	Moderate

[1] 95-percent confidence range wider than ±30 percent of EC_{50} value.

Table 30-- EC_{50} *of* Photobacterium phosphoreum *exposed to sediment pore water*

[LB, RB, and MS indicate samples were collected on right side (toward the "right bank" from mid channel), left side (toward the "left bank" from mid channel), and near the mid-section channel, respectively, numbers 1 and 2 denote different sites toward the same bank; EC_{50} value, 50 percent reduction in light output of *Photobacterium phosphoreum*; lower EC_{50} values indicate higher toxicity response; values in parentheses are duplicate samples; N, no apparent toxicity)]

Site number	Site name (see plate 1 for complete name)	5-minute reading EC_{50} value (percent)	Toxicity response	15-minute reading EC_{50} value (percent)	Toxicity response
	Reference site				
62	Sanpoil River MS	No apparent toxicity	None	No apparent toxicity	None
	Major tributaries to Columbia River				
4	Kootenay River MS	7.7	High	[1]8.7	High
	Columbia River, Northport reach				
12	Goodeve Creek LB	[1]61	Moderate	55	Moderate
15	Onion Creek LB	[1]91	Low	[1]84	Low
	Major tributaries to Lake Roosevelt				
25	Kettle River RB1	13	High	12	High
29	Colville River MS	72	Low	No apparent toxicity	None
53	Spokane River LB	No apparent toxicity	None	[1]90	Low
	Lake Roosevelt, upper reach				
17	China Bend RB	No apparent toxicity	None	No apparent toxicity	None
19	Bossborg RB	[1]70	Moderate	54	Moderate
20	Summer Island RB1	[1]36	High	[1]27	High
21	Summer Island RB2	No apparent toxicity	None	No apparent toxicity	None
	Lake Roosevelt, mid reach				
22	Marcus Island MS	No apparent toxicity	None	No apparent toxicity	None
28	West Kettle Falls LB	53	Moderate	32	High
35	Haag Cove RB	No apparent toxicity	None	No apparent toxicity	None
38	French Point Rocks MS	[1]59	Moderate	[1]43	Moderate
40	Cheweka Creek LB	No apparent toxicity	None	No apparent toxicity	None
41	Gifford MS	No apparent toxicity	None	No apparent toxicity	None
46	Hunters LB	[1]79	Low	No apparent toxicity	None
49	Ninemile Creek RB	No apparent toxicity	None	No apparent toxicity	None
51	Fort Spokane RB	No apparent toxicity	None	No apparent toxicity	None
	Lake Roosevelt, lower reach				
57	Seven Bays RB[1]	No apparent toxicity (N)	None	[1]81	Low
61	Whitestone Creek MS	53 ([1]39)	Moderate (High)	[1]65 ([1]33)	Moderate (High)
66	Keller Ferry RB	No apparent toxicity	None	No apparent toxicity	None
69	Swawilla Basin LB	No apparent toxicity	None	No apparent toxicity	None
71	Grand Coulee Dam RB	No apparent toxicity	None	No apparent toxicity	None
	Minor tributaries				
45	Hall Creek MS	83	Low	31	High
55	Hawk Creek RB	No apparent toxicity	None	No apparent toxicity	None

[1] 95-percent confidence range wider than ±30 percent of EC_{50} value.

Comparison Between Sediment Toxicity Tests

Toxicity tests of bed sediment of the Columbia River near and downstream from the international boundary indicated a toxicity response significantly different from that of controls or reference samples in all three test organisms. Survival or reproduction of at least one, and in some cases all three, of the organisms tested was adversely affected in the Northport reach of the Columbia River from the international boundary to Onion Creek LB (RM 730). *C. dubia* and *H. azteca* were mostly affected close to the international boundary, and *P. phosphoreum* were affected farther down. River sediment from Boundary LB and Auxiliary Gage LB resulted in low *H. azteca* survival and *C. dubia* survival and reproduction. *C. dubia* reproduction was significantly reduced at Goodeve Creek LB. In contrast, the *P. phosphoreum* results did not show any toxicity at sites containing mostly sand, but they did indicate toxic responses downstream at sites containing less sand, particularly Fivemile Creek LB, Onion Creek RB, and Onion Creek LB (table 28).

Toxicity tests of bed sediment from Lake Roosevelt caused toxicity responses from *C. dubia* in two of nine samples. Significantly reduced reproduction of *C. dubia* at Whitestone Creek MS and Grand Coulee Dam RB indicated sublethal toxicity. However, *P. phosphoreum* exposed to fine-grained sediment showed mostly moderate to high toxicity responses in the mid to lower reach of the reservoir starting at French Point Rocks MS and continuing downstream to Grand Coulee Dam RB (table 29). More bioassay tests on bed sediment from the lower reach of the reservoir would augment the findings of this study.

Of the major tributaries, bed sediment from the Kootenay MS, Spokane MS, Sanpoil MS, and Kettle River RB1 caused high toxicity responses in at least one of the three tests; however, each of the three bioassays in tributary sediment did not always support the results of the others. *H. azteca* showed significantly low survival when exposed to Sanpoil River MS sediment; but the other organisms showed no toxic responses. The *P. phosphoreum* toxicity response to Spokane River MS sediment was high, but in contrast, survival of *C. dubia* and *H. azteca* was 100 percent. *C. dubia* reproduction and survival were significantly depressed at the Kettle River RB1, and *P. phosphoreum* results also indicated a moderate toxicity response. The *P. phosphoreum* toxicity response was high in Kootenay MS, but the other two tests showed no significant toxicity response.

BENTHIC INVERTEBRATE COMMUNITIES

In contrast to bioassays, which provide information on the toxicity of water and sediment under laboratory conditions, field studies of benthic invertebrate communities permit an assessment of existing conditions in the ecosystem. Benthic invertebrates are commonly used for assessing water and sediment quality because they play a key role in aquatic environments owing to their intermediate position in the food chain, they show the cumulative effects of present and past conditions, they are mainly sedentary, their ecological relationships are relatively well understood (Herricks and Cairns, 1982; Wilhm, 1975; Resh and Rosenberg, 1984), and they reflect spatial and temporal changes in contaminant exposure (LaPoint and Fairchild, 1992). Benthic invertebrate communities are used for assessing contaminants under a variety of conditions and are an important tool in monitoring programs (Plafkin and others, 1989; Gibbons and others, 1993; MacDonald and others, 1992).

Both response and exposure indicators are necessary for assessing environmental health (Hunsaker and Carpenter, 1990). Response indicators include measures of the structure of the benthic invertebrate community (for example, diversity). Alterations in the community imply that deleterious or improved conditions may have occurred, but it may not be possible to identify the cause of an effect. Exposure indicators (for example, bioaccumulation) establish that organisms have been subjected to a potentially deleterious contaminant, and the indicators quantify exposure, but they cannot determine whether a deleterious effect has occurred. Thus, in most instances, both response and exposure indicators are needed to establish that effects are occurring and to identify relations between changes in community structure and contaminant levels.

There are various approaches for assessing sediment quality, most of which rely on some combination of analyses of benthic invertebrate community structure, sediment bioassays, and sediment chemistry (Chapman, 1990; Chapman and others, 1992; Ginn and Pastorok, 1992; LaPoint and Fairchild, 1992). This study has used an integrated approach.

The objective of the benthic invertebrate part of this study was to determine whether benthic invertebrate communities in the Lake Roosevelt ecosystem indicated impairment and whether any observable patterns could be associated with concentrations of trace elements in sediments or physical habitat conditions. The benthic communities were divided for discussion into two habitats—erosional, dominated by coarse-grained substrate, and depositional, dominated by fine-grained substrate—because results of a cluster analysis showed that the habitats contained very different taxa.

Data in this section of the report will show the following results.

- Benthic invertebrate communities in the erosional habitats of the Columbia River resembled those commonly associated with contaminated or habitat-degraded areas or both. Communities were relatively low in abundance and diversity and were dominated by stress-tolerant organisms.
- Benthic invertebrate communities in depositional habitats of Lake Roosevelt and tributaries were more difficult to assess because of naturally low diversity of benthic organisms in reservoirs. The present benthic invertebrate communities likely had been affected by the elevated concentrations of sediment-bound trace elements.

Methods

The methods of this study for assessing benthic invertebrate communities can be divided conveniently into reach and site selection, field and laboratory procedures, and analysis.

Reach and Site Selection

The study area was divided into two habitat types, erosional and depositional, because benthic invertebrate communities naturally differ in these two habitat types (fig. 27, table 31). The only riverine erosional habitat (shallow riffle habitat) was in the Northport reach of the Columbia River, which contained three benthic invertebrate sites. In contrast, the depositional habitat consisted of five groups of sites: the tributaries (including the Kootenay LB1 River site because of its physical similarity), the Northport reach of Columbia River, the upper reach of Lake Roosevelt, the mid reach of the reservoir, and the lower reach of the reservoir. The depositional site at Lower Arrow Lake site was not grouped with any other sites because it is behind Hugh Keenleyside Dam in Canada (see plate 1 for site location).

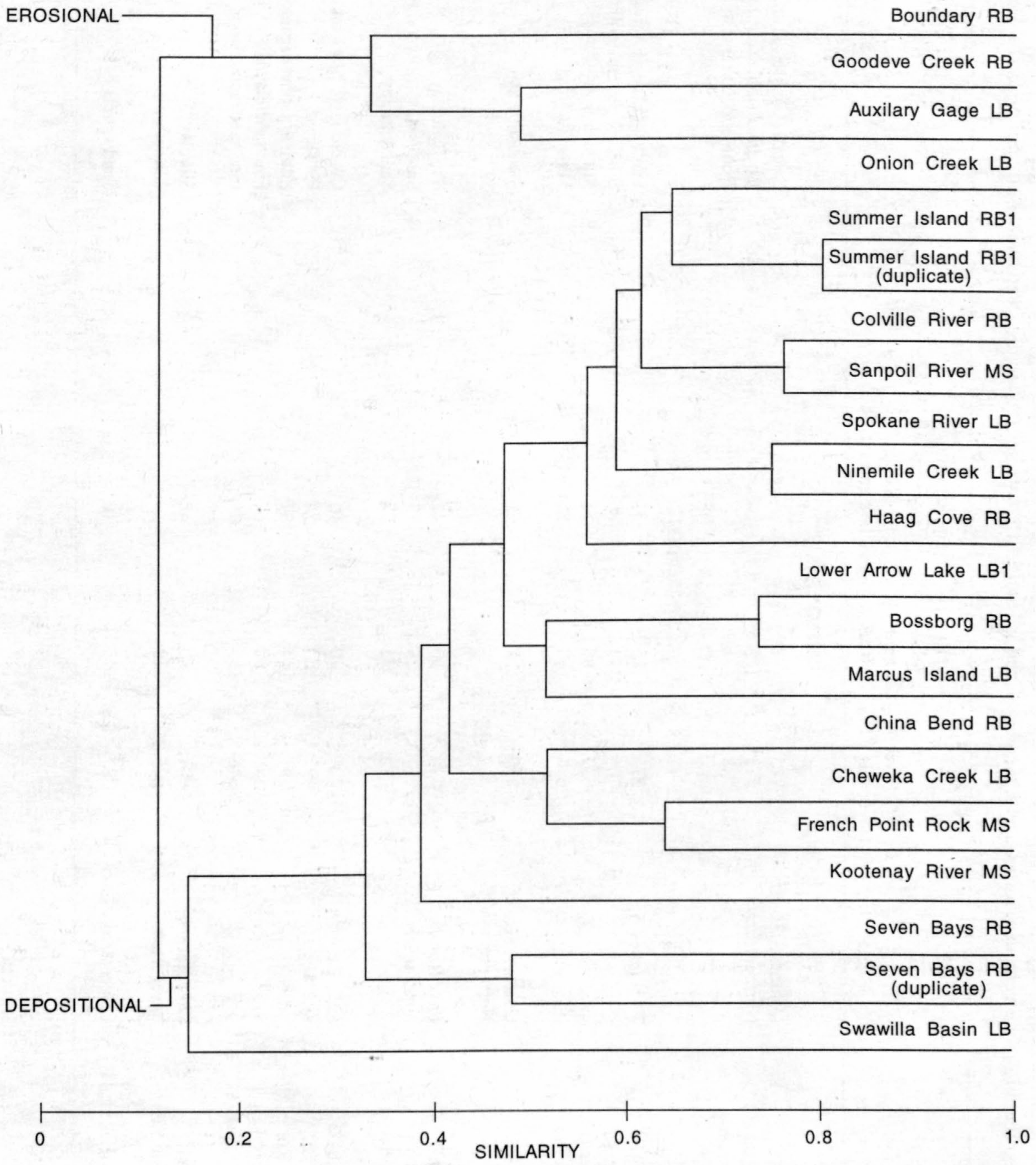
Field Procedures

The physical characteristics of erosional and of depositional habitats were measured by different methods. Habitat assessment of the shallow erosional areas included measuring a mean water-current velocity and water depth and qualitatively assessing substrate particle size by methods outlined by Plafkin and others (1989). Water-current velocity was measured near the river bed (0.8 of the total depth below the water surface). Habitat assessment at the depositional sites included water depth and the percentage of silts and clays in the bed sediments. Total organic carbon was also determined at all sites.

Because the methods for collecting benthic invertebrate samples depend on the habitat being sampled, this study used two different sampling approaches, one for the erosional sites and one for the depositional sites. Erosional habitats were sampled with a 0.1-square-meter circular Hess sampler fitted with a 0.25 mm mesh net. The depth of the substrate was generally less than 10 centimeters (3.9 inches), and individual samples were collected over a 5-minute period in order to standardize the sampling effort. Five replicate Hess samples were collected at each site and analyzed individually (fig. 28). Samples were taken in downstream-to-upstream order to minimize the physical disruption of the communities not yet sampled. The sampler was placed on the surface of the substrate and individual rocks were brushed to dislodge the invertebrates into the net; the finer material was then stirred to dislodge remaining organisms.

In the depositional habitats two types of grab samplers were used depending on local conditions, either a 0.05-square-meter Ponar or a 0.1-square-meter van Veen grab sampler. In order to obtain a representative sample of the local benthic community, multiple grab samples were collected at each site and the individual samples were then composited into a single sample from each site (fig. 28). The number of samples composited depended on the sampler: five samples for the Ponar and three to four samples for the van Veen. Individual grab samples were accepted if the sample was intact and the sampler jaws were completely closed. To ensure collection of all organisms captured, all water collected in a tub from each sample and respective washing of the sampler was poured into buckets and retained. Sediment samples were thoroughly mixed in the collection tub, and a portion of the homogenized mixture was isolated using a quartering divider blade designed to fit into the tub. One quarter of the sample was removed with a scoop, placed into a sieve box, and passed through the 0.25 mm mesh. After one quarter of the retained water was also poured through the sieve, the organisms and material collected on the sieve were washed with native water from the sieve box into containers.

Benthic invertebrate samples were preserved in the field with 10 percent formalin in a 1:1 ratio with the sample. The sample containers were inverted several times to ensure fixative penetration and then were shipped to Chadwick and Associates in Littleton, Colo., for processing.



EXPLANATION

RB, LB, and MS indicate samples were collected on right side (toward the "right bank" from mid channel), left side (toward the "left bank" from mid channel), and near the mid-section channel, respectively. Numbers 1 and 2 denote different sites toward the same bank.

Figure 27.--Cluster analysis of benthic invertebrate communities from three erosional sites in the Northport reach of the Columbia River and 16 depositional sites in major tributaries, the Northport reach of Columbia River, and Lake Roosevelt.

Table 31.--*Physical habitat at benthic invertebrate sites in the Lake Roosevelt study area*

[--, no data; LB, RB, and MS indicate samples were collected on right side (toward the "right bank" from mid channel), left side (toward the "left bank" from mid channel), and near the mid section channel, respectively, numbers 1 and 2 denote different sites toward the same bank; mm, millimeters]

Site number	Site name (see plate 1 for complete name)	Reach	River mile	Water depth (feet)	Percentage of sediment finer than 0.062 mm	Velocity (feet per second)	Remarks
				Erosional habitat			
7	Boundary RB	Columbia River, Northport reach	745	2.1	--	1.4	Boulder/cobble substrate with slag
10	Auxiliary Gage LB		743	1.4	--	1.1	Boulder/cobble substrate with slag
11	Goodeve Creek RB		738	1.7	--	1.6	Boulder/cobble substrate with slag
				Depositional habitat			
4	Kootenay River MS	Tributaries	775	25	38	--	Sand/silt/clay with macrophytes
30	Colville River RB		700	12	80	--	Silt/clay with macrophytes
53	Spokane River LB		639	65	53	--	Silt/sand/soft
62	Sanpoil River MS		616	40	85	--	Silt/sand
15	Onion Creek LB	Columbia River, Northport reach	730	25	22	--	Sand/silt/clay
17	China Bend RB	Lake Roosevelt, upper reach	724	50	41	--	Sand/silt/clay
19	Bossborg RB		717	20	33	--	Sand/silt, some wood fragments
20	Summer Island RB1		710	22	82	--	Sand/silt/clay
22	Marcus Island LB	Lake Roosevelt, mid reach	708	40	46	--	Coarse sand, black and gray
35	Haag Cove RB		697	30	74	--	Fine sand
38	French Point Rocks MS		691	144	97	--	Silt/clay, some organic fragments
40	Cheweka Creek LB		681	50	67	--	Fine sand/clay/silt
48	Ninemile Creek LB		648	55	44	--	Fine sand, some wood fragments
57	Seven Bays RB	Lake Roosevelt, lower reach	634	60	48	--	Silt/clay
69	Swawilla Basin LB		605	70	86	--	Clay/silt/sand
1	Lower Arrow Lake LB1	Lower Arrow Lake	787	45	10	--	Sand/silt/clay

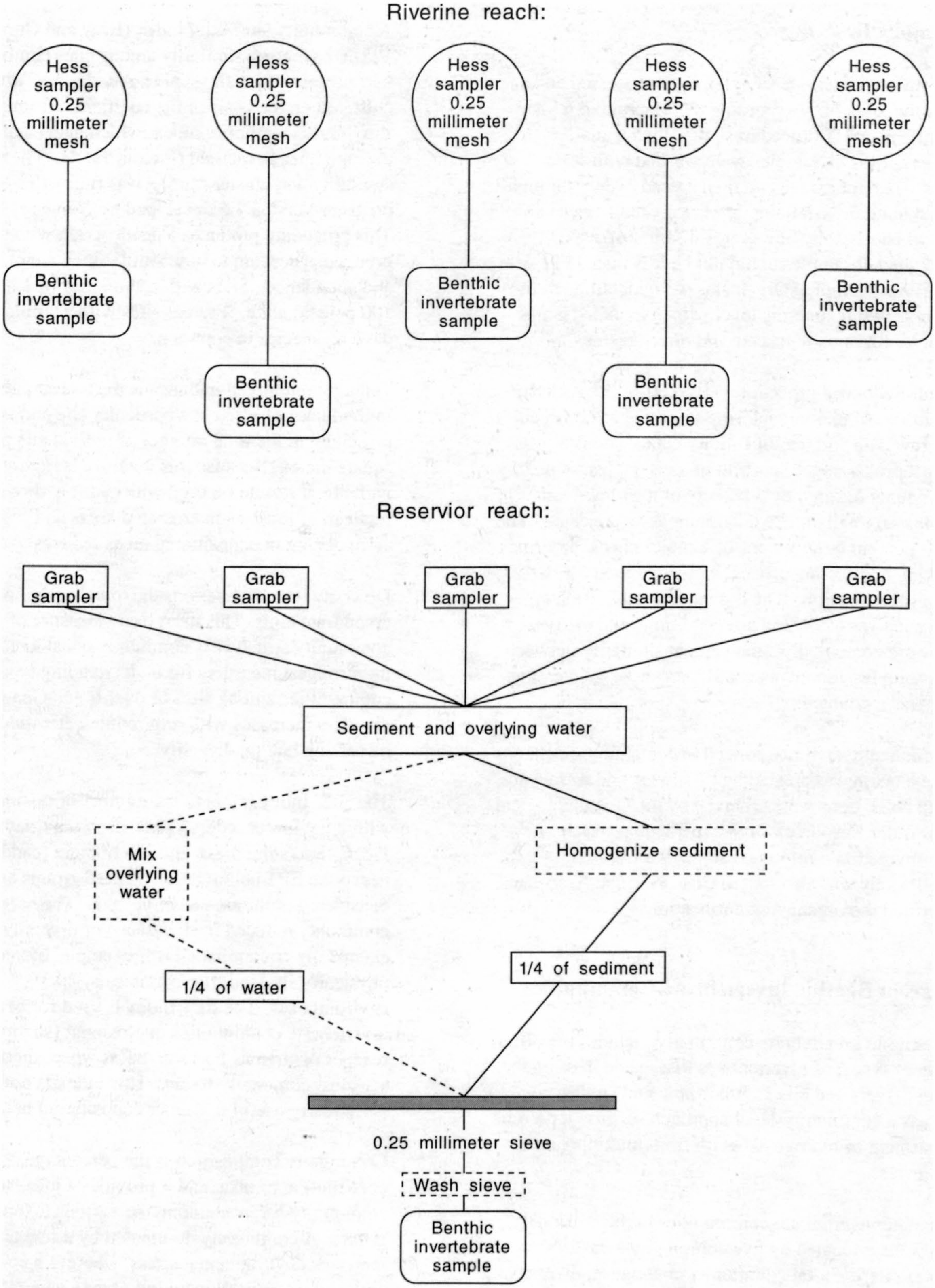


Figure 28.--Schematic of benthic invertebrate sampling in erosional and depositional habitats in the Lake Roosevelt study area.

Laboratory Procedures

Benthic invertebrate samples were processed and analyzed in the laboratory according to "Macroinvertebrate Standard Operating Procedures" (Chadwick and Associates, 1992). Samples were washed with water through a 0.25 mm sieve and then spread evenly throughout a picking pan. All animals were picked from each sample when feasible; however, subsampling was allowed, but subsamples could not be less than 25 percent of the original sample. Organisms were identified to the lowest practical taxonomic level, which included genus and species for aquatic insects and oligochaetes.

Quality-control procedures were followed to ensure completeness of picking and sorting and to ensure accuracy of raw data and identification. Quality control was done by reprocessing 10 percent of the samples. If quality control counts differed by 5 percent of the total number of organisms originally picked, the sample was rejected. The same 10-percent quality-control samples checked during the picking and sorting process were also used for purposes of identification. The organisms within each taxonomic group were counted a second time, and the two counts were compared. If the percent similarity between the two samples count was not 90 percent or greater, the sample was recounted.

A duplicate reference collection containing specimens from each taxon was created by Chadwick and Associates, and both collections were archived by the U.S. Geological Survey, Water Resources Division, Tacoma, Wash. A benthic invertebrate reference collection from the CRIEMP study was also sent to Chadwick and Associates, who verified the organism identifications.

Analysis of Benthic Invertebrate Communities

A benthic invertebrate community includes the different taxa, or types, of invertebrates that reside in or on the bottom of rivers and lakes. Environmental studies commonly use a community-level approach because it permits an assessment of biological health from multiple taxonomic levels.

Benthic invertebrate communities in the erosional habitat were evaluated by five community measures: community similarity, total community abundance, diversity, EPT Index, and community composition (Plafkin and others, 1989), and all measures except the EPT Index were used in the depositional habitat.

- A community similarity index (Bray and Curtis, 1957) to measure similarity among sites combined the taxa present and their relative abundances. Sites were clustered on the basis of the coefficient from the Bray-Curtis similarity index, which also entailed the average linkage method (Pielou, 1984). The similarity and cluster routine was run with a Fortran program Version 1.5 developed by Nemec (1991). This procedure produces a dendrogram with sites grouped according to how similar they are in species and abundance. Sites with a similarity of 1 are 100 percent alike, whereas sites with a similarity of 0 have no species in common.

- Total community abundance is the total number of individuals collected at a particular site and is presented as the total number of individuals per square meter. Because this measure is highly variable, it should be used with caution, though replicating samples in erosional areas and compositing in depositional areas reduces variability.

- Diversity (taxa richness) is the total number of taxa or taxonomic units. This most basic measure of community structure is commonly considered one of the strongest measures for understanding benthic communities among sites or over time. Generally, diversity increases with improving water quality and increasing habitat diversity.

- The EPT Index refers to the number of distinct taxa within the insect orders Ephemeroptera (mayflies), Plecoptera (stoneflies), and Trichoptera (caddisflies), hence the EPT abbreviation. These groups are considered pollution-sensitive taxa. They are commonly reduced in abundance or diversity in chemically contaminated (for example, by metals) or physically stressed (for example, by silt) environments. The EPT Index is used for benthic invertebrate communities in erosional (shallow riffle) reaches of streams because that is where these groups are most commonly found. This index is not particularly useful in deeper depositional habitats.

- Community composition is the percentage contribution of taxa, and it provides a measure of community balance among the various taxonomic groups. A community dominated by a few taxa indicates environmental stress, whereas a community with a more even distribution of taxa generally indicates good water quality.

Statistical correlations determine whether there is an association between two variables. Pearson correlation coefficients were used to determine whether there was a statistical correlation between benthic invertebrate community measures (total abundance, diversity, and percentage abundance of dominant taxonomic groups), sediment trace-element chemistry (arsenic, cadmium, copper, lead, mercury and zinc), and physical habitat (depth in feet, percentage of fines less than 0.062 mm, and total organic carbon). Some of the variables were transformed in order to meet the assumptions of normality (Ott, 1977). Transformations included log(x) or log(x+1) for all non-normal data and square root arc-sin for percent data. Statistical tests for both normality and Pearson correlation coefficients used SAS software (SAS Institute, Inc., 1990).

Riverine Erosional Habitat

Benthic invertebrate communities in three erosional habitats of the Northport reach of the Columbia River were relatively low in total abundance, diversity, and individuals that compose the EPT index. The types of benthic invertebrates collected at erosional sites are listed in table 36 at the end of the report. The mean abundance of invertebrates ranged from 68 to 146 individuals per square meter (table 32). The number of taxa (diversity) was low, 3 to 14 at the three riverine sites. There were also few of the EPT taxa (mayflies, stoneflies and caddisflies) considered indicators of good water quality. The EPT index was 1 at Goodeve Creek RB and Auxiliary Gage LB and 4 at Boundary RB.

Table 32.--*Benthic invertebrate community structure from three riverine erosional sites*

[Abundance, invertebrates per square meter; diversity, number of taxa; EPT, number of individuals within the aquatic insect orders Ephemeroptera (mayflies), Plecoptera (stoneflies), and Trichoptera (caddisflies); SD, standard deviation, based on the five replicate samples from each station; LB, RB, indicate samples were collected on left side (toward the "left bank" from mid channel) and right side (toward the "right bank" from mid channel), respectively]

	Site name[1]					
	Boundary RB		Goodeve Creek RB		Auxiliary Gage LB	
Mean abundance (SD)	68	(59)	136	(137)	146	(110)
Diversity	14		3		8	
EPT Index	4		1		1	
	Diversity	Percent abundance	Diversity	Percent abundance	Diversity	Percent abundance
Insecta						
Coleoptera (beetles)	1	6	0	0	0	0
Diptera (mainly midges)	6	50	2	94	7	96
Ephemeroptera (mayflies)	1	12	0	0	1	4
Plecoptera (stoneflies)	1	6	0	0	0	0
Trichoptera (caddisflies)	2	12	1	6	0	0
Nematoda (worms)	1	6	0	0	0	0
Gastropoda (snails)	2	9	0	0	0	0

[1] See plate 1 for complete name.

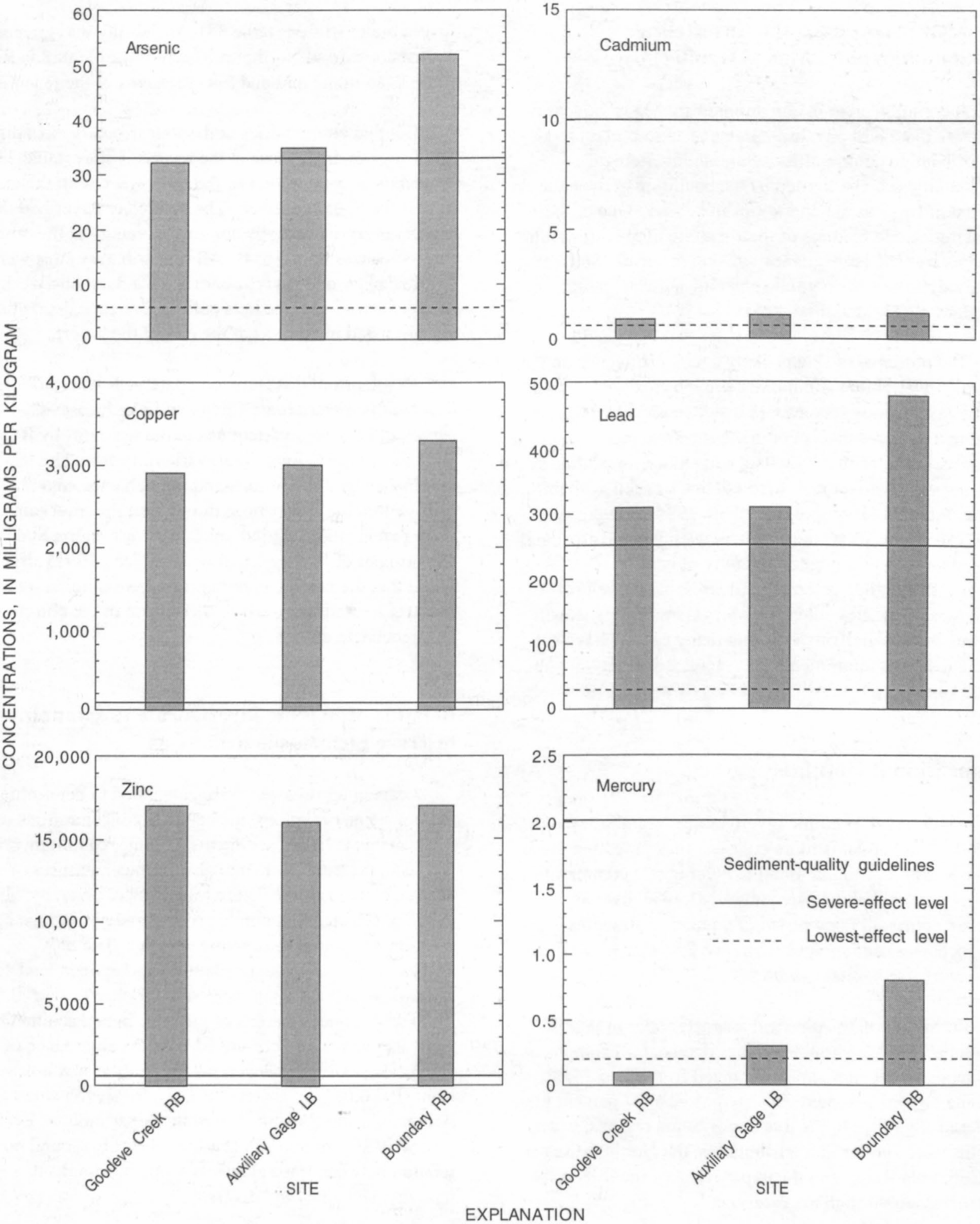
The benthic invertebrate communities in the erosional habitats were dominated by aquatic insects; species of midges (chironomids) composed the largest percentage. Although species within this family are common in all freshwater habitats, many are classified as stress tolerant and therefore may dominate a community that has undergone physical or chemical stress. Boundary RB was the only riffle site that contained all three taxa of the EPT index, although the actual number of taxa in each insect order was low. Besides insects, the only other taxonomic groups observed were worms (nematodes) and snails (gastropods). Aquatic earthworms (oligochaetes), a common component of benthic communities, were not observed from any of the three sites.

Benthic invertebrate communities vary naturally among habitats. However, benthic communities in erosional habitats commonly consist of a diverse assemblage of species (mayflies, stoneflies, caddisflies) classified as sensitive to physical or chemical stressors. For example, Munn and Brusven (1991) found that a large river in Idaho contained 36 taxa, not including the family Chironomidae. Of the 36 taxa, approximately 75 percent, or 27 taxa, were in the EPT (Ephemeroptera, Plecoptera, Trichoptera) group. In contrast to the previous finding, the present study found only 3 to 14 taxa in the erosional habitats and only 1 to 4 taxa within the EPT group. Data characterizing the structure of the benthic invertebrate community prior to the loading of trace elements to the Columbia River are not available; therefore, it is not possible to state whether the present communities have changed over time. Also, there is insufficient information about reference sites for comparison with erosional sites. Regardless of these two limitations, benthic invertebrate communities in the three riffle reaches resembled those commonly associated with a chemical or physical disturbance.

Relation Between Benthic Invertebrate Communities and Trace Elements in Sediments

Results from the analysis of benthic invertebrate communities, sediment trace-element chemistry, and sediment toxicity tests indicated that concentrations of trace elements in bed sediments may have influenced the present benthic community. Other studies have documented that, in general, trace elements have toxic effects on invertebrates under both laboratory conditions (Warnick and Bell, 1969; Clubb and others, 1975; Nebeker and others, 1984; Hodson and others, 1979) and field conditions (Wiederholm, 1984; Leland and Kuwabara, 1984; Leland and others, 1989). To cause toxic effects, trace elements must be present in a biologically available form, and when they are available in such a form, benthic invertebrate communities may undergo a reduction in total abundance and diversity and a shift in community composition (Wiederholm, 1984). This change in the community composition commonly includes a decrease or complete loss of the more metal-sensitive groups, such as mayflies, and an increase in the more metal-tolerant groups, such as midges (Wiederholm, 1984).

The benthic invertebrate communities in the erosional habitats of the Northport reach of the Columbia River reflected the patterns observed in areas where trace-element concentrations are elevated. Furthermore, the concentrations of trace elements in sediments collected in the vicinity of the erosional habitats greatly exceeded concentrations reported to produce changes in invertebrate communities. For example, sediment samples from areas adjacent to the erosional habitats contained the largest concentrations of trace elements reported in this study. Concentrations of four trace elements (arsenic, copper, lead, and zinc) exceeded the Canadian severe-effect level sediment guidelines based upon effects on benthic organisms (fig. 29; Persaud and others, 1991). Of these four, copper and zinc exceeded their severe-effect levels by an order of magnitude. The average concentrations of cadmium and mercury in bed sediments of benthic sites exceeded the lowest-effect level but were less than the severe-effect level (Persaud and others, 1991). Concentrations of trace elements in bed sediments from the riffle sites also exceeded many other reported levels (chronic or acute) that have been associated with impairment of benthic communities (Long and Morgan, 1990). Additional evidence of the toxicity of trace elements in bed sediment came from the sediment toxicity tests discussed previously and from an extensive sediment toxicity study done on slag (Nener, 1992). The combined results from the benthic invertebrate study, trace-element bed-sediment chemistry, and bed-sediment toxicity tests indicated potential effects on the benthic invertebrate communities.



EXPLANATION

RB, LB, and MS indicate samples were collected on right side (toward the "right bank" from mid channel), left side (toward the "left bank" from mid channel), and near the mid-section channel, respectively. Numbers 1 and 2 denote different sites toward the same bank.

Figure 29.--Concentrations of trace elements in bed sediment from erosional sites in the Northport reach of the Columbia River and sediment-quality guidelines. Guidelines are based upon lowest-to severe-effect levels on benthic invertebrates (Persaud and others, 1991). Lowest-effect level of copper and zinc not visible at scale shown.

Relation Between Benthic Invertebrate Communities and Physical Habitat

A common error in contaminant studies is the tendency to disregard physical habitat as an important modifier of benthic communities. Benthic invertebrate communities can be limited by the condition of the natural habitat or by physical alterations in habitat. One of the most noticeable features of the substrate in the three riffle reaches was the large quantity of slag material. Slag surrounded most of the natural substrate and was found throughout the interstitial areas.

The presence of slag is likely a major influence on the benthic invertebrate communities in the erosional habitat. Many invertebrate species that reside in erosional habitats require the spaces that occur in the substrate matrix. Small grain particles, as in silt or slag, can reduce liveability by altering water movement, food quality, oxygen availability, and interstitial spaces (Minshall, 1984). Heterogeneous substrate, as is common in many unaltered erosional habitats, contains a greater diversity of benthic invertebrates and a higher percentage of stress-sensitive taxa (mayflies, stoneflies, and caddisflies). Part of the reason for this increased diversity is that many species have specific substrate requirements; therefore, a diversity of substrate supports a diversity of species (Minshall, 1984).

Depositional Habitats

Assessing the benthic invertebrate communities in the depositional habitat is more complex than assessing those in the erosional habitat. Benthic invertebrate communities in depositional habitats are naturally low in diversity and are commonly composed of aquatic earthworms (oligochaetes) and midges (chironomids) that are adapted to less diverse habitat conditions.

Furthermore, the physical characteristics of depositional habitats are variable. Water depths, for example, at the depositional sites sampled ranged from 12 to 144 ft, and the bottom sediment consisted of 10 to 97 percent fine material (fig. 30). In the five depositional regions, water depths were similar in the tributaries, the Northport reach of Columbia River, and the upper reach of the reservoir but increased through the reservoir.

The cluster analysis (fig. 27) showed that depositional sites differed in taxa and relative abundance. This dissimilarity was perhaps due to the large size of the river-reservoir system and the heterogeneity of chemical and physical conditions. The high variability among sites is further shown by the abundance and diversity of benthic invertebrates (fig. 31; table 33). Variability was greatest in the tributaries and Northport Reach of the Columbia River and less so in the mid and lower reaches of the reservoir.

Benthic communities at the four tributary sites differed slightly from those at the reservoir sites (table 33). Abundances were higher in the tributaries, with the exception of the Spokane River. The Kootenay River had the highest diversity (14); by contrast, diversity at the other three sites was only 5 to 6. All four tributary sites were dominated by midges (chironomids) and aquatic worms (oligochaetes). All the taxa collected at each depositional site are listed in table 37 at the end of the report.

Results from this study compare well with those from past benthic invertebrate studies in Lake Roosevelt. A survey of benthic invertebrates in the reservoir by Robeck and others (1954) found high variability from site to site, dominance by chironomids and oligochaetes, and no distinct longitudinal pattern throughout the reservoir. A more recent study (Arthur Johnson, Washington State Department of Ecology, written commun., 1991) also found that the benthic communities were dominated by few species and that most of these were in the chironomid or oligochaete groups.

Relation of Benthic Invertebrate Communities to Trace Elements in Sediments

Pearson correlations were calculated to determine if there were any relationships between concentrations of trace elements in bed sediments (arsenic, cadmium, copper, lead, mercury, and zinc) and various measures of benthic community structure (abundance, diversity, abundance of selected taxonomic groups, and percentage composition of selected taxonomic groups). The only statistically significant correlation was between lead concentrations and the abundance of oligochaetes ($r = -0.51$; $P = 0.04$). Concentrations of mercury in bed sediments were also negatively correlated with the abundance of oligochaetes (-0.49); however, the correlation was not significant ($P = 0.06$). In a previous Lake Roosevelt study, Arthur Johnson (Washington State Department of Ecology, written commun., December 1991) also found no correlation between trace elements (copper, iron, lead, mercury, and zinc) and diversity.

The lack of a statistical relation between concentrations of trace elements in bed sediments and measures of benthic community structure is likely related to a number of factors: (1) trace elements must be biologically available to cause adverse effects, and the percentage that is biologically available is presently unknown, even though concentrations of total trace elements are large; (2) benthic communities in the reservoir are low in diversity and high in variability, so the use of measurements of community structure may not be sensitive enough to show relations; (3) benthic communities in the reservoir were exposed to trace elements since the initial filling of the reservoir, and therefore the present communities could reflect taxa that have adapted to trace elements; and (4) the source of the trace elements is at the upstream end of the reservoir, so there are no "clean" sites with which to compare benthic communities.

Midges (Chironomidae) can be intolerant or tolerant of trace elements, depending on the genera, according to preliminary work by Ferrington (Leonard Ferrington, personal commun., December 1993). Of the four tributary sites (Colville, Kootenay, Sanpoil, and Spokane Rivers), the Spokane River site had the largest concentrations of trace elements and two tolerant genera of chironomids (*Cricotopus* and *Thienemannimyia*), with no intolerant genera. This contrasts with the Kootenay site, which had some of the smallest concentrations of trace elements in the bed sediments and had one tolerant genus (*Thienemannimyia*) and three intolerant genera (*Rheotanytarsus*, *Stictochironomus*, and *Tribelos*). Assessing the reservoir sites using this approach is more complicated. The reservoir sites contained 10 genera of chironomids: 3 tolerant, 3 intolerant, and 4 unknown. One observation is that six reservoir sites contained three intolerant taxa and all sites contained some intolerant genera. However, there was no distinct pattern of more tolerant taxa at sites with larger concentrations of trace elements.

When the concentrations of trace elements in sediments from the depositional sites were compared to sediment-quality guidelines (Persaud and others, 1991), concentrations of arsenic, cadmium, copper, lead, mercury, and zinc commonly exceeded the lowest-effect level at most sites in the Northport reach and at all reservoir reaches (fig. 32). Concentrations of trace elements in bed sediments were typically largest in the Northport reach (Onion Creek LB) and the upper and middle reaches of the reservoir, with most of the sites in the system exceeding the severe-effect level for copper, lead, and zinc, and a few sites for mercury. Concentrations of trace elements in the lower reach of the reservoir were smaller than upstream concentrations, with levels that commonly fell between the lowest- and severe-effect levels.

The concentrations of trace elements in bed sediments from the tributary sites were commonly between the lowest- and severe-effect levels. The Spokane River LB site had the largest concentrations of trace elements in relation to the other tributaries, where zinc exceeded the severe-effect level. In contrast, the concentrations of trace elements in bed sediments from Lower Arrow Lake were consistently below even the lowest-effect level.

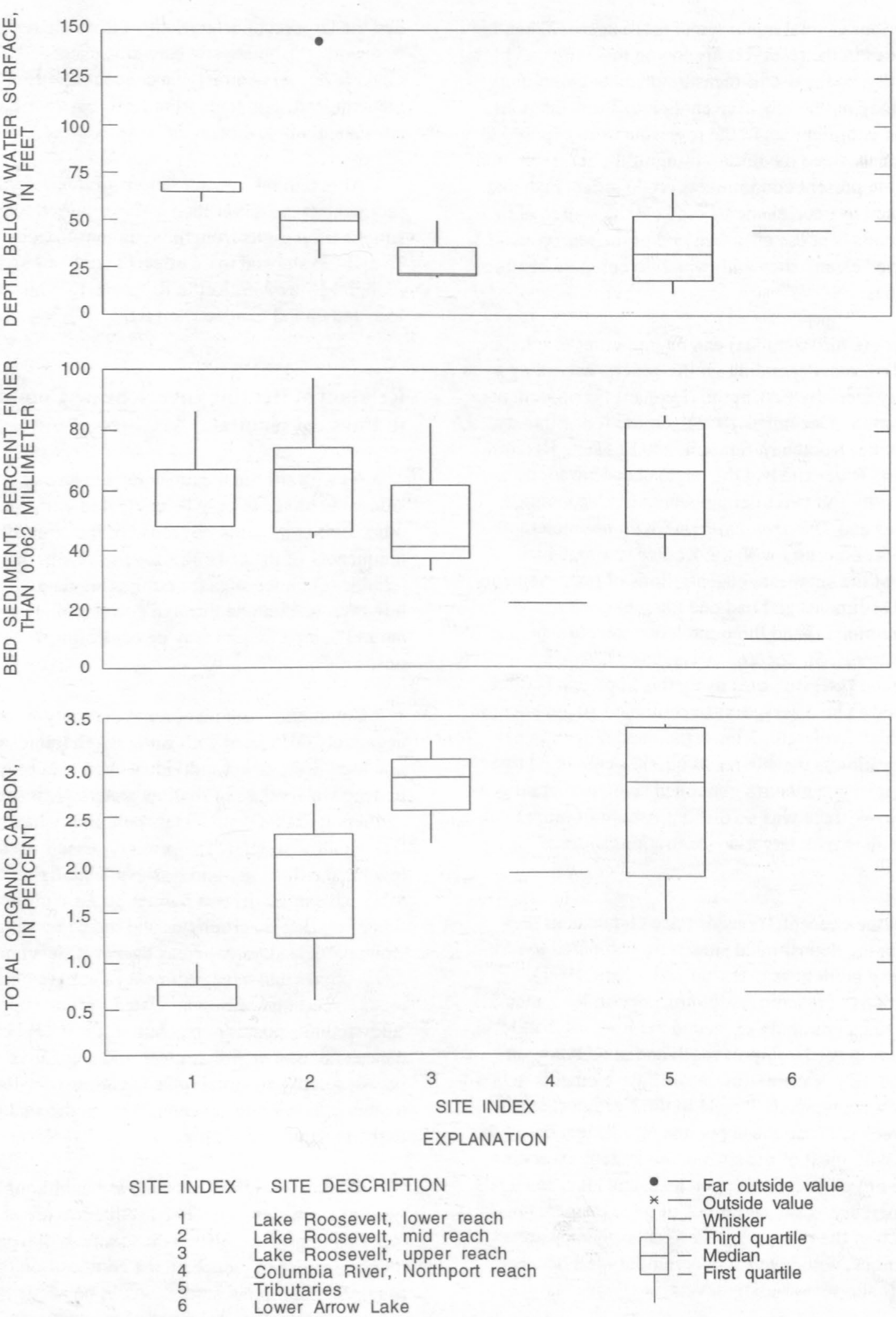
Although the concentrations of trace elements in bed sediments were larger than levels reported to be toxic to aquatic life, results from the sediment-toxicity tests (tables 26 and 27) showed toxic effects at only a few sites (Sanpoil River MS, Kettle River RB1, Whitestone Creek MS, and Grand Coulee Dam RB).

Relation of Benthic Invertebrate Communities to Physical Habitat

As with sites in the erosional habitat, sites in the depositional habitat can only be compared with each other and other similar systems. Because of the large size and uniqueness of the Lake Roosevelt system, there were no reliable reference sites for comparing data. It is possible, however, to examine through correlational analysis what natural habitat factors may be controlling the communities.

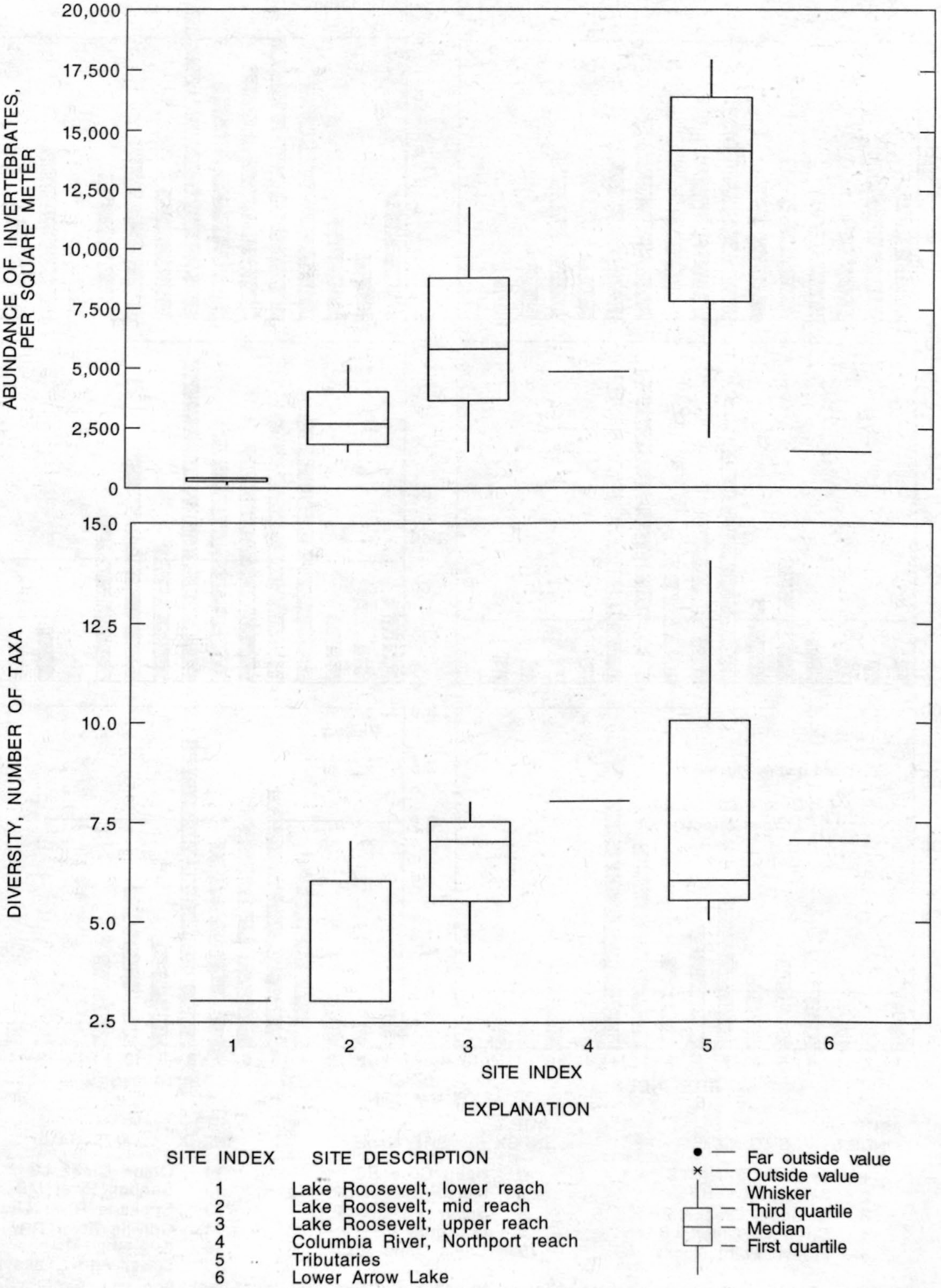
Community abundance and diversity were weakly negatively correlated with water depth (table 34), meaning that there were fewer individuals and taxa of invertebrates in deep waters than in shallow waters. Minshall (1984) had reported that deep waters commonly have fewer taxa than shallow waters. The primary reason for this is likely low habitat diversity and less available light. Shallow areas have more diverse habitat because of the combination of aquatic macrophytes and the wider range of substrate particle sizes, whereas deeper waters contain no macrophytes and have sediment of a more uniform size range. A second reason is related to food supply. This study found a positive correlation ($r = 0.71$) between abundance and total organic carbon and a negative correlation between depth and total organic carbon ($r = -0.49$). Larger total organic carbon concentrations in the shallows are due to the greater food supply.

Results from this study show that although concentrations of trace elements in bed sediments are at levels reported to produce effects on aquatic biota, physical habitat has a major influence on the composition of the communities. Additional studies would be needed to begin to identify the relative influence of the various controlling factors.



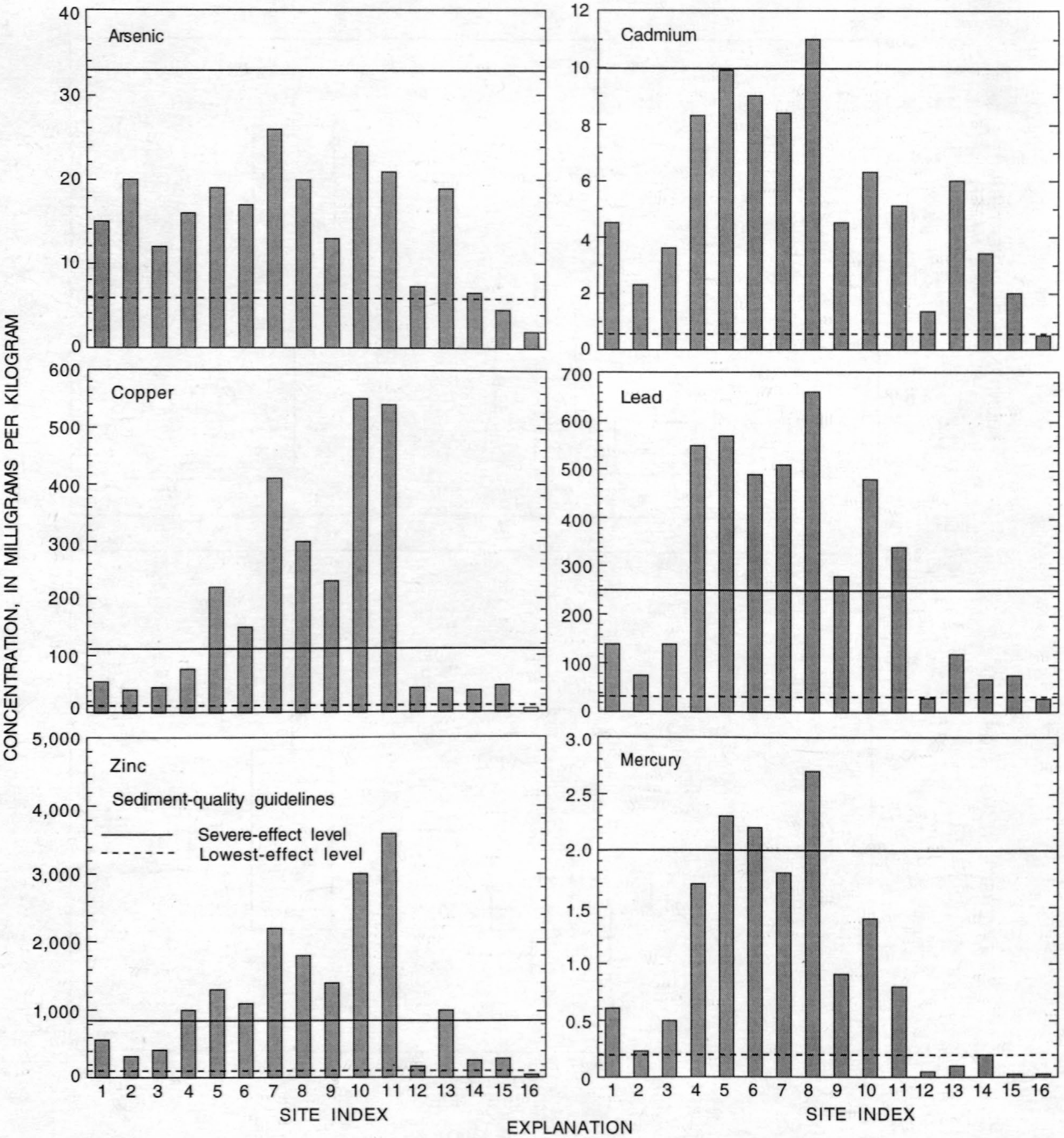
SITE INDEX	SITE DESCRIPTION
1	Lake Roosevelt, lower reach
2	Lake Roosevelt, mid reach
3	Lake Roosevelt, upper reach
4	Columbia River, Northport reach
5	Tributaries
6	Lower Arrow Lake

Figure 30.--Physical and chemical habitat characteristics of depositional sites in major tributaries, the Northport reach of the Columbia River, and Lake Roosevelt.



SITE INDEX	SITE DESCRIPTION
1	Lake Roosevelt, lower reach
2	Lake Roosevelt, mid reach
3	Lake Roosevelt, upper reach
4	Columbia River, Northport reach
5	Tributaries
6	Lower Arrow Lake

Figure 31.--Total abundance and diversity of benthic invertebrates from six depositional sites in major tributaries, the Northport reach of the Columbia River, and Lake Roosevelt.



EXPLANATION

SITE INDEX	SITE NAME	SITE INDEX	SITE NAME	SITE INDEX	SITE NAME
1	Swawilla Basin LB	6	Haag Cove RB	11	Onion Creek LB
2	Seven Bays RB	7	Marcus Island LB	12	Sanpoil River MS
3	Ninemile Creek LB	8	Summer Island RB1	13	Spokane River LB
4	Cheweka Creek LB	9	Bossborg RB	14	Colville River RB
5	French Point Rocks MS	10	China Bend RB	15	Kootenay MS
				16	Lower Arrow Lake LB1

RB, LB, and MS indicate samples were collected on right side (toward the "right bank" from mid channel), left side (toward the "left bank" from mid channel), and near the mid-section channel, respectively. Numbers 1 and 2 denote different sites toward the same bank.

Figure 32.--Concentrations of trace elements in bed sediment from depositional sites in major tributaries, the Northport reach of the Columbia River, and Lake Roosevelt and sediment-quality guidelines. Guidelines are based upon the severe-effect level on aquatic biota (Persaud and others, 1991).

Table 33.--*Benthic invertebrate communities from 18 depositional sites in the Lake Roosevelt study area*

[Data are based on 3-5 composite samples; diversity, taxa per station; Rep., replicate; LB, RB, and MS indicates samples were collected on right side (toward the "right bank" from mid channel), left side (toward the "left bank" from mid channel), and near the mid-section channel, respectively, numbers 1 and 2 denote different sites toward the same bank]

Site name (see plate 1 for complete name)	Community		Diptera		Oligochaeta		Crustacea		Mollusca		Other	
	Abundance (per square meter)	Diversity	Percent	Diversity	Percent	Diversity	Percent	Diversity	Percent	Diversity	Percent	Diversity
Tributaries												
Kootenay River MS	13,440	14	89	6	3	2	4	1	3	2	2	3
Colville River RB	14,784	5	19	2	78	1	0	0	3	1	0	1
Spokane River LB	2,048	6	69	3	25	1	3	1	3	1	0	0
Sanpoil River MS	17,920	6	54	3	45	2	0	0	1	1	0	0
Columbia River, Northport reach												
Onion Creek LB	4,800	8	35	4	56	1	0	0	9	3	0	0
Lake Roosevelt, upper reach												
China Bend RB	1,472	4	65	2	0	0	0	0	35	2	0	0
Bossborg RB	5,760	8	98	6	1	1	0	0	0	0	1	1
Summer Island RB1 (Rep. 1)	12,096	8	85	3	14	3	0	0	1	1	1	1
Summer Island RB1 (Rep. 2)	11,328	6	92	2	6	3	0	0	2	1	0	0
Lake Roosevelt, mid reach												
Marcus Island MS	1,472	7	48	5	48	1	0	0	0	0	4	1
Haag Cove RB	3,990	6	92	2	3	1	0	0	1	1	5	2
French Point Rocks MS	5,107	3	100	3	0	0	0	0	0	0	0	0
Cheweka Creek LB	2,660	3	100	3	0	0	0	0	0	0	0	0
Ninemile Creek LB	1,800	6	73	3	18	1	2	1	7	1	0	0
Lake Roosevelt, lower reach												
Seven Bays RB (Rep. 1)	384	2	67	1	33	1	0	0	0	0	0	0
Seven Bays RB (Rep. 2)	384	3	83	1	8	1	8	1	0	0	0	0
Swawilla Basin LB	96	3	67	2	33	1	0	0	0	0	0	0
Lower Arrow Lake LB1	1,472	7	91	6	9	1	0	0	0	0	0	0

Table 34.--*Pearson correlation coefficients between habitat characteristics and benthic abundance and diversity at sites in Lake Roosevelt*

[Correlations were accepted as statistically significant if P is less than 0.05; *, significant at 0.05; diversity, taxa per site; r, correlation coefficient; P, probability level, shown in parenthesis; mm, millimeters; --, not applicable]

Habitat characteristics	Percentage of bed sediment, finer than 0.062 mm		Total organic carbon, in percent		Abundances, in invertebrates per square meter		Diversity, in taxa per site	
	r	P	r	P	r	P	r	P
Water depth, in feet	0.18	(0.51)	-0.49	(0.05)	-0.54	(0.03)*	-0.59	(0.02)*
Bed sediment, percentage finer than 0.062 mm	--	--	0.31	(0.24)	0.12	(0.67)	-0.44	(0.09)
Total organic carbon, in percent	--	--	--	--	0.71	(0.002)*	0.36	(0.17)

MONITORING AND INVESTIGATIVE STUDIES

To protect the water resources of Lake Roosevelt, an integrated program to monitor trends in environmental quality and investigative studies to fill in gaps of information could provide feedback to each other. The monitoring program and the investigative studies would be flexibly reciprocal. In other words, new findings from an investigation in progress could readily effect modifications in the established monitoring program, or conversely, notable findings in the monitoring program could launch new studies.

The role of a monitoring program would be to determine whether conditions in the Columbia River-Lake Roosevelt system were changing over time. This information is critical in order to determine whether changes in land-use or discharge practices are influencing water-resource conditions. A monitoring program also can provide important data on the long-term effects of contaminants in the system. The approach in many monitoring programs is to collect data on everything in order to assess the entire ecosystem. Such an approach is very expensive and may not likely produce needed results. An approach that focuses on monitoring key indicators of environmental or human health would be more effective. If a monitoring program detects a change in a particular indicator, a more intensive study could be initiated to assess the change. A monitoring program could, for instance, include these components.

- Monitoring water and sediment chemistry at key sites could determine whether there are changes in existing constituents or appearances of new constituents in the Columbia River or Lake Roosevelt system.

- Monitoring benthic invertebrate communities at key sites in both the Columbia River and Lake Roosevelt could help detect long-term trends. Benthic invertebrate data from the present study provide baseline information on the status of these communities; future data would permit the assessment of long-term trends resulting from changes in constituent loading and therefore in water and sediment quality.

- Monitoring the concentration of trace elements and organic constituents in fillets of fish could enable assessments of potential threats to human health.

Investigative studies can complement long-term monitoring programs by filling in data gaps and thus refining a monitoring program.

- An investigative study could determine the changes in fate and distribution of trace elements, dioxins, and furans in the Lake Roosevelt system. For example, factors affecting bioaccumulation may change in time if major sources of these constituents are reduced or eliminated. Such an investigative program could analyze sediment core segments to determine the vertical distributions of trace elements, dioxins, and furans in sediment throughout the reservoir and thus provide information on the amounts of these constituents accumulated over time in the reservoir bottom. If sedimentation rates were also determined, these data would enable an estimate of the capacity of cleaner riverine and bank-eroded sediments to cap or dilute existing reservoir sediments.

- An investigative study could also focus on processes that affect the availability and bioconcentration of trace elements, dioxins, and furans in aquatic organisms. Bed sediments probably will be a primary residual source of these constituents if point-source discharges to the Columbia River are reduced or eliminated. Bed sediments can be resuspended by the drawdown and fluctuation of water levels because of reservoir operations. The study could investigate how the resuspended sediment affects the bioavailability of constituents.

SUMMARY AND CONCLUSIONS

This report presents a study that assessed the sediment quality of Franklin D. Roosevelt Lake and the upstream reach of the Columbia River downstream from the international boundary. The study also assessed the water quality of the Columbia River entering Lake Roosevelt. The study included analyses of trace elements; dioxins, furans, and other organic compounds; benthic invertebrate communities; and bed-sediment toxicity.

The U.S. Geological Survey (USGS) conducted the assessment in cooperation with the U.S. Environmental Protection Agency (USEPA). The USEPA also supported a separate but related trend-monitoring study conducted by the Washington State Department of Ecology (Ecology) to measure, over time, concentrations of dioxins and furans in suspended sediment of the Columbia River entering Lake Roosevelt and in fish fillets from Lake Roosevelt. USGS and Ecology personnel worked jointly to obtain samples and share data collected on the Columbia River at Northport, Wash. The timing of the USGS and Ecology studies also corresponded to the Columbia River Integrated Environmental Monitoring Program (CRIEMP) study of the lower Columbia River in British Columbia by Canadian investigators.

The study area included Lake Roosevelt and the Columbia River upstream from Lake Roosevelt to the international boundary. The Columbia River from the international boundary to about 15 miles downstream from the boundary was designated as the Northport reach, and Lake Roosevelt was divided into upper, mid, and lower reaches. The upper reach of the reservoir is a relatively narrow channel about 22 miles long. The mid reach, about 70 miles long, begins where the reservoir changes to a wide channel above the city of Kettle Falls and extends to the Spokane River confluence. The lower reach, about 43 miles long, is the deepest part of the reservoir and extends from the Spokane River confluence to Grand Coulee Dam.

Relative to trace-element concentrations in reference sites, elevated concentrations of total arsenic, cadmium, copper, lead, mercury, and zinc were found in the bed sediments of Lake Roosevelt and the Northport reach of the Columbia River. Trace-element concentrations in these bed sediments were larger than concentrations in the reference sites, which included river bed sediments upstream of a smelter at Trail, British Columbia, local soils, and bed sediments of the Columbia River downstream of Grand Coulee Dam. Moreover, they were larger than median concentrations of trace elements in bed sediments of other rivers and lakes nationwide. In the Columbia River and Lake Roosevelt, copper, lead, and zinc exceeded sediment-quality guidelines developed by the Ontario Ministry of Environment and Energy by 100 percent or more at 18 of 41 sites. Most sites exceeding the guidelines were clustered in the Columbia River and the upper reach of Lake Roosevelt. Sediment-quality guidelines are the trace-element concentrations above which pronounced disturbances to sediment-dwelling organisms are expected to occur.

Total copper and zinc concentrations in bed sediments were elevated in the Northport reach of the Columbia River and then declined with downstream distance in Lake Roosevelt. The median concentrations of copper and zinc in the Northport reach were elevated by factors of six to nine, compared to the upper reach of Lake Roosevelt. For example, median copper and zinc concentrations were 2,600 and 13,000 milligrams per kilogram (mg/kg) in the Northport reach of the Columbia River and 300 and

2,000 mg/kg in the upper reach of Lake Roosevelt. Several other trace elements, including antimony, arsenic, barium, chromium, copper, iron, manganese, and zinc, followed the same general pattern of larger concentrations near the international boundary (river mile 745) that declined rapidly to smaller concentrations down reservoir to French Point Rocks (river mile 691). Further down reservoir, beyond French Point Rocks, the concentrations of these eight elements were fairly uniform.

Elevated copper and zinc concentrations were associated with sandy sediment found in the Northport reach of the Columbia River and upper Lake Roosevelt. The elevated concentrations in bed sediments can be explained by the presence of slag particles that contained concentrations of these trace elements as large as 6,000 and 25,000 mg/kg, respectively. The slag particles, consisting of dark glassy needles and angular grains, were progressively finer at sites downstream. Thus, slag particles carried by the Columbia River and deposited in Lake Roosevelt are a source of copper and zinc enrichment to bed sediments.

Concentrations of total cadmium, lead, and mercury in bed sediment display a different pattern of spatial variability: elevated concentrations of cadmium, lead, and mercury were found in bed sediment downstream of the Northport reach of the Columbia River rather than within the Northport reach. Thus, cadmium, lead, and mercury are probably associated with finer particles rather than primarily with slag deposits found in the Northport reach. Elevated total cadmium concentrations were found throughout the reservoir; the median concentrations in the upper, mid, and lower reach of the reservoir were 6.3, 7.0, and 4.7 mg/kg, respectively. The median concentrations of total lead and mercury in bed sediments of the upper, mid, and lower reaches of the reservoir were 430, 380, and 190 mg/kg for lead and 1.4, 1.4, and 0.5 mg/kg for mercury, respectively.

The trace elements cadmium, lead, and mercury may be associated with nonslag effluent discharged to the Columbia River as part of the smelter operations. Most notable of these trace elements is mercury; because mercury concentrations in slag tend to be small, the effluent is probably the primary source of mercury in the reservoir bed sediment. Large concentrations of cadmium, lead, and mercury in suspended sediments in the Northport reach of the Columbia River entering Lake Roosevelt are evidence that suspended sediments are a source of enriched concentrations of these trace elements in the bed sediments of Lake Roosevelt.

The major and minor tributaries to the reservoir are also sources of riverine sediment containing trace elements. Total concentrations of arsenic, cadmium, copper, lead, mercury, and zinc in bed sediment of the Colville, Kettle, and Sanpoil Rivers were considerably smaller than those in Lake Roosevelt sediment. Elevated zinc concentrations in the Spokane River are a potential source of zinc to the lower reach of the reservoir. The Pend D'Oreille and Kootenay Rivers contained elevated trace elements in bed sediments that may enter the Columbia River as suspended sediment. The banks along Lake Roosevelt are also a source of sediment to the reservoir because of the active sliding and slumping of sediments, but even though bank sediments may be a natural source of arsenic, they are probably not a significant source for enriched concentrations of other trace elements. Overall, the evidence indicates that sediment carried by the Columbia River is the primary source of the widespread trace-element-enriched bed sediment of Lake Roosevelt and the Northport reach of the Columbia River.

In whole water (water and suspended-sediment phases), the concentrations of trace elements sampled from the Columbia River at Northport were below the maximum and continuous criteria established by the USEPA for fresh-water organisms. In whole-water samples, the concentrations of trace elements were relatively small, reflecting the small suspended-sediment concentrations and the large water-diluting capacity of the Columbia River.

The total discharge of a trace element is equal to the rate of flow in the river multiplied by the concentration of the trace element in the water and suspended phases. The total discharge of trace elements measured during a 10-hour period at low flow was found to be dominated by transport in the water phases as opposed to the suspended-sediment phase. This distribution of trace-elements discharge between suspended sediment and water was in contrast to many large rivers of the world where the majority of trace-element transport is associated with the suspended-sediment transport during infrequent periods of high discharge. The small discharge of trace elements in the suspended-sediment phase of the Columbia River at Northport is attributable to the small concentrations of suspended sediment, which are in turn attributable to the many large dams and reservoirs located upstream of this location. These reservoirs reduce the magnitude of high and low flows and also trap and retain suspended sediment, thereby reducing the suspended-sediment concentration in the river at Northport. Even at high discharges, above the 95th percentile (175,000 to 217,000 cubic feet per second), when suspended-sediment concentrations are expected to be largest, the concentrations in the Columbia River at Northport ranged from 2 to 19 milligrams per liter, with a median of 13 milligrams per liter. These concentrations are small for a major river with this magnitude of discharge. Because the variability in sediment and water discharge of the Columbia River at Northport has been substantially reduced by upstream dams, periods of major transport of contaminant associated with suspended sediment that normally occur during periods of high flow may not occur at this site. Even though the fraction of trace-element discharge is larger for the water phase than for the suspended-sediment phase, the suspended sediments cause elevated levels of trace elements in bed sediments of Lake Roosevelt when the trace-element-enriched particles settle from the water column to the lake bottom.

Most dioxins and furans in the sediments of Lake Roosevelt originate primarily from pulp-mill effluent discharged to the Columbia River, although atmospheric deposition may contribute some portion. From the beginning of operations of the pulp-mill plant near Castlegar, British Columbia, in 1961 until plant modernization in 1991 and 1992, the plant has used the chlorine bleach process, which produces dioxins and furans. Tetrachlorinated dioxins (TCDD's), including 2,3,7,8-tetrachlorodibenzo-*p*-dioxin (2,3,7,8-TCDD), the isomer most toxic to some laboratory animals, were not detected in water or suspended sediment. For the samples of this study, the smallest quantifiable concentrations (the minimum detection levels, which vary with the sample) for 2,3,7,8-TCDD ranged from 1.5 to 3.7 picograms per gram (pg/g) in suspended sediment and from 0.01 to 0.02 picograms per liter (pg/L) in water. Hepta- and octachlorinated dioxin congeners (HpCDD and OCDD) were found in both suspended sediment and water. Concentrations of the higher chlorinated dioxin congeners varied among suspended-sediment samples as follows: from 57 to 380 pg/g for total HpCDD, from 25 to 210 pg/g for 1,2,3,4,6,7,8-HpCDD, and from 180 to 1,300 pg/g for OCDD.

In contrast to the tetrachlorinated dioxins, tetrachlorinated furans (TCDF's) were detected in water and suspended sediment. Concentrations of total TCDF's ranged from 24 to 49 pg/g in suspended sediment and from 0.05 to 1.6 pg/L in water. Concentrations of 2,3,7,8-TCDF were detected in suspended sediment; the average concentration of replicate sample was 6.1 pg/g. The higher chlorinated congeners, HpCDF and OCDF, were detected only in suspended sediment but not in water.

Concentrations of 2,3,7,8-TCDF in suspended sediment in 1992 were substantially smaller than the concentrations in suspended sediment observed by Ecology in 1990. As recently as 1990, pulp-mill effluent contained 2,3,7,8-TCDF concentrations that averaged about 660 pg/L. During 1992, however, the average concentration of 2,3,7,8-TCDF in plant effluent decreased to about 13 pg/L. The decline in the effluent discharge of TCDF could explain the decrease in 2,3,7,8-TCDF concentrations found in suspended sediment. Other variables such as plant operations and sample collection procedures could also cause changes in observed concentrations. Collections of representative samples over time will be needed to establish trends.

The overall toxicity of the mixture of dioxins and furans in the suspended-sediment samples can be compared to the toxicity of other samples by toxicity equivalent concentrations (TEC's). The TEC's of the suspended-sediment samples ranged from 0.37 to 4.9 pg/g in 1992. These sample TEC's of the 1992 suspended-sediment samples were much smaller than the TEC of 11 obtained by Ecology in 1990. The smaller TEC in the 1992 sample resulted from an order of magnitude decline in the concentration of 2,3,7,8-TCDF, which makes up a significant part of the TEC calculation.

Two isomers (HpCDD and OCDD) were detected in both the suspended-sediment and water phases of the river flow. Calculation of the discharge of these isomers in both phases showed that the discharge in the water phase ranged from 32 to 84 percent of the total discharge. River-flow conditions during the sampling period indicated that 60 percent of a theoretical 2,3,7,8-TCDD discharge would be in the water phase and that flow conditions in the Columbia River at Northport generally are such that the bulk of the 2,3,7,8-TCDD discharge is transported in the water phase. However, the dioxin isomer 2,3,7,8-TCDD was not detected in any of the suspended- sediment or water samples. Consequently, the discharge of 2,3,7,8-TCDD could not be measured for comparison with the total maximum daily load (discharge) of 2.3 milligrams per day (mg/d) established by the USEPA for the Columbia River at the international boundary. Detection limits were generally not low enough to assure that the total maximum daily load established by the USEPA was not exceeded during the sampling period.

Targeted chlorinated phenols and several classes of wood-pulp-related compounds were not detected in reconnaissance sampling of bed-sediment sites 37 miles and 52 miles downstream from the international boundary. However, a few targeted chlorinated guaiacols and catechols were found in the bed sediment of Lake Roosevelt at small concentrations that ranged from 2.2 to 6.2 micrograms per kilogram (µg/kg). Methylene-chloride extractable compounds, which mostly originate from urban and industrial sources, were not found in concentrations above the minimum reporting level in bed sediment of Lake Roosevelt and its major tributaries. A few methylene-chloride extractable compounds were detected but at concentrations that were not quantified because they were less than the minimum reporting level for the analytical procedure used. Of 54 methylene-chloride extractable compounds analyzed, 15 compounds were detected at non-quantifiable concentrations, usually below 50 µg/kg. The concentrations of these compounds detected in Lake Roosevelt sediment were several orders of magnitude smaller than interim criteria developed by the USEPA.

Toxicity tests used three test organisms to determine the spatial extent of bed-sediment toxicity in the Columbia River and Lake Roosevelt. The lowest survival rates of the first organism, *Hyalella azteca* (an amphipod), which ranged from 10 to 57 percent, resulted from its exposure to sediment from three sites in the Northport reach of the Columbia River. The sediments causing the low survival rates of *H. azteca* contained slag with greatly elevated concentrations of copper and zinc. The survival rates of *H. azteca* exposed to sediment from the mid and lower reaches of Lake Roosevelt were relatively high and were not significantly different from rates involving control samples or reference sediment.

Survival rates for the second organism, *Ceriodaphnia dubia* (a water flea), exposed to bed sediment from the Northport reach of the Columbia River were also low. In a toxicity text, *C. dubia* showed complete mortality (zero percent survival) from exposure to sediment from one site near the international boundary and a low survival rate of 40 percent from exposure to sediment from another site 2 mi downstream from the international boundary. When exposed to sediment from these same sites, *C. dubia* also showed decreased reproductive success. In tests with sediment from the upper and mid reaches of Lake Roosevelt, the survival and reproduction rates of *C. dubia* were high and not significantly different from rates involving control samples or reference sediments. In the lower reach of the reservoir, even through the survival rates of *C. dubia* were high, ranging from 80 to 100 percent, *C. dubia* reproduction rates were low at two of three sites.

Toxicity tests involving the third organism, *Photobacterium phosphoreum* (Microtox®), were conducted with whole sediment from 42 sites. *P. phosphoreum* bacteria showed elevated toxicity responses when exposed to mostly sandy sediment from three sites in the Northport reach of the Columbia River. These sites contained slightly more fine-grained sediment (silts and clays) than do the nearly all-sandy upstream sites near the international boundary. Thus, constituents associated with silts and clays may be causing the elevated toxicity response at these lower sites in the Northport reach of the Columbia River. In Lake Roosevelt, *P. phosphoreum* showed mostly moderate to high toxicity responses to sediment. Most of the *P. phosphoreum* bioassays exposing bacterium to sediment pore water showed low or no toxicity, possibly indicating that any toxic constituents were tightly bound to sediment. Pore-water toxicity was variable within the reservoir.

A comparison between sediment toxicity tests indicated that sediment of the Columbia River entering Lake Roosevelt was toxic to all three test organisms. The survival or reproduction of at least one, and in some cases all three, of the organisms tested was adversely affected in the Northport reach of the Columbia River from the international boundary to 15 miles downstream from the boundary. *C dubia* and *H. azteca* were most affected close to the international boundary, and *P. phosphoreum* was affected farther down river in the Northport reach.

Benthic invertebrate communities in the erosional habitats of the Northport reach of the Columbia River resembled those often associated with contaminated or habitat-degraded areas. Benthic invertebrate communities were relatively low in abundances and diversity. Although it is not possible to state definitively the degree to which elevated trace-element concentrations have influenced the present structure of the benthic community, results from the benthic invertebrate, sediment chemistry, and sediment toxicity parts of this study indicate that concentrations of trace elements may have affected the benthic community. The presence of slag in the erosional habitats of the Northport reach of the Columbia River may also be a factor because slag has filled in interstitial spaces, thereby reducing available habitat.

Benthic invertebrate communities were more difficult to assess in depositional habitats of tributaries, the Northport reach of the Columbia River, and Lake Roosevelt because of the naturally low diversity found in depositional habitats. This study showed benthic diversity to be low at all reservoir sites, with the communities dominated by chironomids and oligochaetes. Results indicated that the abundance of oligochaetes (worms) was lower in areas where the concentrations of lead in bed sediment were large; no relation was found between benthic invertebrate community measures and other trace elements.

However, the concentrations of trace elements at most of the depositional sites in Lake Roosevelt exceeded concentrations reported to have detrimental effects on benthic organisms.

A monitoring program could track long-term changes in water, sediment, and aquatic organisms in the Columbia River and Lake Roosevelt. Investigative studies can complement long-term monitoring programs and could define further the fate and distribution of trace elements, dioxins, and furans and also provide optimum monitoring procedures.

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Table 35.--*Total arsenic, cadmium, copper, lead, mercury, and zinc concentrations in bed sediment*

[LB, RB, and MS indicate samples were collected on right side (toward the "right bank" from mid channel), left side (toward the "left bank" from mid channel, and near the mid-section channel, respectively, numbers 1 and 2 denote different sites toward the same bank; sediment wet-sieved to less than 2 millimeters; concentrations based on dry weight; --, no data; <, less than]

Site number	Site name[1]	Date	Time	Concentration, in milligrams per kilogram					
				Arsenic	Cadmium	Copper	Lead	Mercury	Zinc
	Columbia River and major tributaries								
3	Keenleyside Dam LB	10-10-92	1200	<2.0	<0.5	9.0	17	<0.05	47
4	Kootenay River MS	10-10-92	1430	4.6	2.0	48	76	<0.05	290
5	Kootenay River LB	10-10-92	1600	<7.0	0.5	20	27	<0.05	120
6	Pend D'Oreille River LB	10-09-92	1500	13	8.7	18	220	0.1	1,600
7	Boundary RB	10-05-92	1300	52	1.2	3,300	480	0.8	17,000
8	Boundary LB	10-05-92	1445	34	1.0	2,700	280	0.2	13,000
9	Auxiliary Gage RB	10-05-92	1640	43	1.1	2,600	270	0.2	13,000
10	Auxiliary Gage LB	10-05-92	1505	35	1.1	3,000	310	0.3	16,000
11	Goodeve Creek RB	10-03-92	1230	32	0.9	2,900	310	0.1	17,000
12	Goodeve Creek LB	10-03-92	1430	22	5.7	670	370	0.9	3,200
14	Fivemile Creek LB	10-06-92	1215	4.5	1.2	45	72	0.1	330
15	Onion Creek LB	10-06-92	1315	21	5.1	540	340	0.8	3,600
16	Onion Creek RB	10-06-92	1515	19	3.8	800	300	0.6	4,600
25	Kettle River RB1	10-08-92	1300	<4.0	0.5	23	20	<0.05	70
26	Kettle River RB2	10-08-92	1415	<2.0	<0.5	28	17	<0.05	44
27	Kettle River LB	10-08-92	1520	2.4	<0.5	10	20	<0.05	40
29	Colville River MS	10-08-92	1130	3.6	0.7	21	28	0.06	110
30	Colville River RB	10-08-92	1230	6.6	3.4	39	68	0.2	260
31	Colville River LB	10-08-92	1300	6.0	3.3	41	74	0.3	260
52	Spokane River MS	10-13-92	1630	30	11	49	150	0.1	1,800
53	Spokane River LB	10-13-92	1800	19	6.0	42	120	0.1	1,000
54	Spokane River RB	10-13-92	1850	15	4.9	40	80	0.06	980
62	Sanpoil River MS	10-15-92	1240	7.3	1.4	36	23	0.06	160
63	Sanpoil River LB	10-15-92	1355	6.3	0.9	24	21	<0.05	110
64	Sanpoil River RB	10-15-92	1420	7.3	0.8	43	29	0.05	170
72	Rufus Woods Lake LB	10-16-92	1450	6.1	0.7	16	28	<0.05	130
	Reservoir								
1	Lower Arrow Lake LB1	10-10-92	0900	2.0	0.5	7.0	28	<0.05	49
2	Lower Arrow Lake LB2	10-10-92	1030	1.5	0.5	7.0	32	<0.05	60
17	China Bend RB	10-07-92	1010	24	6.3	550	480	1.4	3,000
18	China Bend MS	10-07-92	1200	33	0.6	3,000	430	<0.05	22,000
19	Bossborg RB	10-07-92	1250	13	4.5	230	280	0.9	1,400
20	Summer Island RB1	10-07-92	1440	20	11	300	660	2.7	1,800
21	Summer Island RB2	10-07-92	1630	15	8.2	170	420	1.4	2,000
22	Marcus Island MS	10-08-92	1500	14	5.5	170	310	1.2	1,000
23	Marcus Island RB	10-08-92	1625	8.5	3.3	96	150	0.6	420
24	Marcus Island LB	10-08-92	1645	26	8.4	410	510	1.8	2,200
28	West Kettle Falls LB	10-09-92	1145	17	8.0	290	440	1.4	1,700
35	Haag Cove RB	10-09-92	1235	17	9.0	150	490	2.2	1,100
36	Haag Cove MS	10-09-92	1220	16	7.2	260	400	1.5	1,800
37	French Point Rocks RB	10-09-92	1615	9.3	7.8	99	390	1.7	930
38	French Point Rocks MS	10-09-92	1540	19	9.9	220	570	2.3	1,300
39	French Point Rocks LB	10-09-92	1710	10	4.2	57	230	0.8	470
40	Cheweka Creek LB	10-10-92	1015	16	8.3	77	550	1.7	1,000

Table 35.--*Total arsenic, cadmium, copper, lead, mercury, and zinc concentrations in bed sediment--Continued*

Site number	Site name[1]	Date	Time	Concentration, in milligrams per kilogram					
				Arsenic	Cadmium	Copper	Lead	Mercury	Zinc
	<u>Reservior--Continued</u>								
41	Gifford MS	10-10-92	1200	14	9.7	110	470	2.8	1,000
42	Gifford LB	10-10-92	1210	19	8.4	110	480	2.5	940
43	Gifford RB	10-10-92	1240	8.6	2.0	40	94	0.4	220
46	Hunters LB	10-10-92	1645	13	6.7	87	380	1.5	760
47	Ninemile Creek MS	10-12-92	1410	14	5.6	82	270	1.2	590
48	Ninemile Creek LB	10-12-92	1540	12	3.6	45	140	0.5	410
49	Ninemile Creek RB	10-12-92	1500	22	1.5	42	57	0.2	180
51	Fort Spokane RB	10-12-92	1710	21	6.0	79	240	1.1	550
56	Seven Bays MS	10-13-92	1200	13	2.6	35	78	0.2	320
57	Seven Bays RB	10-13-92	1330	20	2.3	40	75	0.2	320
58	Seven Bays LB	10-13-92	1405	17	10	69	320	1.4	1,100
61	Whitestone Creek MS	10-14-92	1345	16	9.8	76	290	1.4	1,000
66	Keller Ferry RB	10-15-92	1130	15	3.9	52	200	0.5	570
68	Swawilla Basin RB	10-16-92	1130	14	4.7	41	130	0.5	560
69	Swawilla Basin LB	10-16-92	1340	15	4.5	55	140	0.6	560
70	Swawilla Basin MS	10-16-92	1420	21	9.9	73	310	1.6	1,100
71	Grand Coulee Dam RB	10-16-92	1645	18	6.2	61	190	0.8	730
	<u>Minor tributaries</u>								
33	Sherman Creek MS	10-08-92	1630	1.4	1.8	9.0	49	0.1	140
44	Hall Creek LB	10-10-92	1430	8.0	1.2	30	50	0.1	150
45	Hall Creek MS	10-10-92	1450	5.5	1.3	30	28	0.07	140
55	Hawk Creek RB	10-13-92	0930	20	1.0	29	35	<0.05	170
	<u>Beach</u>								
13	Big Sheep Creek RB[2]	10-06-92	1100	11	2.5	--	180	0.3	1,600
32	Colville River LB	10-08-92	1730	3.2	<0.5	9.0	23	<0.05	75
34	Bradbury LB	10-08-92	1730	3.2	<0.5	9.0	23	<0.05	75
67	Keller Ferry LB	10-15-92	1800	9.1	<0.5	11	15	<0.05	61
	<u>Bank</u>								
50	Ninemile Creek RB	10-13-92	1200	22	<0.5	--	26	<0.05	140
59	Seven Bays LB1	10-13-92	1200	18	<0.5	--	21	<0.05	93
60	Seven Bays LB2	10-13-92	1300	20	<0.5	--	21	<0.05	88
65	Sanpoil River RB	10-15-92	1200	16	<0.5	--	28	<0.05	200
	<u>Procedure blanks</u>								
	Brazilian quartz	--	--	<4	0.4	--	0.4	<0.05	--
	Acid	--	--	--	<.5	0.0	0.2	<0.05	0.0

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[1] See plate for complete name.

[2] Delta deposits.

Table 36.--*Types of benthic invertebrates collected at erosional sites in the Lake Roosevelt study area*

[LB, RB, and MS indicate samples were collected on right side (toward the "right bank" from mid channel), left side (toward the "left bank" from mid channel), and near the mid-section channel, respectively, numbers 1 and 2 denote different sites toward the same bank; sp., species; sp. grp., species group]

	Number of individuals per square meter collected at erosional site[1]							
	Boundary RB[2] (replicate 1)	Boundary RB[2] (replicate 2)	Boundary RB[2] (replicate 3)	Boundary RB[2] (replicate 4)	Boundary RB[2] (replicate 5)	Goodeve Creek RB[2] (replicate 1)	Goodeve Creek RB[2] (replicate 2)	Goodeve Creek RB[2] (replicate 3)
Taxa								
Annelida								
Nematoda								
Unidentifiable nematode	10	0	0	0	10	0	0	0
Gastropoda								
Fossaria sp.	10	0	0	0	0	0	0	0
Gyraulus sp.	0	0	0	20	0	0	0	0
Insecta								
Coleoptera								
Zaitzevia parvula	0	20	0	0	0	0	0	0
Diptera								
Cricotopus tremulus	0	0	10	10	0	0	0	0
Cricotopus sylvestris	0	40	0	0	0	0	0	0
Cricotopus trifasciata	0	0	40	0	0	160	0	0
Einfeldia sp.	0	0	0	0	0	0	0	0
Eukiefferiella sp.	0	0	0	0	0	0	0	0
Orthocladius sp.	0	0	0	10	0	0	0	0
Synorthocladius sp.	0	0	10	10	10	0	0	0
Thienemannimyia sp. grp.	0	0	10	0	0	0	0	0
Chironomidae pupa	0	0	0	0	0	80	40	0
Unidentifable chironomid	0	20	0	0	0	0	0	0
Ephemeroptera								
Baetis tricaudatus	0	40	0	0	0	0	0	0
Baetidae sp.	0	0	0	0	0	0	0	0
Plecoptera								
Sweltsa sp.	0	20	0	0	0	0	0	0
Trichoptera								
Hydropsyche sp.	0	0	0	0	0	0	0	0
Micrasema sp.	0	20	10	0	0	0	0	0
Psychomyia sp.	0	0	10	0	0	0	0	0

Table 36.--*Types of benthic invertebrates collected at erosional sites in the Lake Roosevelt study area--Continued*

	Number of individuals per square meter collected at erosional site[1]						
	Goodeve Creek RB[2] (replicate 4)	Goodeve Creek RB[2] (replicate 5)	Auxiliary Gage LB[2] (replicate 1)	Auxiliary Gage LB[2] (replicate 2)	Auxiliary Gage LB[2] (replicate 3)	Auxiliary Gage LB[2] (replicate 4)	Auxiliary Gage LB[2] (replicate 5)
Taxa							
Annelida							
Nematoda							
Unidentifiable nematode	0	0	0	0	0	0	0
Gastropoda							
Fossaria sp.	0	0	0	0	0	0	0
Gryaulus sp.	0	0	0	0	0	0	0
Insecta							
Coleoptera							
Zaitzevia parvula	0	0	0	0	0	0	0
Diptera							
Cricotopus tremulus	0	0	0	0	0	10	0
Cricotopus sylvestris	0	0	0	0	0	0	0
Cricotopus trifasciata	240	40	0	120	160	60	50
Einfeldia sp.	0	0	0	40	0	0	0
Eukiefferiella sp.	0	0	0	0	0	0	10
Orthocladius sp.	0	0	0	0	0	0	10
Synorthocladius sp.	0	40	0	0	120	0	10
Thienemannimyia sp. grp.	0	0	20	0	40	0	40
Chironomidae pupa	40	0	0	0	0	10	0
Unidentifable chironomid	0	0	0	0	0	0	0
Ephemeroptera							
Baetis tricaudatus	0	0	0	0	0	20	10
Baetidae sp.	0	0	0	0	0	0	0
Plecoptera							
Sweltsa sp.	0	0	0	0	0	0	0
Trichoptera							
Hydropsyche sp.	40	0	0	0	0	0	0
Micrasema sp.	0	0	0	0	0	0	0
Psychomyia sp.	0	0	0	0	0	0	0

[1] Collected with a 0.1 square-meter Hess sampler.

[2] See plate 1 for complete name.

Table 37.--*Benthic invertebrate data collected at depositional sites in the Lake Roosevelt study area*

[LB, RB, and MS indicate samples were collected on right side (toward the "right bank" from mid channel), left side (toward the "left bank" from mid channel), and near the mid-section channel, respectively, numbers 1 and 2 denote different sites toward the same bank; sp., species; sp. grp., species group; Un. Imm., unidentified immature]

	Number of individuals per square meter collected at depositional site								
	Kootenay MS[1,2]	Colville River RB[1,2]	Spokane River LB[1,2]	Sanpoil River MS[1,2]	Onion Creek LB[1,2]	China Bend RB[1,2]	Bossborg RB[1,2]	Summer Island RB1[1,2] (replicate 1)	Summer Island RB1[1,2] (replicate 2)
Number of samples composited	5	5	5	5	5	5	5	5	5
Taxa									
Insecta									
Ephemeroptera									
Baetidae sp.	64	0	0	0	0	0	0	0	0
Trichoptera									
Mystacides sp.	64	0	0	0	0	0	64	0	0
Oecetis sp.	192	0	0	0	0	0	0	0	0
Psychomyia sp.	0	0	0	0	0	0	0	64	0
Diptera									
Brilla sp.	0	0	0	0	0	0	0	0	0
Cricotopus tremulus	0	0	64	0	0	0	0	0	0
Cricotopus trifasciata	0	0	0	0	0	0	256	0	0
Culicoides sp.	128	0	0	128	64	0	192	0	0
Einfeldia sp.	3,840	1,152	128	640	480	192	256	4,480	5,120
Eukiefferiella sp.	0	0	0	0	0	0	0	0	0
Polypedilum sp.	0	0	0	0	0	0	1,280	0	0
Rheotanytarsus sp.	1,280	0	0	0	0	0	256	0	0
Stictochironomus sp.	640	0	0	0	0	0	0	0	0
Synorthocladius sp.	0	0	0	0	0	0	0	0	0
Thienemannimyia sp. grp.	1,280	1,664	1,152	8,960	640	640	3,264	5,120	5,120
Tribelos sp.	4,480	0	0	0	80	0	0	640	0
Chironomidae pupa	0	0	64	0	64	0	128	64	128
Unidentifiable chironomid	0	0	0	0	336	128	0	0	0
Annelida									
Oligochaeta									
Aulodrilus pluriseta	0	0	0	0	0	0	0	512	64
Potomothrix vejdovskyi	0	0	0	1,600	0	0	0	688	64
Rhyacodrilus coccineus	0	1,920	0	3,200	1,024	0	0	64	192
Rhynchelmis sp.	128	0	0	0	0	0	0	0	0
Telmatodrilus vejdovskyi	64	0	0	0	0	0	0	0	0
Un. Imm. Tubificidae with capiliform chaetae	0	0	0	0	896	0	0	336	320
Un. Imm. Tubificidae without capiliform chaetae	256	9,600	512	3,200	768	0	64	64	64

Table 37.--*Benthic invertebrate data collected at depositional sites in the Lake Roosevelt study area--Continued*

Taxa	Number of individuals per square meter collected at depositional site								
	Kootenay MS^{1,2}	Colville River RB^{1,2}	Spokane River LB^{1,2}	Sanpoil River MS^{1,2}	Onion Creek LB^{1,2}	China Bend RB^{1,2}	Bossborg RB^{1,2}	Summer Island RB1^{1,2} (replicate 1)	Summer Island RB1^{1,2} (replicate 2)
Hirundinea									
Erpobdella punctata punctata	0	64	0	0	0	0	0	0	0
Nematoda									
Unidentifiable nematod	0	0	0	0	0	0	0	0	0
Crustacea									
Amphipoda									
Hyalella azteca	576	0	0	0	0	0	0	0	0
Isopoda									
Caecidotea sp.	0	0	64	0	0	0	0	0	0
Hydracarina									
Limnesia sp.	0	0	0	0	0	0	0	0	0
Gastropoda									
Fossaria sp.	0	0	0	0	0	0	0	0	0
Gryaulus sp.	64	0	0	0	64	0	0	0	0
Valvata sp.	0	0	0	0	0	64	0	0	0
Pelecypoda									
Corbicula fluminea	0	0	0	0	64	0	0	0	0
Sphaeriidae sp.	384	384	64	192	320	448	0	64	256

Table 37.--*Benthic invertebrate data collected at depositional sites in the Lake Roosevelt study area--Continued*

	Number of individuals per square meter collected at depositional site								
	Marcus Island LB[1,2]	Haag Cove RB[1,3]	French Point Rocks MS[1,3]	Cheweka Creek LB[1,3]	Nine Mile Creek LB[1,3]	Seven Bays RB[1,2] (replicate 1)	Seven Bays RB[1,2] (replicate 2)	Swawilla Basin LB[1,2]	Lower Arrow Lake LB1[1,2]
Number of samples composited	6	3	3	3	4	5	5	5	5
Taxa									
Insecta									
Ephemeroptera									
Baetidae sp.	0	0	0	0	0	0	0	0	0
Trichoptera									
Mystacides sp.	0	53	0	0	0	0	0	0	0
Oecetis sp.	64	0	0	0	0	0	0	0	0
Psychomyia sp.	0	0	0	0	0	0	0	0	0
Diptera									
Brilla sp.	0	0	0	0	0	0	0	0	128
Cricotopus tremulus	0	0	0	0	0	0	0	32	0
Cricotopus trifasciata	256	0	0	0	0	0	0	0	512
Culicoides sp.	0	0	0	0	0	0	0	0	0
Einfeldia sp.	32	479	4,043	213	230	0	0	0	192
Eukiefferiella sp.	0	0	0	0	0	0	0	0	0
Polypedilum sp.	0	0	213	0	0	0	0	32	64
Rheotanytarsus sp.	0	0	0	0	120	0	0	0	64
Stictochironomus sp.	32	0	0	0	0	0	0	0	0
Synorthocladius sp.	32	0	0	0	0	0	0	0	0
Thienemannimyia sp. grp.	224	3,032	851	2341	930	256	320	0	320
Tribelos sp.	0	0	0	106	0	0	0	0	0
Chironomidae pupa	128	106	0	0	40	0	0	0	64
Unidentifiable chironomid	0	0	0	0	0	0	0	0	0
Annelida									
Oligochaeta									
Aulodrilus pluriseta	0	0	0	0	0	0	0	0	0
Potomothrix vejdovskyi	0	0	0	0	0	0	0	0	0
Rhyacodrilus coccineus	224	53	0	0	200	0	32	0	0
Rhynchelmis sp.	0	0	0	0	0	0	0	0	0
Telmatodrilus vejdovskyi	0	0	0	0	0	0	0	0	0
Un. Imm. Tubificidae with capiliform chaetae	192	0	0	0	0	0	0	0	0
Un. Imm. Tubificidae without capiliform chaetae	288	53	0	0	120	128	0	32	128

Table 37.--*Benthic invertebrate data collected at depositional sites in the Lake Roosevelt study area--Continued*

	Number of individuals per square meter collected at depositional site								
	Marcus Island LB[1,2]	Haag Cove RB[1,3]	French Point Rocks MS[1,3]	Cheweka Creek LB[1,3]	Nine Mile Creek LB[1,3]	Seven Bays RB[1,2] (replicate 1)	Seven Bays RB[1,2] (replicate 2)	Swawilla Basin LB[1,2]	Lower Arrow Lake LB1[1,2]
Taxa									
Hirundinea									
Erpobdella punctata punctata	0	0	0	0	0	0	0	0	0
Nematoda									
Unidentifiable nematode	0	0	0	0	0	0	0	0	0
Crustacea									
Amphipoda									
Hyalella azteca	0	0	0	0	0	0	0	0	0
Isopoda									
Caecidotea sp.	0	0	0	0	40	0	32	0	0
Hydracarina									
Limnesia sp.	0	160	0	0	0	0	0	0	0
Gastropoda									
Fossaria sp.	0	0	0	0	0	0	0	0	0
Gryaulus sp.	0	0	0	0	0	0	0	0	0
Valvata sp.	0	0	0	0	0	0	0	0	0
Pelecypoda									
Corbicula fluminea	0	53	0	0	0	0	0	0	0
Sphaeriidae sp.	0	0	0	0	120	0	0	0	0

[1] See plate 1 for complete name.

[2] Collected with a 0.5 square-meter Ponar sampler.

[3] Collected with a 0.1 square-meter van Veen sampler.

APPENDIX A.--DATA STORAGE AND FIELD CLEANING PROCEDURES

Data storage.--Site files have been established for each site where sediment and water were collected. These files, as well as the resulting trace element and methylene chloride extractable compounds data, have been stored in NWIS (National Water Information System). These data are automatically stored in the U.S. Environmental Protection Agency's data base STORET (Storage and Retrieval System). Data can be retrieved by using the site identification numbers shown on plate 1.

Field Cleaning Procedures.--Sample collection and processing procedures were designed to eliminate or minimize contamination. To the extent possible, Teflon and glass were the materials of choice for sample handling. In addition, care was taken to clean all equipment thoroughly. Prior to field use, all equipment was cleaned as follows:

1) Phosphate-free detergent wash;
2) Copious rinse with native water;
3) Rinse with deionized water;
4) Nitric acid rinse;
5) Copious rinse with deionized water;
6) Methanol rinse;
7) Air drying; and
8) Storage in plastic bags.

Between sampling at each site, equipment such as glass mixing bowls, Teflon stirring blades, and sieves were cleaned by using steps 1 through 5. Between grabs at each site, the van Veen sampler was cleaned of all sediment by using a hydraulic winch to move it rapidly up and down through the water column.

GLOSSARY

Benthic. Relating to or occurring at the bottom of a body of water; bottom dwelling.

Bioaccumulation. General term for the process by which organisms take up chemicals directly from water or indirectly from food.

Bioluminescent. The giving off of light by living matter.

Bioassay. A determination of the biological effect of some substances, factor, or condition employing living organisms or cells as the indicator.

Biota. Bacteria, plants, and animals living in a region.

Bioconcentration. The accumulation of a chemical in tissues of an organism to concentrations larger than the concentrations in the medium in which the organism resides.

Blind sample. A sample submitted for analysis whose composition is known to the submitter but unknown to the analyst.

Clarified. For purposes of this study, clarified water refers to the water collected after centrifugation. Clarified water may contain some colloidal material.

Clay size. Soil or sediment particles having diameters of less than 0.004 mm (4 μm).

Colloid. A state of matter intermediate between a true solution and a suspension of material. Colloidal particles cannot settle out of a stream or lake through the force of gravity, and they lie in the range of 1 nanometer to 1 micrometer in diameter.

Congener. Group of isomers with the same number of substituent atoms (for example, same number of chlorine atoms) on the molecule.

Contaminant. A substance that is not naturally present in the environment or is present in unnatural concentrations or amounts and which can, in sufficient concentration, adversely alter an environment. Contaminant sinks are the areas in the environment where contaminants accumulate over time; for example, in sediments in urban embayments.

Detection limit. The minimum concentration of a substance that can be identified, measured, and reported by a given analytical method with 99-percent confidence that the analyte concentration is greater than zero.

Discharge. The rate at which a constituent of interest passes a section of a stream, expressed as mass per unit.

Isomer. Individual chemical compounds having the same constituent elements in the same proportion by weight but differing in physical or chemical properties because of differences in the structure of their molecules.

Lethal. Causing death by direct action.

Minimum reporting level. The smallest measured concentration of a constituent that may be reliably reported using a given analytical method.

Phase. A homogeneous, physically distinct portion of matter.

Relative percent difference. A statistic defined as the difference between two analyses divided by the mean of the two analyses; this quantity is then multiplied by 100.

Replicate (duplicate) samples. A group of samples that are collected in a manner such that the samples are thought to be essentially identical in composition. Replicate is the general case for which a duplicate is the special case of two samples.

Sand size. Soil or mineral particles having diameters in the range of 0.062 to 2 mm.

Sediment. Fragmental material, both mineral and organic, that is suspended in or is transported by the water mass or is deposited on the bottom of the aquatic environment.

Silt size. Soil or sediment particles having diameters in the range of 0.004 to 0.062 mm.

Sorb (sorption). A general term for the processes of absorption or adsorption that is not distinguished.

sp. Species (singular) and spp. (plural); used to refer to one species in a genus when the actual species is not known.

Spike sample. A sample to which known concentrations of specific analytes have been added in such a manner as to minimize the change in the matrix of the original sample. Every spiked sample analyzed should have an associated reference to the spike solution and volume added.

Spike solution. A solution with one or more well established analyte concentrations that is added in known quantities to an environmental sample to form a spike sample.

Sublethal. Involves a stimulus or effect below the level that causes death.

Suspended sediment. Material actively transported by a fluid.

Suspended-sediment phase. In this report, refers to the suspended sediment retained after centrifugation of a water and suspended-sediment mixture.

Total. This term is used only when the analytical procedure ensures measurement of at least 95 percent of a constituent in a sediment sample.

Total, recoverable. Pertains to the constituents in solution after a representative sediment sample is digested. Complete dissolution of all particulate matter is often not achieved by the digestion treatment, and thus the determination may represent less than the “total” amount (that is, less than 95 percent) in a sediment sample.

Toxicity. Quality, state, or degree of the harmful effect resulting from alteration or an environmental factor.

Trace element. A metal or metalloid present in the Earth’s crust in minor amounts, usually less than about 0.01 percent (100 milligrams per kilogram).

Water phase. In this report, refers to the clarified water retained after centrifugation of a water and suspended-sediment mixture.

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