Concentrations and Distribution of Slag-Related Trace Elements and Mercury in Fine-Grained Beach and Bed Sediments of Lake Roosevelt, Washington, April-May 2001

Water-Resources Investigations Report 03-4170

Lake Roosevelt near Marcus Island Campground

Lake Roosevelt sediments near Kettle Falls

Lake Roosevelt near confluence with Spokane River

Lake Roosevelt near Seven Bays

Prepared in cooperation with the

CONFEDERATED TRIBES OF THE COLVILLE RESERVATION, LAKE ROOSEVELT WATER QUALITY COUNCIL, BUREAU OF RECLAMATION, and NATIONAL PARK SERVICE

U.S. DEPARTMENT OF THE INTERIOR
U.S. GEOLOGICAL SURVEY

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Cover: Photographs of Lake Roosevelt, Washington, clockwise from upper left: (1) Exposed lakebed sediment near the Marcus Island Campground (lake elevation 1,222 feet, March 13, 2001). Windblown dust is visible near the opposite shoreline. Photograph taken by Sue C. Kahle, U.S. Geological Survey. (2) Exposed sediments near Kettle Falls (lake elevation 1,217 feet, April 24, 2001). Photograph taken by Michael S. Majewski, U.S. Geological Survey. (3) Seven Bays and Lake Roosevelt (lake elevation 1,222 feet, March 13, 2001). Photograph taken by Sue C. Kahle, U.S. Geological Survey. (4) Wind-blown dust along the shore at the confluence of the Spokane River and Lake Roosevelt (lake elevation 1,222 feet, March 13, 2001). Photograph taken by Sue C. Kahle, U.S. Geological Survey.

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By Michael S. Majewski, Sue C. Kahle, James C. Ebbert, *and* Edward G. Josberger

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Tacoma, Washington
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CONVERSION FACTORS AND DATUMS

CONVERSION FACTORS

Multiply	By	To obtain
	Length	
inch (in.)	2.54	centimeter
inch (in.)	25.4	millimeter
foot (ft)	0.3048	meter
mile (mi)	1.609	kilometer
	Area	
acre	4,047	square meter
acre	0.004047	square kilometer
	Mass	
ton per day (ton/d)	0.9072	metric ton per day

Concentrations of chemical constituents in water are given either in milligrams per liter (mg/L) or micrograms per liter (µg/L) or in parts per million (ppm).

DATUMS

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.

Vertical coordinate information is referenced to the National Geodetic Vertical Datum of 1929 (NGVD 29).

Horizontal coordinate information is referenced to the North American Datum of 1983 (NAD83).

Concentrations and Distribution of Slag-Related Trace Elements and Mercury in Fine-Grained Beach and Bed Sediments of Lake Roosevelt, Washington, April-May 2001

By Michael S. Majewski, Sue C. Kahle, James C. Ebbert, *and* Edward G. Josberger

ABSTRACT

A series of studies have documented elevated concentrations of trace elements such as arsenic, cadmium, copper, lead, mercury, and zinc in the water, bed sediment, or fish of Lake Roosevelt and the upstream reach of the Columbia River. Elevated concentrations of some trace elements in this region are largely attributable to the transport of slag and metallurgical waste discharged into the Columbia River from a smelter in Canada. Although most recent studies have focused on contamination levels in water, bed sediment, and fish, there is growing concern in the region over the potential threat of airborne contaminants to human health. In response to these concerns, the U.S. Geological Survey conducted an assessment of trace-element concentrations in the relatively shallow fine-grained sediment along the shore of Lake Roosevelt that is exposed annually during periods of reservoir drawdown. During each winter and spring, the water level of Lake Roosevelt is lowered as much as about 80 feet to provide space to capture high river flows from spring runoff, exposing vast expanses of lake-bottom sediment for a period of several months. Upon drying, these exposed areas provide an extremely large source for wind-blown dust.

This study concluded that trace elements associated with slag and metallurgical waste are present in the fine-grained fraction (less than 63 micrometers) of bed sediments along the length of Lake Roosevelt, and as such, could be components of the airborne dust resulting from exposure, drying, and wind mobilization of the sediments exposed during the annual drawdowns of the reservoir. Trace-element concentrations in the surficial bed sediment varied, but the major components in slag—arsenic, cadmium, copper, lead, and zinc—showed generally pronounced gradients of decreasing concentrations from near the International Border to the Grand Coulee Dam. The results of this study provide base-line information needed to plan and conduct air monitoring of trace elements in wind-blown dust along Lake Roosevelt.

INTRODUCTION

Contamination of Lake Roosevelt (formally named Franklin D. Roosevelt Lake) was discovered in the early 1980s, when elevated concentrations of the trace elements arsenic, cadmium, lead, and zinc were reported in fish collected near Grand Coulee Dam (Lowe and others, 1985). The occurrence of these trace elements is attributed primarily to the transport of slag and metallurgical waste from a lead-zinc smelter in Trail, British Columbia, Canada (Bortleson and others, 2001). This smelter discharged slag directly into the Columbia River at a rate of about 397 tons per day from 1930 until the early 1990s (Cominco, Ltd., 1991). The smelter also discharged dissolved trace elements directly into the water from its wastewater system. In addition, particulate matter was discharged into the atmosphere from the furnace smokestacks until 1997, when a new smelter with improved air emission and effluent treatment controls began operation. Other sources of trace elements in Lake Roosevelt include runoff from active and abandoned mining operations in the region, and the Spokane and Pend'Oreille Rivers, which transport trace elements from mining areas around the Coeur d'Alene drainage basin (Yake, 1979).

In 1992, the U.S. Geological Survey (USGS), in cooperation with the U.S. Environmental Protection Agency (USEPA) and the Lake Roosevelt Water-Quality Council, initiated a large-scale study of sediment quality in Lake Roosevelt (Bortleson and others, 2001). The USGS reported that Lake Roosevelt beach and bed sediments contained elevated concentrations of the trace elements—arsenic, cadmium, copper, lead, mercury, and zinc—relative to background reference sites. Concentrations of these six trace elements were highest at the sites closest to the smelter source and decreased downstream. Laboratory tests showed that the sediments were toxic to benthic invertebrates, and that these communities in the Lake Roosevelt system were stressed, most likely from the elevated trace-element concentrations and from the loss of physical habitats due to the extensive slag deposits.

In mid-1995, the lead-zinc smelter ceased discharging slag into the Columbia River under normal operating conditions. By 1999, effluent discharge was further reduced with the construction of a new smelter and improved effluent treatment controls (G3 Consulting, Ltd., 2001). Although these actions resulted in a significant decrease in the current (2001) loadings of trace elements and slag to the system, large quantities of contaminated sediments remain in Lake Roosevelt.

Previous studies conducted in Lake Roosevelt focused on contamination levels in fish, water, and bed sediment. There is, however, growing concern over the potential threat of airborne contaminants to human health. From about January through April every year, the water level in Lake Roosevelt declines substantially for flood-control purposes and extensive reaches of contaminated sediments are exposed. When the exposed sediments dry, the fine-grained material can become airborne and be transported throughout the Lake Roosevelt area by the prevailing winds. The water level also is drawn down for about 1 month in late summer. Bed sediments are exposed during this period as well, but to a lesser extent than during the primary winter-spring drawdown.

Trace metals associated with the fine-grained particle fraction, designated as PM10 and having a mean diameter of less than or equal to 10 μm (micrometers), have a high potential for being entrained into the lower atmosphere by wind gusts. Once airborne, the particles are transported varying distances downwind, depending on their size and the magnitude and duration of the prevailing winds.

The population residing in the Lake Roosevelt area is concerned that they and the many visitors to the lake may be exposed to elevated concentrations of trace elements and total particulate matter during periods of high winds. Inhaled PM10 particles travel deeper into the lungs and are retained for longer periods of time. This is why PM10 is a primary health concern. The conclusions and recommendations section of the USEPA Preliminary Assessment Report (U.S. Environmental Protection Agency, 2000) expresses the extent of this concern with the following statement:

> "Additional concerns include potential exposure to the contaminated sediments during lake draw-down periods, such as the potential for health effects resulting from dermal contact with the sediment, or from inhalation of airborne sediment particles."

To address these concerns, the USGS, in cooperation with the Confederated Tribes of the Colville Reservation, Lake Roosevelt Water-Quality Council, the Bureau of Reclamation, and the National Park Service, conducted a survey of beach and bed sediments in April and May 2001 to determine the concentrations and distribution of trace elements in the fine-grained fraction of exposed beach, bed, and bank sediments along the Columbia River from the Canadian border to the Grand Coulee Dam. For this study, the fine-grained sediments were defined as those less than 63 µm. These results are the first of a two-part study to assess the contributions from trace elements in exposed bed sediments to elemental concentrations of airborne particles measured during ambient and high-wind conditions.

The primary focus of the study was the trace elements of environmental significance found in slag discharge. Copper, lead, and zinc are the major trace elements in slag, and arsenic and cadmium are the minor elements (G3 Consulting, Ltd., 2001). Mercury, although not a direct component of slag, also was a focus of the study. Mercury has entered the Columbia River at Trail as a component of slurry effluent from the smelting facility that was, until recently, also directly discharged into the Columbia River (Bortleson and others, 2001; G3 Consulting, Ltd., 2001). Other trace elements that were detected in the bed-sediment samples may have originated from the various mining operations in the watershed, as well as from mineralization, erosion, and slumping of bank deposits along the shoreline of the reservoir, especially in the middle and lower reaches (Jones and others, 1961).

Purpose and Scope

The purpose of this report is to present the results of the assessment of concentrations and distribution of slag-related trace elements in the beach and bed sediments along Lake Roosevelt. Samples were collected during the winter and spring drawdown of the lake, and concentrations were compared with concentrations at reference sites above lake level and upstream of contamination sources, with concentrations in a riverine slag deposit, and with concentrations measured in previous studies. Concentrations also were compared with Canadian sediment-quality guidelines.

Description of Study Area

Lake Roosevelt, a reservoir formed on the Columbia River by the Grand Coulee Dam, is located in north-central Washington and extends about 135 mi upstream from the dam, reaching within about 15 mi of the International Boundary with Canada (fig. 1). The original purpose of the Grand Coulee Dam, completed in the early 1940s, was to provide irrigation water and flood control and to produce hydroelectric power. The reservoir, however, has developed into a major recreational and economic resource for the surrounding area. From 1992 to 2000, boating, fishing, camping, and general sightseeing attracted an average of 1.4 million visitors each year to the Lake Roosevelt National Recreation Area (Roberta Miller, National Park Service, written commun., November 2001). In addition to the high-use camping and boating areas along Lake Roosevelt, there are several towns and many private residences close to the reservoir. Year-round residents who live near the reservoir and use it extensively include members of the Confederated Tribes of the Colville Reservation and the Spokane Tribe of Indians. Reservation lands currently border more than one-half the length of Lake Roosevelt (fig. 1).

Each winter, beginning in January, the water level of Lake Roosevelt is lowered to provide space to capture high river flows, primarily from the Columbia River, that typically occur in May, June, and July from snowmelt in the drainage basin. The level of the lake can be lowered from the full pool level of 1,290 ft elevation above sea level (as referenced to NGVD 29) to 1,208 ft by the end of April or May, depending upon the amount of water predicted to flow through the system during the flood season. Typically, the reservoir is refilled (elevation 1,280 ft or higher) by July 1. During the flood-control drawdown period, power production, fishery issues, and irrigation also can affect daily water levels (Craig Sprankle, U.S. Bureau of Reclamation, Grand Coulee Power Office, written commun., November 2001). Since 1995, the lake level also has been lowered in August to increase downstream flow for salmon mitigation, but to a lesser extent than the winter drawdown.

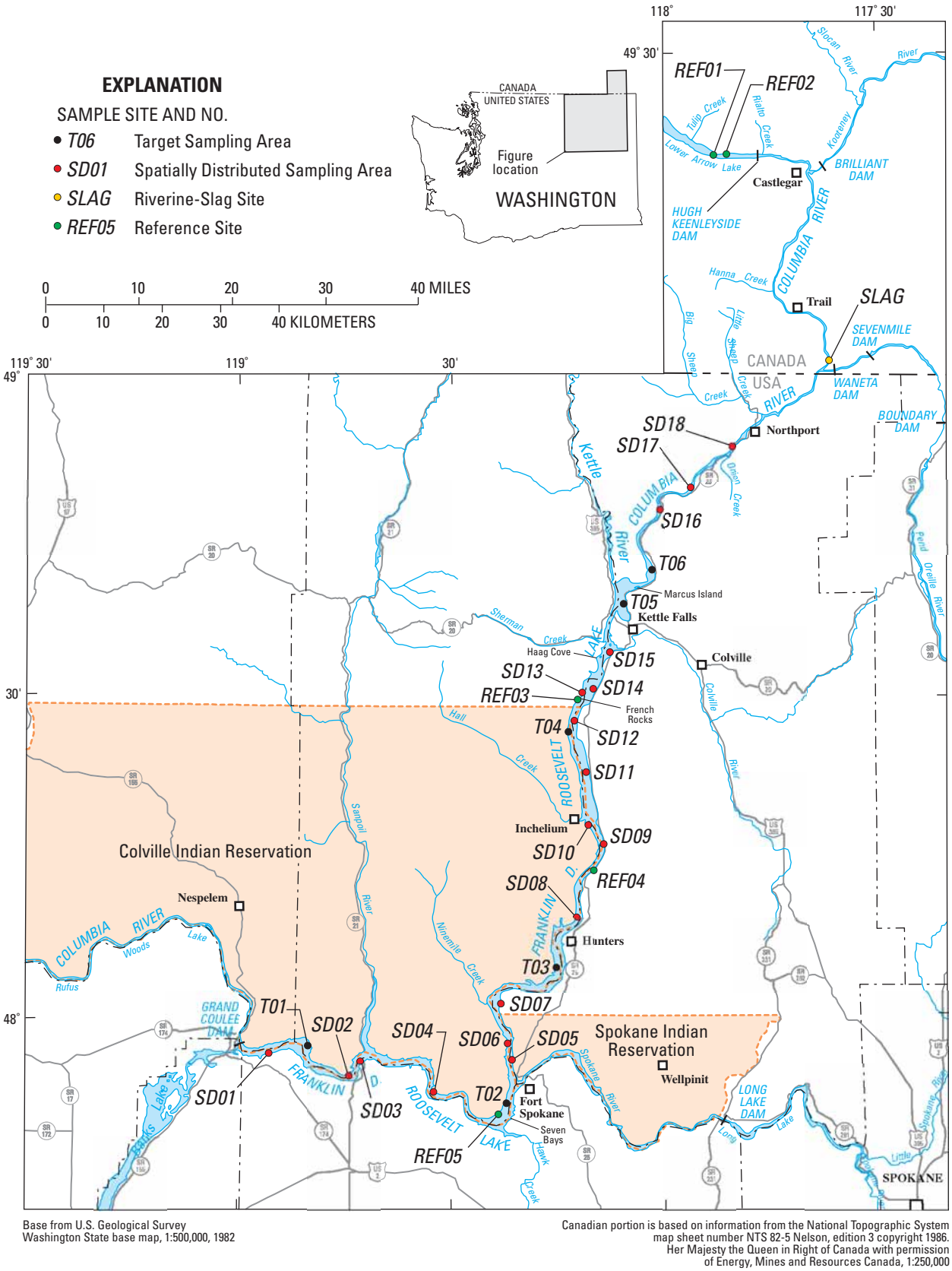


Figure 1. Location of the study area and sediment collection sites on Lake Roosevelt and the upper Columbia River, Washington and British Columbia, April-May 2001.

At full pool (1,290 ft), the reservoir has a surface area of about 80,000 acres. With the resulting lowering of water levels in Lake Roosevelt each year, vast expanses of beach and lake-bottom sediment can be exposed for a period of up to several months. Upon drying, these exposed areas provide an extremely large source for wind-blown dust. The maximum exposed area during the 2001 drawdown was estimated to be 29,000 acres, or about 36 percent of the total surface area of the lake.

Currently, the USEPA has established national ambient air-quality standards only for lead (1.5 g/m^3) and PM10 (50 g/m^3 annual mean, and 150 g/m^3 24-hour average). The results of this study and the air-monitoring study will be used to assess the significance of the exposed contaminated bed sediments as a source of trace metals in the atmosphere above and around Lake Roosevelt.

Acknowledgments

This study was completed with the assistance of many individuals and organizations. We thank Mark Munn, U.S. Geological Survey, and Patti Stone, Confederated Tribes of the Colville Indian Reservation, for their assistance in planning this investigation; Craig Sprankle, U.S. Bureau of Reclamation at Grand Coulee Dam, for providing notices of changing lake levels and descriptions of drawdown operations; and Ray DePuydt, National Park Service at Kettle Falls, for providing archaeological oversight in the field. Art Horowitz, U.S. Geological Survey Trace Element Laboratory in Atlanta, Ga., oversaw analysis of the samples and provided sampling guidance. We also thank Don Hurst of Fulcrum Environmental Consultants, Inc., and Bill Duncan of Teck Cominco Metals Ltd. for their technical reviews. Funding in support of this study was provided by the Confederated Tribes of the Colville Reservation, the Lake Roosevelt Water-Quality Council, the U.S. Bureau of Reclamation, the National Park Service, and the U.S. Geological Survey.

DATA COLLECTION AND ANALYSIS

Samples of beach and bed sediments, reference sample material, and riverine slag deposits were collected along Lake Roosevelt and the upper Columbia River between April 23 and May 4, 2001. Surficial samples of exposed beach and bed sediments were collected using two different, but complementary, sampling designs—targeted (T) and spatially distributed (SD). Reference samples were taken along the length of Lake Roosevelt and the Columbia River at locations above the influence of the reservoir and, on the river, upstream of contamination sources (fig. 1). In addition, a riverine slag sample was taken at about river mile (RM) 747 near Waneta, British Columbia, about 8 mi downstream from Trail, British Columbia. The location of each of the reference and riverine-slag sampling sites was recorded to the nearest second of latitude and longitude, or within approximately the nearest 100 ft, using a portable Global Positioning System (GPS) unit at the time of collection.

Sampling Design

Six targeted sampling areas were identified during a pre-sampling reconnaissance survey in early March 2001 with members of the Lake Roosevelt Water-Quality Council. The sampling areas (fig. 1, table 1) were selected because they contained large expanses of exposed, fine-grained material known to be sources for airborne particulate matter during high wind events. They also were selected on the basis of their proximity to downwind communities and recreational areas. Because several of the T sites were extremely large, a sampling strategy was designed to determine the variation in the trace-element concentrations over the large depositional areas, and to determine if concentration gradients were present from the shoreline to the 1,290-foot contour of full-pool elevation.

Table 1. Location and description of sediment-sampling sites on Lake Roosevelt and the upper Columbia River, Washington and British Columbia, April-May 2001

[**Sampling site:** See figure 1 for location of sample sites. SD, spatially distributed sampling area; T, targeted area; REF, reference site. **River mile**: Estimated distance from the mouth of the Columbia River. **Riverbank**: Refers to the bank position as one travels downstream. **Abbreviations:** mi, mile]

Sample site	River mile	Riverbank	Site description
SD01	601	Left bank	Spring Canyon, south bank of Lake Roosevelt about 4 mi upstream from Grand Coulee Dam
T01	605	Right bank	Swawilla Cove, about 8 mi upstream from Grand Coulee Dam on the north shore
SD02	612	Right bank	North bank of Lake Roosevelt, about 3 mi downstream from the Keller Ferry
SD03	614	Left bank	Keller Ferry, south bank of Lake Roosevelt
SD04	625	Right bank	North bank of Lake Roosevelt, about 10 mi upstream from the Keller Ferry
REF05	635	Right bank	Upper bluff area, west bank of Lake Roosevelt across from Seven Bays
T02	637	Right bank	West bank of Lake Roosevelt across from Seven Bays, about 40 mi upstream from Grand Coulee Dam
SD05	642	Left bank	East bank of Lake Roosevelt, about 3 mi upstream from the confluence of the Spokane River and Lake Roosevelt
SD06	644	Right bank	West bank of Lake Roosevelt, about 6 mi upstream from the confluence of the Spokane River and Lake Roosevelt
SD07	648	Left bank	East bank of Lake Roosevelt, about 9 mi upstream from the confluence of the Spokane River and Lake Roosevelt
T03	657	Right bank	Rogers Bar, about 17 mi downstream from the Gifford Ferry on the west bank of Lake Roosevelt
SD08	664	Right bank	West bank of Lake Roosevelt, across lake from Cedonia
REF04	670	Left bank	Upper bluff at road cut on Hwy 25 about 6 mi north of Cedonia
SD09	673	Left bank	Gifford Ferry, east bank of Lake Roosevelt
SD10	675	Right bank	Inchelium, west bank of Lake Roosevelt
SD11	681	Left bank	East bank of Lake Roosevelt, about 2 mi north of Daisy
T04	686	Right bank	Barnaby Creek area, about 12 mi upstream from the Gifford Ferry on the west bank of Lake Roosevelt
SD12	687	Left bank	East bank of Lake Roosevelt, 3 mi north of Rice
REF03	690	Right bank	Upper bluff area on north side of French Rocks boat ramp
SD13	691	Right bank	French Rocks area, west bank of Lake Roosevelt
SD14	691	Left bank	Bradbury beach, east bank of Lake Roosevelt
SD15	699	Left bank	East bank of Lake Roosevelt, south side of confluence of Colville River and Lake Roosevelt
T05	705	Left bank	Marcus Flats, north of the Kettle Falls bridge on the east bank near the junction of Columbia River and Kettle River
T06	711	Left bank	Evans, about 6 mi upstream from the Kettle Falls bridge on the east bank of Lake Roosevelt
SD16	719	Left bank	North Gorge, east bank of Lake Roosevelt
SD17	724	Right bank	China Bend, west bank of Lake Roosevelt
SD18	731	Right bank	West bank of the Columbia River, about 4 mi downstream from Northport
Riverine slag	747	Left bank	East bank of the Columbia River, about 8 mi downstream from Trail
REF02	786	Left bank	North bank of Lower Arrow Lake about 8 mi upstream from Castlegar
REF01	787	Left bank	North bank of Lower Arrow Lake about 10 mi upstream from Castlegar

Selection of SD sampling areas was based largely on location and size of the exposed bed-sediment areas. The depositional areas needed to be large enough that they would not be inundated if the reservoir water level rose slightly between the time of selection and the time of sampling. Eighteen SD depositional areas were selected between Northport and Grand Coulee Dam to provide a broad assessment of the distribution of trace elements in exposed beach and bed sediments (fig. 1, table 1).

Reference samples are defined as those natural sediments above the influence of the Columbia River and the high water level of Lake Roosevelt. These samples were collected to assess the concentrations of trace elements from two areas. The first area consisted of beach- and bank-sediment samples from two locations on Lower Arrow Lake, upstream from Trail, British Columbia (REF01 at RM 787, and REF02 at RM 786, table 1; fig. 1). The second area was the glacial sediments above the high-water elevation along the upper banks of Lake Roosevelt. Three sites (REF03 at RM 690, REF04 at RM 670, and REF05 at RM 635, table 1; fig. 1) were randomly selected and sampled on the basis of accessibility to exposed fine-grained material.

A sample of a riverine-slag deposit was taken at RM 747, about 8 mi downstream of the smelter at Trail, British Columbia (fig. 1). This sample was taken from a depositional zone and consisted of mostly fine-grained, black, sandy material, which is consistent with treated slag. The location of the riverine-slag sample was about 2 mi upstream from the site used in 1995 and 1999 sediment surveys (Aquatic Resources Ltd., 2001; G3 Consulting Ltd., 2001).

Before the sampling began, each of the T and SD sampling areas was identified on high-resolution (15 to 30 m; 50 to 100 ft), near-infrared satellite images obtained from the LANDSAT-7 satellite. The images were photographed on March 6, 2001, when the reservoir pool elevation was low (1,224.6 ft). After each T and SD sampling area was identified and located on the LANDSAT images, the site image was enlarged and five approximately equally spaced transects were drawn across the sampling area. Three points were located along each transect (fig. 2), resulting in 15 sampling sites per area. The central point of each transect was located roughly midway between the water level and the full-pool elevation (the 1,290-foot contour) as shown in figure 2. Full-pool elevation data were available in a Geographic Information System (GIS) coverage, which was combined with the LANDSAT image using image-processing software. The other two points were placed approximately 1/6 and 5/6 of the distance between the two water levels (fig. 2). Once the points were located on the LANDSAT image of the sampling areas, the coordinates of each point were determined using image-processing software. Each of the 15 sampling points at each of the T and SD sampling areas was located to within 0.5 second (25-50 ft) of the targeted latitude and longitude using a portable GPS unit programmed with the predetermined latitude and longitude.

Sampling Methods

Samples of exposed fine-grained beach and bed sediments were collected at 24 SD and T sampling areas along Lake Roosevelt (fig. 1, table 1) during the lowest low-water period of the 2001 drawdown (fig. 3). At some sampling sites, it was necessary to deviate several feet from the predetermined coordinates in order to avoid cobbles, however, the sample was collected to within 0.5 second of the predetermined latitude and longitude. If a sampling point was inaccessible because it was under water, an alternate sampling point was selected and its coordinates recorded using the portable GPS unit to within 0.5 second of latitude and longitude.

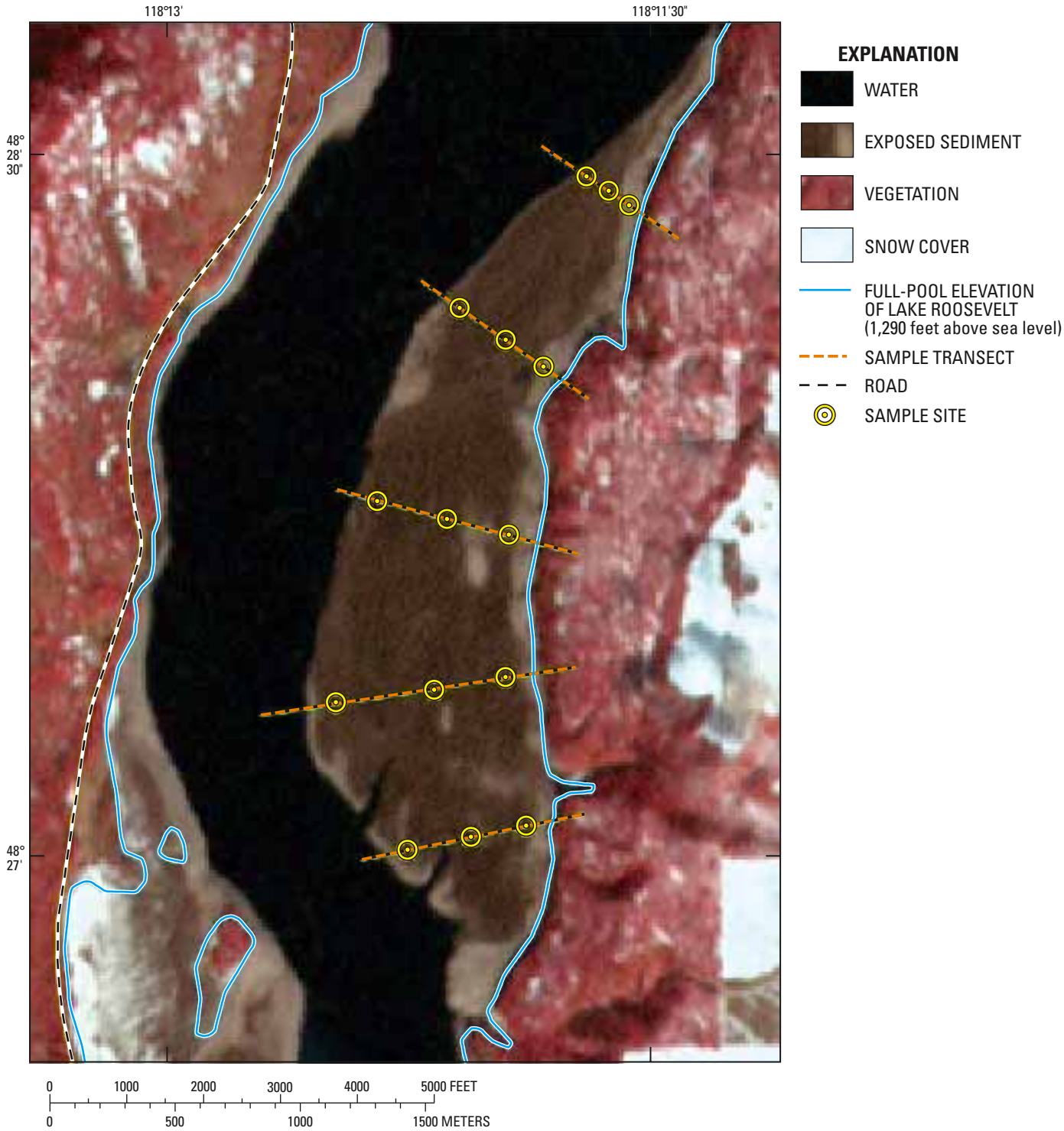


Figure 2. Example of sampling transect and spacing of sampling sites at SD12 across an exposed area of sediment on a section of Lake Roosevelt, Washington.

LANDSAT image was taken on March 6, 2001.

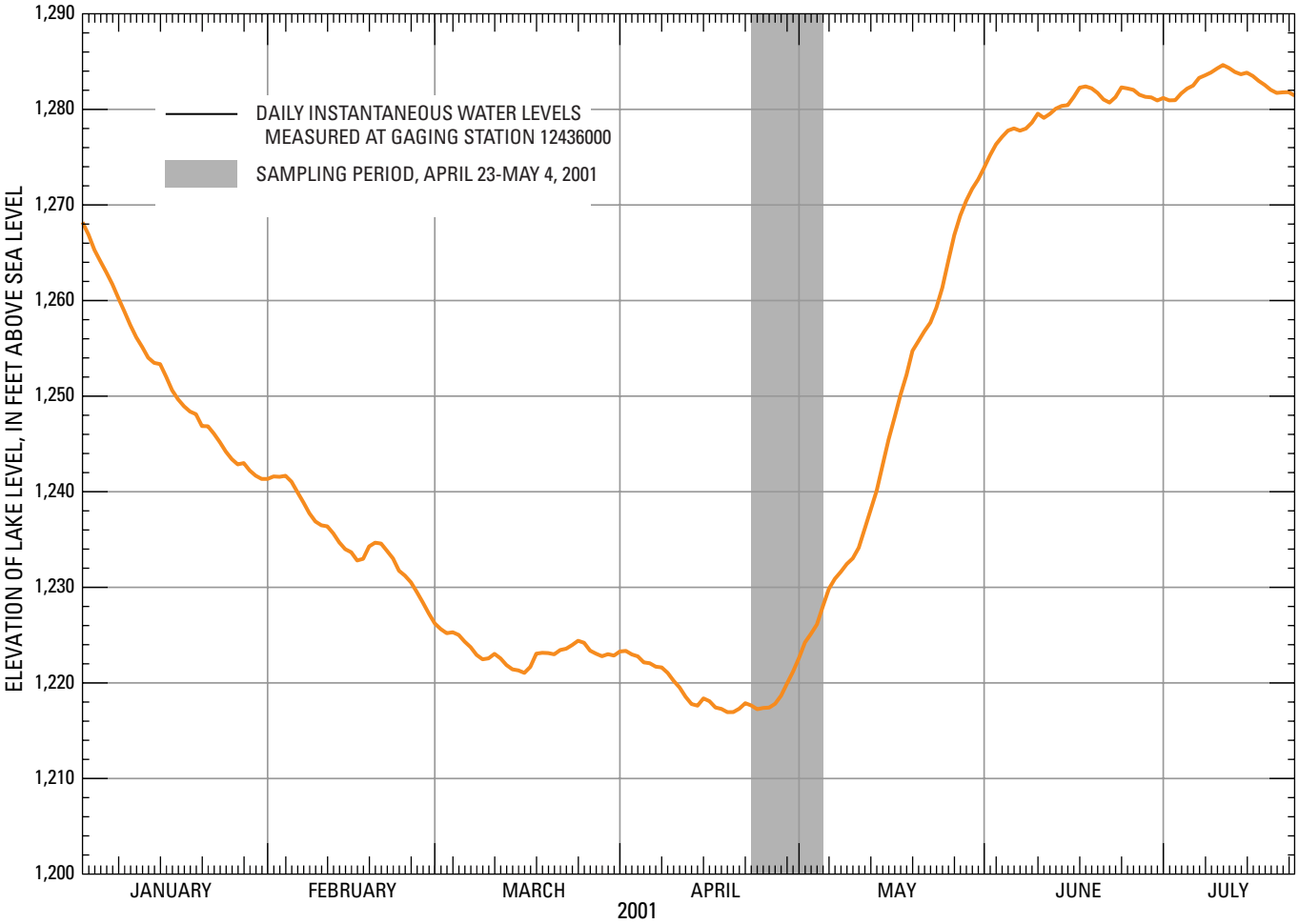


Figure 3. Water-surface elevation of Lake Roosevelt at Grand Coulee Dam during 2001 drawdown.

Samples of the top 2 to 3 cm of exposed beach and bed sediments were collected using a plastic spoon and were placed into a plastic container where they were mixed to form a composite sample. At the T sites, three composite samples were collected from the five transects to determine if there was a gradient in concentrations from the shoreline to the 1,290-foot contour. This was done to assess the spatial variation in concentration of slag associated trace elements at the sampling areas. The three samples were composed of the following:

1. A composite of the five sampling sites nearest the water's edge;
2. A composite of the five sampling sites midway between the water and the 1,290-foot contour; and
3. A composite of the five sampling sites nearest the 1,290-foot contour (see fig. 2).

At the SD sampling areas, samples from each of the 15 sites were composited into one sample. Mixing of each sample was done sequentially. That is, as new material was added to the container at each sampling site, the entire sample was thoroughly mixed. The resulting sample volume from each sample area was approximately 2 liters. The sample material then was removed from the container and placed in plastic bags for shipment to a laboratory for analysis. All equipment was cleaned between sites according to the following procedure:

1. Wash with a dilute solution of phosphate-free detergent;
2. Rinse with deionized water;
3. Rinse with dilute solution of nitric acid;
4. Rinse with deionized water;
5. Allow to air dry;
6. Store in plastic bag.

All samples were shipped to the laboratory on ice because some of the beach and bed sediments were moist.

Reference samples REF03, REF04, and REF05 were subsurface composites. That is, an exposed bank above the high water line was selected, and at least the top 15 cm of material was removed before the sample was taken. Reference samples REF01 and REF02, collected along Lower Arrow Lake upstream from Trail, B.C. were surface composites and included the upper 2 to 3 cm of beach sediment. The reference samples were processed and analyzed similarly to the T and SD samples. The riverine-slag sample from close to the source was collected using the same procedures as used at the T and SD sites. Each of the reference and riverine slag samples was composed of material taken from only one site, not 15 as at the T and SD areas.

Laboratory Analysis

Sediment samples were processed at the U.S. Geological Survey Trace Element Laboratory in Tifton, Ga., following methods presented in Fishman and Friedman (1989) and Horowitz and others (1989 and 2001), and are not discussed in detail here. Briefly, the analytical methods included freeze-drying the samples, then sieving to obtain a size fraction of less than (<) 63 µm. Each sample was then digested using a four-acid digestion process and analyzed using Inductively Coupled Plasma - Mass Spectrometry (ICP-MS) or Flame Atomic Absorption Spectroscopy (Flame-AAS) for trace elements (table 2). Cold Vapor-AAS was used to analyze for mercury (table 2). Although air-quality sampling commonly analyzes the size fraction less than 10 µm (PM10), the size fraction less than 63 µm was used as a screening method for this investigation.

The major elements in soil—iron, manganese, aluminum, and titanium—and biological indicators total organic carbon and total carbon, sulfur, and nitrogen were analyzed for using combustion/gas analysis (table 2). Although not required for this study, these data are provided as a percentage of the sample composition to assist in the general characterization of each sediment sample.

Quality Assurance

Quality-control samples were used to assess analytical variability, bias, and percent recovery of each of the trace elements analyzed for. To assess variability, duplicate samples were taken at selected sites and composed about 15 percent (n = 6) of the total samples submitted to the laboratory for analysis. Twenty percent of the samples analyzed were reagent blanks prepared in the laboratory that were used to determine if contamination was introduced during sample digestion and preparation. Standard reference material was used to assess percent recovery and the accuracy of the analytical method. Analytical results for the quality-control samples are included in Appendix 1.

Table 2. Trace elements and other constituents analyzed for in fine-grained beach- and bed-sediment samples from Lake Roosevelt and the upper Columbia River, Washington and British Columbia, April-May 2001

[For total concentrations; wt, weight; %, percentage of sample weight; ppm, part per million; ICP-MS, Inductively Coupled Plasma-Mass Spectrometry; AAS, Atomic Absorption Spectrometry]

Trace element or constituent	Reporting limit	Unit	Method	Reference
Aluminum	0.1	%	ICP-MS	Fishman and Friedman, 1989
Antimony	.1	ppm	Hydride Generation AAS	Fishman and Friedman, 1989
Arsenic	.1	ppm	Hydride Generation AAS	Fishman and Friedman, 1989
Barium	1.0	ppm	ICP-MS	Fishman and Friedman, 1989
Beryllium	.1	ppm	ICP-MS	Fishman and Friedman, 1989
Cadmium	.1	ppm	Flame AAS	Fishman and Friedman, 1989
Carbon (organic)	.1	%	Combustion/Gas Analysis	Horowitz and others, 1989, 2001
Carbon (total)	.1	%	Combustion/Gas Analysis	Horowitz and others, 1989, 2001
Chromium	1.0	ppm	ICP-MS	Fishman and Friedman, 1989
Cobalt	1.0	ppm	ICP-MS	Fishman and Friedman, 1989
Copper	1.0	ppm	ICP-MS	Fishman and Friedman, 1989
Iron	.1	%	ICP-MS	Fishman and Friedman, 1989
Lead	1.0	ppm	Flame AAS	Fishman and Friedman, 1989
Lithium	1.0	ppm	ICP-MS	Fishman and Friedman, 1989
Manganese	1.0	ppm	ICP-MS	Fishman and Friedman, 1989
Mercury	.01	ppm	Cold Vapor AAS	Fishman and Friedman, 1989
Molybdenum	5.0	ppm	ICP-MS	Fishman and Friedman, 1989
Nickel	1.0	ppm	ICP-MS	Fishman and Friedman, 1989
Nitrogen (total)	.1	%	Combustion/Gas Analysis	Horowitz and others, 1989, 2001
Phosphorous	10.0	ppm	ICP-MS	Fishman and Friedman, 1989
Selenium	.1	ppm	Hydride Generation AAS	Fishman and Friedman, 1989
Silver	.5	ppm	Flame AAS	Fishman and Friedman, 1989
Strontium	1.0	ppm	ICP-MS	Fishman and Friedman, 1989
Sulfur (total)	0.1	%	Combustion/Gas Analysis	Horowitz and others, 1989, 2001
Tin	1.0	ppm	ICP-MS	Fishman and Friedman, 1989
Titanium	.01	%	ICP-MS	Fishman and Friedman, 1989
Vanadium	1.0	ppm	ICP-MS	Fishman and Friedman, 1989
Zinc	1.0	ppm	ICP-MS	Fishman and Friedman, 1989

CONCENTRATIONS AND DISTRIBUTION OF SLAG-RELATED TRACE ELEMENTS AND MERCURY

Concentrations of 22 trace elements were determined for all samples along Lake Roosevelt and the upper Columbia River. Concentrations at the SD areas were used to determine the distribution of trace elements along Lake Roosevelt from the Canadian border to Grand Coulee Dam, and concentrations from the T areas were used to determine the distributions from the water line to the shore or bank. Concentrations of slag-related trace elements measured in this study were compared with those from previous studies and with Canadian guidelines for sediment quality.

Reference Sites

Sediment samples taken at the reference sites contained measurable concentrations of the five trace elements associated with slag — arsenic, cadmium, copper, lead, and zinc — and mercury, but at much lower concentrations than samples from the T, SD, and riverine-slag sites. Generally, the concentrations were one or more orders of magnitude lower (table 3). The concentrations of these six trace elements at the reference sites also were fairly uniform throughout the Lake Roosevelt and upper Columbia River study area (fig. 4). Concentrations of arsenic varied the most (mean = 6.48 parts per million, standard deviation = 2.8), but were equal to or less than the measured concentrations at the T and SD areas (fig. 4*A*).

Two of the reference sites, located at Lower Arrow Lake in British Columbia, were at nearly the same location as that reported in Bortleson and others (2001). The concentrations of the six trace elements at the two reference sites upstream from the smelter were nearly equivalent to those reported in the 1992 study.

Riverine-Slag Site

The trace-element concentrations of the riverine-slag deposit are shown in table 3. This site was very near to the site used by two earlier studies (RM 746) that measured the bed-sediment concentrations of arsenic, cadmium, copper, lead, zinc, and mercury in 1995 and in 1999 (Aquatic Resources Ltd., 2001; G3 Consulting Ltd., 2001). A significant reduction in the concentrations of most of the six trace elements was observed between 1995 and 1999 (table 4). The analytical results for the sample taken at a riverine slag deposit in this study (2001) showed that while measured concentrations of arsenic, copper, and zinc generally were equivalent to the 1999 levels, the cadmium, lead, and mercury concentrations were higher than even the 1995 levels (table 4). These differences in concentrations may be attributed to differences in sampling locations, sampling methods, particle-size fraction analyzed (whole in 1995 and 1999 and the fraction <63 µm in 2001), weathering and other dissipation processes, and analytical variability. Although mercury concentrations associated with the treated slag discharged from the smelter were reported to be less than 0.05 ppm in 1995 and 0.02 ppm in 1999 (Aquatic Resources Ltd., 2001; G3 Consulting, Ltd., 2001), its concentration in the 2001 riverine-slag deposit sample was 0.27 ppm. The mean (0.63 ppm) and median (0.41 ppm) mercury concentrations at the 18 SD sampling areas were higher than in the riverine-slag sample, indicating that the mercury concentrations vary along Lake Roosevelt and that the smelter slag may not be the primary source.

Targeted Areas

The T sampling areas were selected for the very large expanses of exposed, fine-grained bed sediments that are thought to be a source of dust and associated trace metals in the air. One objective of the sampling scheme was to determine the uniformity of the trace-element distribution over these large depositional areas. This was done by analyzing near-water, mid-area, and near-bank composite samples separately to determine whether trace-element concentrations displayed gradients between the water line and the shore. Concentrations of several of the trace elements associated with slag displayed gradients between the water and the bank at various sampling sites. At the sampling areas T01, T02, and T03 in the lower part of the reservoir (fig. 1), concentrations of cadmium, copper, lead, and zinc all decreased from the water to the bank/shore (table 3). At T04 (RM 686), the concentration gradients for lead, zinc, and mercury were reversed, increasing from the water to the bank. At T05 and T06, gradient trends were not apparent for any of the trace elements analyzed for.

Table 3. Concentrations of trace elements and other constituents analyzed for in sediment samples collected from Lake Roosevelt and the upper Columbia River, Washington and British Columbia, April-May 2001

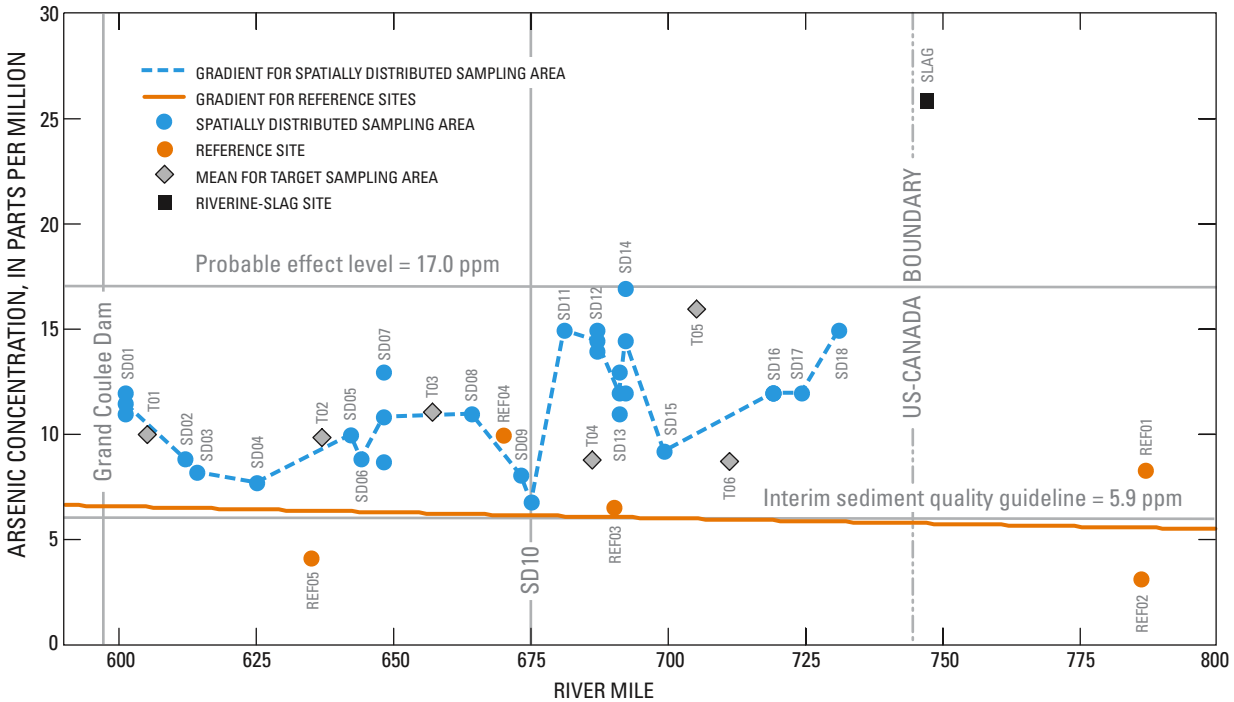
[Results in microgram per gram, part per million; composition; Dup, duplicate sample; <, less than]

Sediment samples	Silver	Copper	Lead	Zinc	Cadmium	Chromium	Cobalt	Nickel	Barium	Vanadium	Lithium	Beryllium	Molyb-denum	Phos-phorous
	(part per million)													
Riverine slag	5.1	940	500	6,200	4.6	120	33	32	1,200	79	20	1.9	3	1,200
REF01	<.5	25	47	130	.4	130	14	65	1,100	86	30	2.5	<1	1,600
REF02	<.5	9	25	72	.3	110	9	34	820	96	18	2.1	<1	1,700
REF03	<.5	21	18	58	.2	63	10	24	1,100	85	21	1.8	<1	1,300
REF04	<.5	21	15	57	<.1	80	11	31	870	92	21	1.7	<1	1,200
REF05	<.5	25	14	53	<.1	36	8	16	790	63	29	1.7	1	760
SD01	<.5	18	23	120	.4	76	11	22	710	110	26	1.9	<1	1,300
SD01 Dup	<.5	18	20	120	.4	73	11	22	760	110	26	1.9	<1	1,300
SD02	<.5	35	110	420	2.4	67	12	27	780	100	35	2.0	<1	1,000
SD03	<.5	21	24	120	.3	76	11	23	730	110	29	2.0	<1	1,100
SD04	<.5	27	57	270	1.4	81	12	27	790	120	32	2.1	<1	1,100
SD05	<.5	31	98	350	2.2	71	12	29	840	95	31	2.0	<1	1,000
SD06	<.5	30	72	240	1.6	76	12	32	900	99	33	2.1	<1	970
SD07	<.5	29	65	240	1.6	75	12	32	850	93	27	1.8	<1	1,000
SD07 Dup	<.5	32	63	260	1.4	84	14	37	990	100	26	2.0	1	1,100
SD08	.7	47	180	450	3.5	86	13	35	1,000	105	29	2.1	1	1,300
SD09	<.5	32	130	330	2.2	76	12	33	1,000	93	26	2.0	1	1,100
SD10	<.5	24	41	120	.5	73	10	31	1,100	93	24	2.1	<1	1,300
SD11	.9	74	350	840	6.0	87	14	38	1,200	100	36	2.2	2	1,500
SD12	1.5	89	320	820	5.9	80	13	34	1,200	99	33	2.0	2	1,500
SD12 Dup	1.7	89	320	800	5.6	83	13	34	1,300	98	32	2.0	3	1,500
SD13	1.1	65	240	640	4.6	81	11	31	1,200	98	29	2.0	2	1,400
SD13 Dup	.9	69	250	640	6.6	83	12	31	1,300	98	29	2.1	2	1,400
SD14	1.0	91	210	650	4.7	82	13	34	1,300	99	33	2.1	2	1,500
SD14 Dup	1.0	84	210	650	4.3	80	12	33	1,200	99	32	2.1	2	1,400
SD15	.6	60	240	590	3.8	75	11	28	1,200	95	26	2.0	2	1,400
SD16	1.8	125	220	1,200	5.4	80	11	28	1,250	92	23	1.8	2	1,500
SD16 Dup	2.0	130	280	1,200	5.3	80	11	28	1,700	91	22	1.8	2	1,500
SD17	2.3	150	210	1,400	4.4	81	11	28	1,200	91	22	1.9	2	1,500
SD18	2.8	200	250	1,900	5.6	82	12	28	820	88	21	1.9	2	1,500
T01-1	<.5	28	60	300	1.8	79	12	26	800	110	29	2.0	<1	1,300
T01-2	<.5	19	34	190	1.0	70	9	21	820	100	24	1.9	<1	1,200
T01-3	<.5	19	27	170	.6	83	11	24	780	120	25	2.0	<1	1,500
T02-1	<.5	22	44	210	.7	78	11	28	890	110	25	2.0	<1	1,200
T02-2	<.5	18	26	150	.6	72	10	23	840	100	25	1.9	<1	1,200
T02-3	<.5	16	20	130	.3	100	11	25	850	130	21	2.0	<1	1,500
T03-1	<.5	54	170	435	3.4	94	15	42	1,200	110	34	2.3	2	1,300
T03-2	<.5	41	160	390	2.4	100	15	40	1,200	120	28	2.3	1	1,400
T03-3	<.5	21	29	120	.3	87	12	31	1,000	110	24	2.1	<1	1,200
T04-1	<.5	31	74	260	1.5	79	11	29	960	110	30	2.0	1	1,400
T04-2	<.5	38	140	450	4.1	67	11	30	1,000	93	29	2.1	<1	1,400
T04-3	<.5	34	160	580	4.1	73	11	31	1,000	93	29	2.2	1	1,300
T05-1	1.4	110	200	790	4.3	75	13	32	1,400	89	29	2.0	3	1,500
T05-2	1.6	110	300	790	6.1	90	14	38	1,300	100	33	2.2	2	1,600
T05-3	.9	66	160	480	3.5	86	13	36	1,300	99	30	2.2	2	1,500
T06-1	1.5	120	150	970	4.5	74	11	30	1,300	87	25	1.9	3	1,500
T06-2	2.7	140	310	990	7.0	82	12	32	1,400	89	30	2.1	2	1,450
T06-3	2.4	110	300	910	6.5	81	11	31	1,400	89	28	2.0	2	1,500

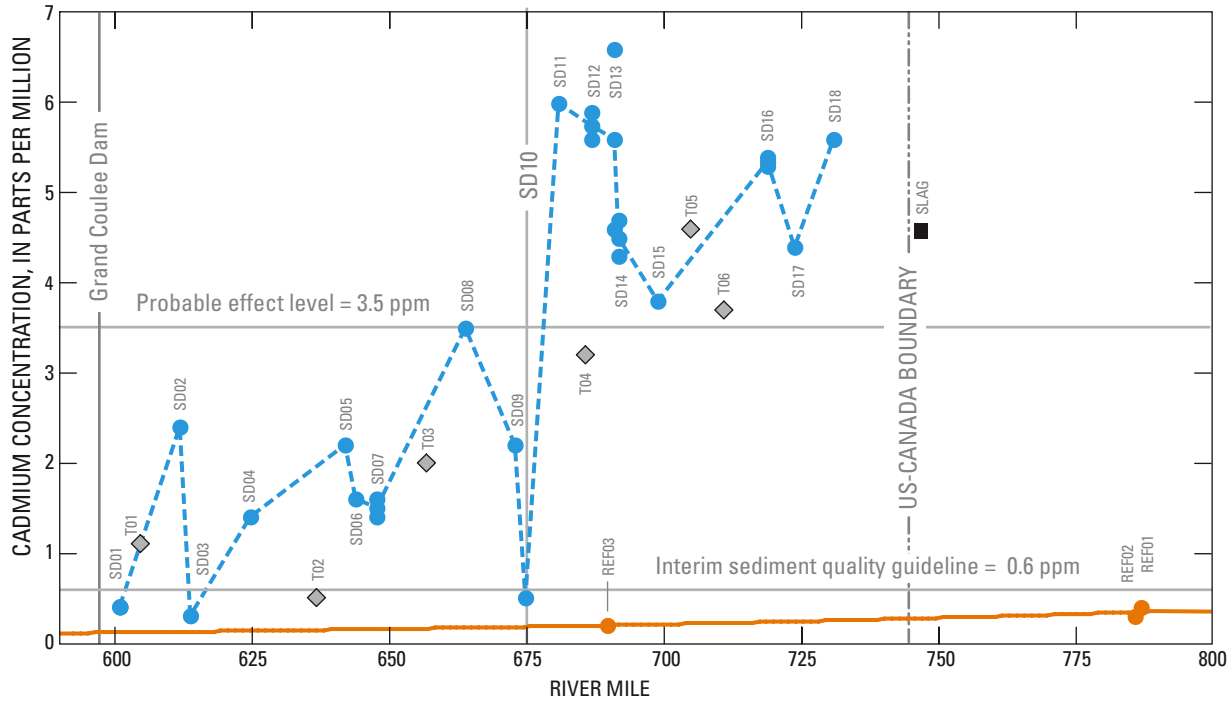
Table 3. Concentrations of trace elements and other constituents analyzed for in sediment samples collected from Lake Roosevelt and the upper Columbia River, Washington and British Columbia, April-May 2001

[Results in microgram per gram, part per million; composition; Dup, duplicate sample; <, less than]

Bed- and beach-sediment samples	Strontium (ppm)	Arsenic (ppm)	Antimony (ppm)	Selenium (ppm)	Tin (ppm)	Mercury (ppm)	Iron (%)	Manganese (ppm)	Aluminum (%)	Titanium (%)	Total organic carbon (%)	Total carbon (%)	Total sulfur (%)	Total nitrogen (%)
Riverine slag	450	26	140	1.2	72	0.27	9.0	1,500	5.5	0.29	2.3	2.6	0.4	0.2
REF01	520	8.4	1.4	.3	2	.07	3.3	1,000	7.0	.42	2.2	2.2	<.1	.2
REF02	530	3.2	.6	.1	2	.02	3.4	800	6.5	.55	.6	.6	<.1	<.1
REF03	550	6.6	.6	.2	<1	.02	3.1	720	7.3	.35	<.1	.6	<.1	<.1
REF04	380	10	1.0	.1	<1	.02	3.2	540	6.2	.41	<.1	.6	<.1	<.1
REF05	370	4.2	.4	.1	1	.01	2.8	630	7.6	.37	.1	.1	<.1	<.1
SD01	320	11	1.0	.1	2	.04	4.0	760	6.4	.55	.4	.6	<.1	<.1
SD01 Dup	340	12	1.0	.2	2	<.01	3.9	670	6.4	.53	.4	.5	<.1	<.1
SD02	310	8.9	1.2	.3	3	.16	3.8	1,000	7.5	.49	1.3	1.4	<.1	.2
SD03	330	8.2	.9	.1	2	.02	4.1	820	7.0	.55	.6	.6	<.1	<.1
SD04	320	7.7	.9	.2	3	.08	4.3	1,100	7.0	.54	1.0	1.1	<.1	.1
SD05	290	10	1.3	.3	2	.17	3.5	800	7.1	.47	.9	1.0	<.1	.1
SD06	310	8.9	1.0	.2	2	.09	3.7	980	7.5	.48	.8	.9	<.1	.1
SD07	300	8.7	1.1	.3	2	.10	3.4	1,000	6.5	.48	1.0	1.0	<.1	.1
SD07 Dup	350	13	1.6	.4	4	.04	3.5	1,000	6.8	.53	1.0	1.0	<.1	.1
SD08	370	11	2.7	.5	3	.36	3.7	1,750	7.2	.44	1.0	1.1	<.1	.1
SD09	410	8.1	1.7	.3	2	.20	3.3	1,000	7.3	.42	.9	.9	<.1	.1
SD10	460	6.8	1.1	.2	1	.05	3.2	820	7.3	.39	.3	.6	<.1	<.1
SD11	360	15	5.7	.9	6	.80	4.0	1,900	7.2	.35	1.5	1.9	.1	.2
SD12	370	14	6.4	.9	6	.79	3.9	1,500	6.7	.34	1.9	2.5	.1	.2
DS12 Dup	370	15	6.7	1.0	6	.72	3.9	1,300	6.6	.34	1.9	2.5	.1	.2
SD13	390	11	4.7	.7	5	.60	3.7	1,100	6.8	.36	1.6	2.0	.1	.2
SD13 Dup	410	13	4.8	.7	5	.64	3.8	1,100	6.7	.36	1.6	2.1	.1	.2
SD14	380	12	5.7	.9	6	.46	4.0	1,200	6.7	.37	2.0	2.5	.1	.2
SD14 Dup	380	17	6.0	1.0	6	.44	4.0	1,200	6.8	.35	2.1	2.6	.1	.2
SD15	410	9.2	4.3	.6	5	.53	3.5	860	6.6	.36	1.4	2.1	.1	.2
SD16	390	12	13	1.0	11	.58	4.0	700	5.7	.33	1.4	2.8	.4	.2
SD16 Dup	390	12	12	.9	11	.55	4.0	690	5.6	.33	1.5	2.8	.3	.2
SD17	420	12	15	.9	16	1.1	4.3	890	6.0	.35	1.6	2.3	.3	.2
SD18	400	15	23	1.1	22	.41	4.8	980	5.8	.33	1.7	2.5	.5	.2
T01-1	330	11	1.4	.4	2	.07	4.2	1,000	6.7	.52	1.3	1.3	<.1	.1
T01-2	390	8.9	1.0	.2	2	.03	3.6	570	6.8	.50	.7	.8	<.1	.1
T01-3	380	10	1.0	.2	3	.01	4.4	890	6.6	.57	.7	.8	<.1	.1
T02-1	390	10	1.1	.2	2	.03	3.7	850	7.0	.51	.7	.7	<.1	<.1
T02-2	400	8.6	.8	.1	2	<.01	3.6	600	7.0	.50	.5	.5	<.1	<.1
T02-3	430	11	.8	.1	2	<.01	4.7	780	6.7	.60	.3	.4	<.1	<.1
T03-1	380	14	3.2	.7	4	.38	4.0	1,500	7.5	.43	.9	.9	<.1	.1
T03-2	440	9.4	2.6	.5	3	.25	4.0	1,200	7.4	.50	.8	.9	<.1	.1
T03-3	430	10	.9	.2	2	.01	3.7	790	6.7	.51	.4	.5	<.1	<.1
T04-1	410	11	1.4	.3	2	.06	3.9	870	7.1	.45	1.4	1.5	<.1	.2
T04-2	450	8.9	1.8	.5	3	.18	3.3	650	7.5	.44	2.2	2.2	<.1	.2
T04-3	460	6.6	1.7	.4	2	.26	3.2	610	7.2	.44	2.0	2.0	<.1	.2
T05-1	380	14	8.7	1.0	7	.26	3.9	960	6.4	.32	2.4	3.0	.3	.3
T05-2	380	19	9.5	1.0	7	.67	4.1	1,700	6.9	.35	1.8	2.2	.1	.3
T05-3	440	15	5.1	.7	4	.35	3.7	1,500	7.2	.37	1.3	1.5	.1	.2
T06-1	400	13	10	.9	7	.34	3.8	660	6.1	.32	1.9	2.8	.4	.2
T06-2	365	14	12	1.2	8	.66	3.7	610	6.3	.32	2.4	3.0	.1	.3
T06-3	380	13	9.0	1.0	7	.79	3.5	630	5.9	.32	2.2	3.0	.1	.2

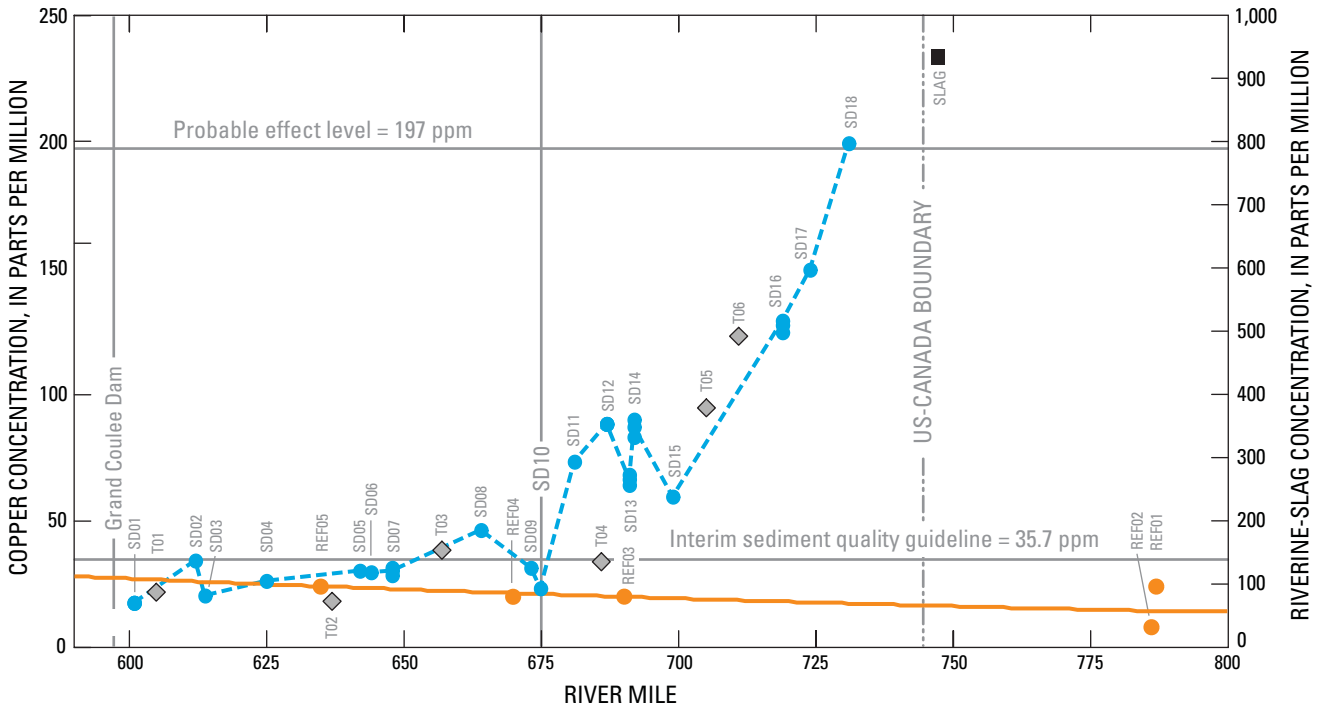


***A.* ARSENIC**

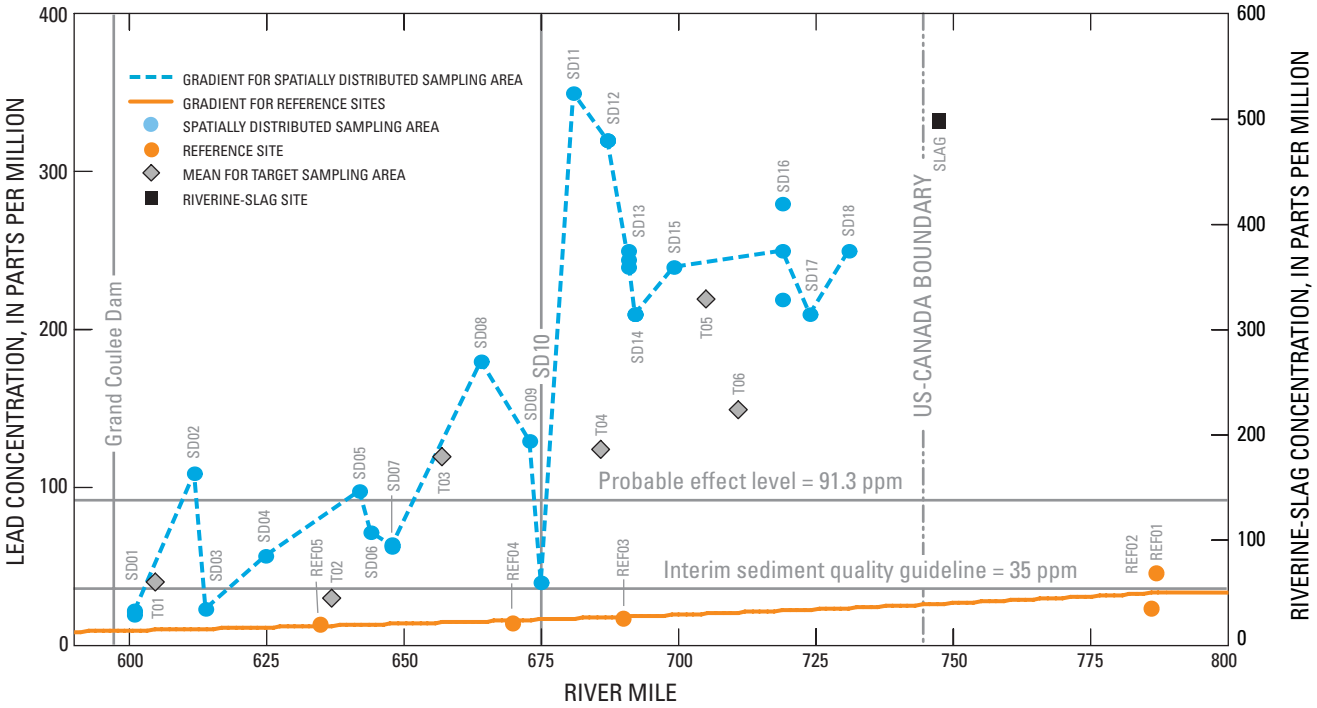


***B.* CADMIUM**

Figure 4. Gradients in concentrations of slag-related trace elements and mercury in fine-grained sediments along Lake Roosevelt and the upper Columbia River, Washington and British Columbia, April-May 2001.

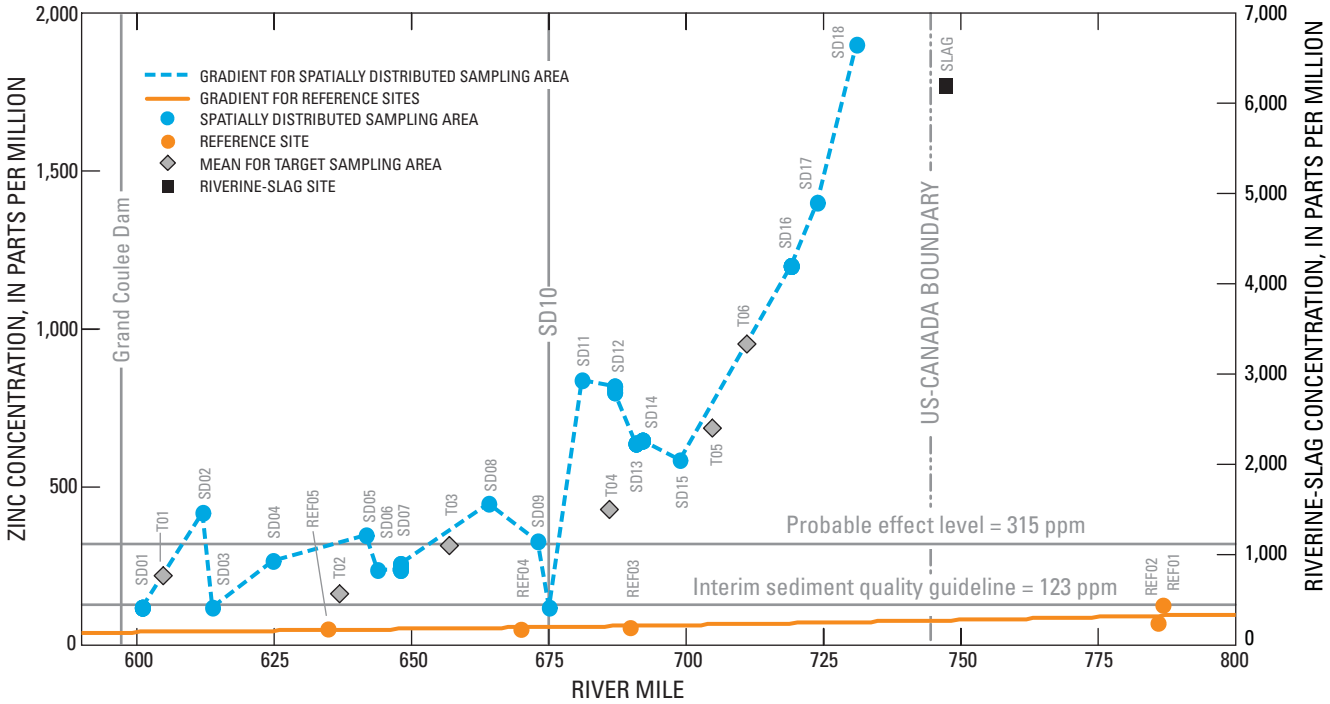


***C.* COPPER**

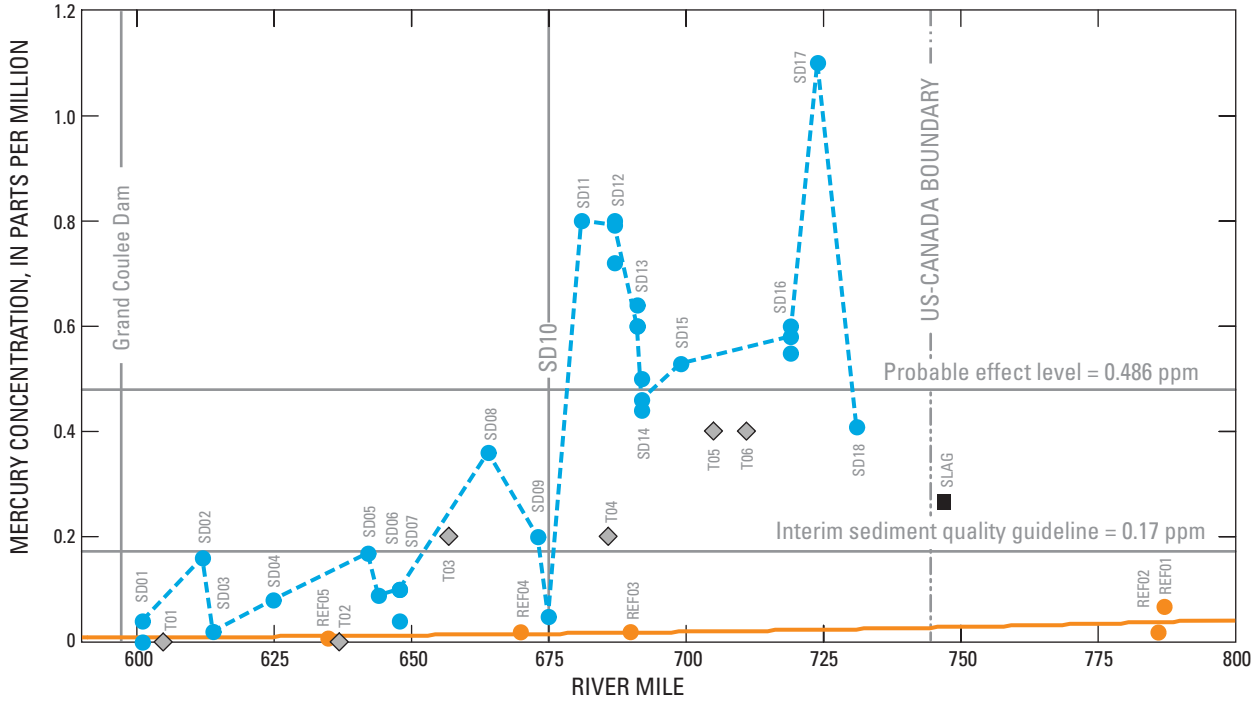


***D.* LEAD**

Figure 4.—*Continued.*



***E.* ZINC**



***F.* MERCURY**

Figure 4.—*Continued.*

Table 4. Comparison of slag-related trace elements and mercury concentrations in samples from riverine slag deposit collected April-May 2001 with concentrations from studies in 1995 and 1999 and from treated slag sampled in 1992, Lake Roosevelt and the upper Columbia River, Washington and British Columbia

[**Concentration: 1995 and 1999**: Data from Aquatic Resources, Ltd. (2001). Sample taken at Waneta, 10 miles downstream from Cominco, Trail plant (about river mile 746). **Concentration: 2001**: 2001 riverine slag deposit taken at river mile 747. **Treated slag**: Data reported in Bortleson and others, 2001. <, less than; µm, micrometer]

Trace element	Concentration, in parts per million (size fraction)			
	1995 (whole)	1999 (whole)	2001 (<63 µm)	Treated slag (whole)
Arsenic	42	24	26	100
Cadmium	4.1	1.1	4.6	10
Copper	3,743	1,112	940	6,000
Lead	312	235	500	870
Zinc	21,433	5,727	6,200	25,000
Mercury	<0.05	<0.02	0.27	<0.005

Variations in concentration gradients from the water to the bank may be attributable to the size of the T areas. The length of the T sampling areas ranged from about 1.5 to about 4 mi, and the width ranged from about 0.3 to 2 mi. At T01, T02, and T03, the widths were fairly uniform, between 0.3 and 0.5 mi, and the 15 sampling sites were nearly evenly spaced. In contrast, T04, T05, and T06 were all about 2 mi long, but their widths ranged from 0.3 to 2 mi. The distances between sampling sites along a transect varied considerably, some being very close together (within 300 ft) and others being separated by almost two-thirds of a mile.

The disparity in the distances of the sampling sites from the water's edge may have contributed to the variation in concentration gradients. The distance between each of the three sampling sites on a transect from T01, T02, T03, and T06 were much less that those of T04 and T05. The occurrence of and variation in gradients also may be attributable to how rapidly the water receded from the sampling areas.

Combining the results from the three composite samples from each of the T sites and calculating a mean concentration for arsenic, cadmium, copper, lead, zinc, and mercury for each T sampling area resulted in a concentration value that was comparable to the nearby SD sites. Mean concentrations of cadmium, copper, lead, zinc, and mercury for the T sampling areas showed a decreasing gradient downstream from the International Border to the dam (figs. 4*A*-4*F*). Arsenic concentrations varied greatly (fig. 4*A*) and did not show any discernible trend.

Spatially Distributed Areas

Concentrations of slag-related trace elements and mercury at the SD sampling areas all showed decreasing gradients from the Canadian border to the Grand Coulee Dam (fig. 4). For the slag-related trace elements, the magnitude and trends were similar to those observed in the means of concentrations at the T sampling areas. All these gradients, with the exception of arsenic, were very pronounced.

The mean trace-element concentrations in surficial bed sediments at the SD sampling areas varied throughout the length of the reservoir, but the trends mostly showed high concentrations in the upper reaches of the reservoir that quickly decreased, highly variable concentrations between SD09 and SD14, and gradually decreasing concentrations at the lower reaches. The gradients are most obvious for copper and zinc (figs. 4*C* and 4*E*) because the magnitudes of the values are much larger than the variability along the obvious predominant trend line. Values of the square of the coefficient of linear correlation (r^2) for plots of the natural logarithm of copper and zinc concentration to river mile are 0.796 and 0.672, respectively. Concentration gradients for cadmium and lead (figs. 4*B* and 4*D*) vary greatly throughout the reservoir but appear to be more linear in nature. In fact, regression analysis for both the natural logarithm and the normal data resulted in similar r^2 values, ranging between 0.5 and 0.6, for both of these elements. Mercury appears to show a similar gradient trend (fig. 4*F*), but with even more variation.

The trends in concentration along the length of Lake Roosevelt at the T and SD sampling areas generally were similar to those of the 1992 study (Bortleson and others, 2001), when Lake Roosevelt bed sediments were sampled at 72 sites between the Northport reach of the Columbia River and Grand Coulee Dam, and on its major and minor tributaries and beaches. The trends in median concentrations for arsenic, cadmium, copper, lead, zinc, and mercury at the T and SD sites in the upper reach (T05 and T06), the mid-reach (T03 and T04), and the lower reach (T01 and T02) were similar to those reported by Bortleson and others (2001), but the concentrations were significantly lower in most cases, especially for copper, lead, and zinc (table 5).

Table 5. Comparison of median concentrations of slag-related trace elements and mercury with median concentrations from a 1992 study and with riverine slag, treated slag, and Canadian sediment-quality guidelines

[Concentrations are given in parts per million. T, targeted site; SD, spatially distributed site; reach boundaries are defined as: Lower–confluence of Spokane River (~ river mile 639) to the Grand Coulee Dam (river mile 596); Mid–Marcus Flats (~ river mile 708) to confluence of Spokane River (~ river mile 639); and Upper–International boundary (river mile 745) to Marcus Flats (~ river mile 708). Concentrations in bold type are greater than or equal to the PEL]

		Arsenic	Cadmium	Copper	Lead	Zinc	Mercury
Upper Reach							
T	Median	14	**5.3**	110	**250**	**850**	0.43
SD	Median	12	**5.4**	140	**235**	**1,300**	**0.57**
1992	Median[1]	**20**	**6.3**	**300**	**430**	**2,000**	**1.40**
Mid Reach							
T	Median	9.7	2.9	36	**150**	**413**	0.21
SD	Median	11	**3.8**	60	**210**	**590**	0.44
1992	Median[1]	**15**	**7.0**	98	**380**	**930**	**1.40**
Lower Reach							
T	Median	9.6	0.7	21	29	120	0.01
SD	Median	8.9	0.4	21	24	120	0.06
1992	Median[1]	16	**4.7**	55	**190**	570	**0.50**
All Reaches							
T	Median	10.5	2.6	35.0	**145**	**401**	0.21
SD	Median	11.5	**3.6**	53.3	**195**	**520**	0.41
1992	Median[1]	16	**6.2**	85	**310**	**970**	**1.3**
Reference sites	Median	6.6	0.3	21	18	58	0.02
Riverine slag deposit	–	**26**	**4.6**	**940**	**500**	**6,200**	0.27
Treated slag[1]	–	**100**	**10**	**6,000**	**870**	**25,000**	<0.005
Interim sediment-quality guidelines[2]	–	5.9	0.6	35.7	35	123	0.17
Probable effect level[2]	–	17.0	3.5	197	91.3	315	0.486

[1]From Bortleson and others, 2001.
[2]Canadian sediment-quality guidelines from Canadian Council of Ministers of the Environment (2002).

Many of the sampling sites in the 1992 study were submerged, and the samples consisted of compositing the top 1.3 to 2.5 cm of several grab samples taken at each site. A limited number of bank deposits also was sampled along the middle and lower reaches of the reservoir. In contrast, in the current (2001) study, only the top few centimeters of exposed surficial sediments were sampled at targeted and spatially distributed depositional zones, and at several randomly chosen reference sites along the length of the reservoir and the Columbia River north of the reservoir. Differences in concentrations of the slag-related trace elements between the two studies can be attributed to natural dissipation processes that occurred over the course of nearly a decade between the studies, especially because the inputs from the major source of the contamination were significantly reduced. Sampling methods, hydrologic setting of sampling sites, grain size selected for analysis, and analytical methods also may have contributed to the differences.

During the 2001 study, concentrations of the major slag components, and most of the other trace elements analyzed for, deviated substantially from the trend between SD14 (RM 691) and SD10 (RM 675). Concentrations of most trace elements in bed sediment generally decreased between SD18 and SD15. Between SD14 and SD11, the concentrations increased, in some cases significantly (figs. 4*A*-*4E*). Concentrations decreased significantly at SD10, then increased slightly at SD09. The subsequent downstream sites showed a gradual decrease in concentration following the general gradient trend.

Numerous creeks, tributaries, and drainages enter the entire length of the reservoir, and between RM 690 and RM 675, they may be the source of additional trace elements that account for the large variations in concentrations from the general trend between SD18 and SD15. These, along with shoreline landslides, appear to be the major source of fine-grained sediments that enter the reservoir at irregular intervals along its entire length. The area around SD10 appears to have a relatively large influx of ‘fresh’ glacial sediments deposited by several streams. This site is just downstream of the mouth of Hall Creek (fig. 1), which is a deep, inundated canyon with nearly vertical walls composed of actively eroding fine-grained sediments. The creeks that flow into the reservoir near SD10 and T04 appear to contribute less-contaminated sediments, and thereby act to dilute the concentrations of slag-related trace elements. Tributaries were not sampled in this study, and the only tributary sampled in this section of the reservoir in the 1992 study was Hall Creek (Bortleson and others, 2001). The reported concentrations were only slightly higher than those measured at SD10 in the 2001 study (table 6).

Table 6. Concentrations of slag-related trace elements and mercury measured at two locations on Hall Creek, a minor tributary entering Lake Roosevelt, and at sampling area SD10 on Lake Roosevelt, Washington

[**Site location: Hall Creek**: Data from Bortleson and others (2001)]

Site location	River mile	Concentration, in parts per million					
		Arsenic	Cadmium	Copper	Lead	Zinc	Mercury
Hall Creek							
left bank	~676	8.0	1.2	30	50	150	0.1
mid-stream	~676	5.5	1.3	30	28	140	0.07
SD10							
right bank	675	6.8	0.5	24	41	120	0.05

Location of the sampling areas with respect to the right or left bank does not appear to have had an influence on the concentration fluctuations in this area because the sites were distributed fairly evenly between the right and left bank and there was no observed systematic bias. Areas SD13 and SD14 were located at the same river mile (RM 691), but were taken at opposite sides of the reservoir and had nearly equivalent values (table 3). Concentrations in duplicate samples taken at SD12, SD13, and SD14 varied only slightly (table 3).

The five slag-related trace elements and mercury also were found at the reference sites, but concentrations generally were much lower than those at the riverine-slag site and at the T and SD sites upstream of SD10 (fig. 4). The trace-element concentrations at the reference sites varied little throughout the study area. Arsenic concentrations varied the most.

Other Trace Elements

Trace-element concentrations may give clues to the distribution and origin of source material of the naturally occurring lake sediments, as well as contaminants associated with those sediments. The distribution of the major elements prominent in rock-forming minerals provides information on the source of the naturally occurring trace elements in the Lake Roosevelt system. The percentage of composition of major elements in soil—iron, aluminum, and titanium—in the T, SD, reference, and riverine-slag samples (table 3) is shown in figure 5. Percentages of iron and aluminum varied somewhat throughout the sampling sites, but the concentrations of all three elements were nearly equivalent to the reference concentrations throughout the reservoir.

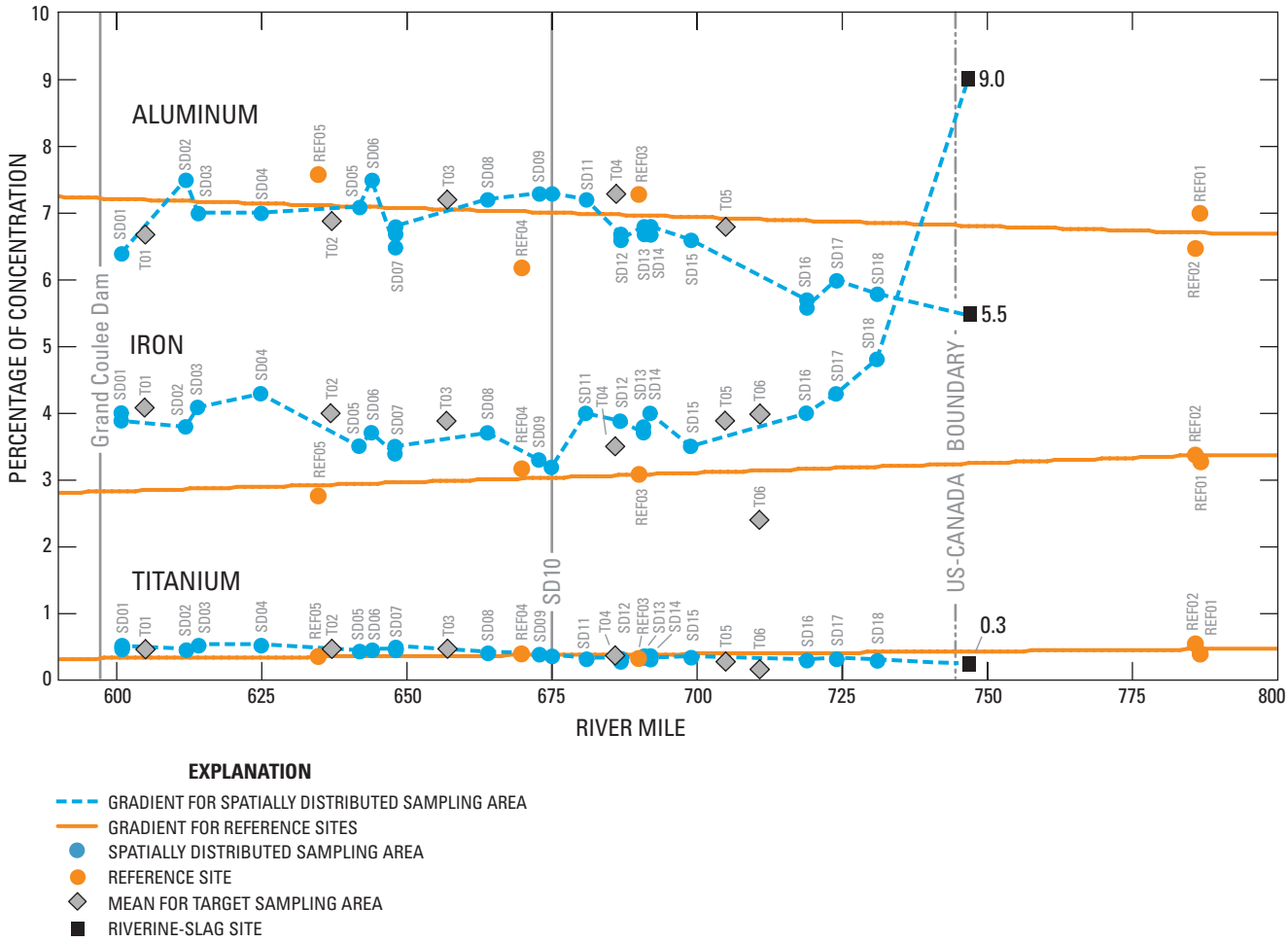


Figure 5. Gradients in concentrations of aluminum, iron, and titanium in fine-grained sediments along Lake Roosevelt and the upper Columbia River, Washington and British Columbia, April-May 2001.

The other trace elements analyzed for in the surficial bed sediments at T and SD areas (table 2) varied throughout the length of the reservoir. Most of them did show a general decrease in concentration from the International Border to the Grand Coulee Dam, with the exception of beryllium, chromium, cobalt, manganese, and nickel. Of these five, all but manganese were near the reference concentrations. Gradients for concentrations of vanadium and lithium were reversed—concentrations increased downstream—but also were near the reference site concentrations.

It is sometimes possible to normalize data and reduce site-to-site variation by using a non-reactive trace element as an indicator. Normalization also can help determine the influence of a source. In the Lake Roosevelt system, there are two primary sources of trace elements in the bed sediments—natural sources such as bank erosion, mineralization, and tributary inputs, and non-natural sources including slag and metallurgical effluent.

Aluminum is a component of clays and is very stable in the environment. The mean aluminum concentration at the reference sites was 6.9 ppm (standard deviation = 0.5), and concentrations increased slightly down lake (fig. 5). The mean aluminum concentration at the SD sites was 6.7 ppm (standard deviation = 0.5), very similar to the reference sites. The corresponding aluminum concentration in the riverine-slag sample was less than (5.5 ppm) the mean concentrations at the SD and reference sites. Plotting the natural logarithm of the aluminum-normalized trace-element concentration from the T and SD sampling areas with respect to river mile produced linear concentration gradients for the six trace elements of interest from the International Border to the dam. The slopes of the regression lines for cadmium, copper, lead, and zinc were all very similar (mean of 0.019±0.002), with r^2 values of about 0.7 when the outlying value at SD18 was omitted from the regression analysis. The slope of the regression line for mercury was slightly higher (0.029). The slope for arsenic, however, was significantly different, at 0.004, as evident when compared with the slopes for copper and zinc (fig. 6).

The decrease in the aluminum-normalized cadmium, copper, lead, and zinc concentrations down lake indicates that the measured concentrations are not an artifact of grain-size variations or were not already in the clay particles. It also shows that the variations in these trace metals are not explained by variations in aluminum. This implies that there is a source other than the natural environment contributing to the presence of cadmium, copper, lead, and zinc in the Lake Roosevelt bed sediments.

Tin is a trace element that was present in the riverine-slag sample at 72 ppm, but only had a median concentration of 1.1 ppm in the reference samples. In addition, tin showed a concentration gradient profile very similar to that of copper, lead, and zinc (fig. 7). Therefore, tin was used as an indicator of slag, and the T and SD data were normalized on the tin concentration.

Plots of the natural logarithm of the tin-normalized concentrations of arsenic, cadmium, copper, lead, and zinc with respect to river mile all showed a bimodal distribution. Between SD18 and SD11, the normalized concentrations increased. Arsenic, cadmium, and lead (fig. 8), showed the strongest correlations, with slopes in the upper part of the lake that ranged from -0.030 to -0.033. The slope of the regression lines in the same part of the lake for copper and zinc were -0.007 and -0.010, respectively. Between SD09 and SD01, the normalized concentrations decreased, with the exception of arsenic (fig. 8). The slope of the arsenic regression line between SD01 and SD09 was still negative (increasing concentrations down lake), but it was less steep. Data from SD10 were not included in the regression analyses.

These results indicate that the treated slag is the most likely source for most of the cadmium, copper, lead, and zinc concentrations and for the variation in concentrations in the bed sediments in the upper part of the lake from RM 747 to about SD11 (RM 681). Down lake of SD11, the influence of the treated-slag contribution to the arsenic, cadmium, copper, lead, and zinc concentrations seems to diminish as the influx of uncontaminated sediments reduce concentrations of these elements.

Mercury also showed a bimodal distribution with increasing Sn-normalized concentrations between SD18 and SD11, with a slope of -0.027. Mercury concentrations in the bed-sediment samples from SD18 to SD08 were two to three times higher than in the upstream riverine-slag sample, and indicate that the mercury is not directly associated with the slag. Analytical data from earlier reports also indicate that mercury is not a component of treated slag (see table 4), however mercury has been associated with slurry effluent from the smelting facility in Trail, British Columbia (Bortleson and others, 2001; G3 Consulting, Ltd., 2001.

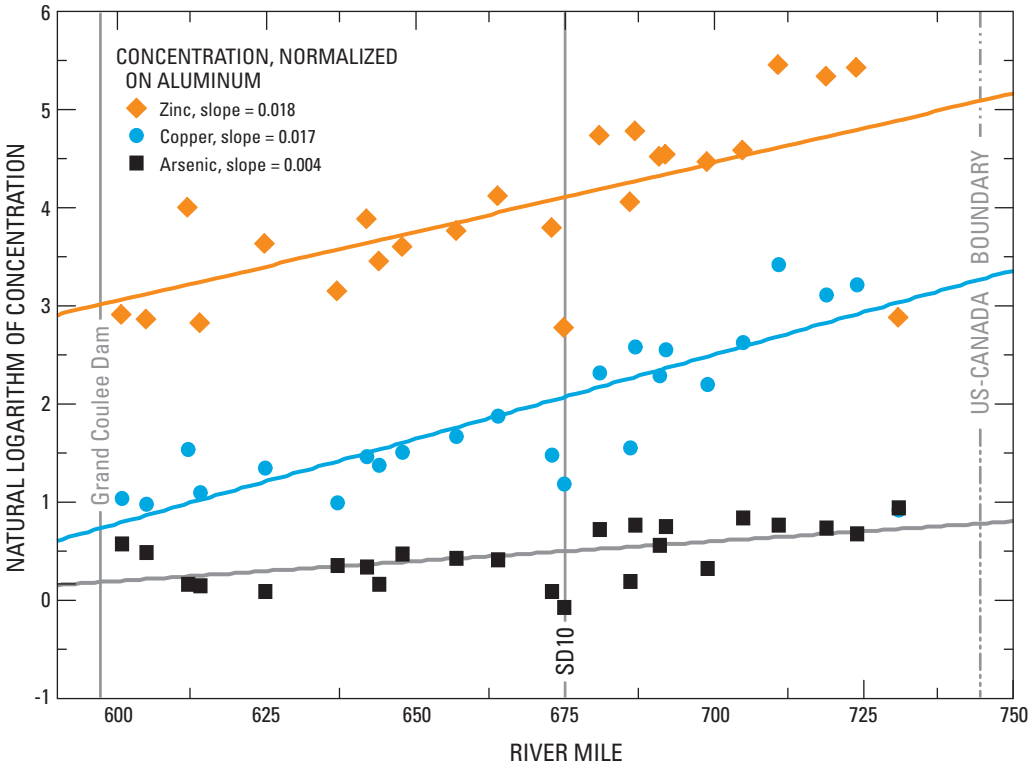


Figure 6. Natural logarithm of the aluminum-normalized concentrations of zinc, copper, and arsenic in fine-grained sediments with respect to river mile along Lake Roosevelt and the upper Columbia River, Washington and British Columbia, April-May 2001.

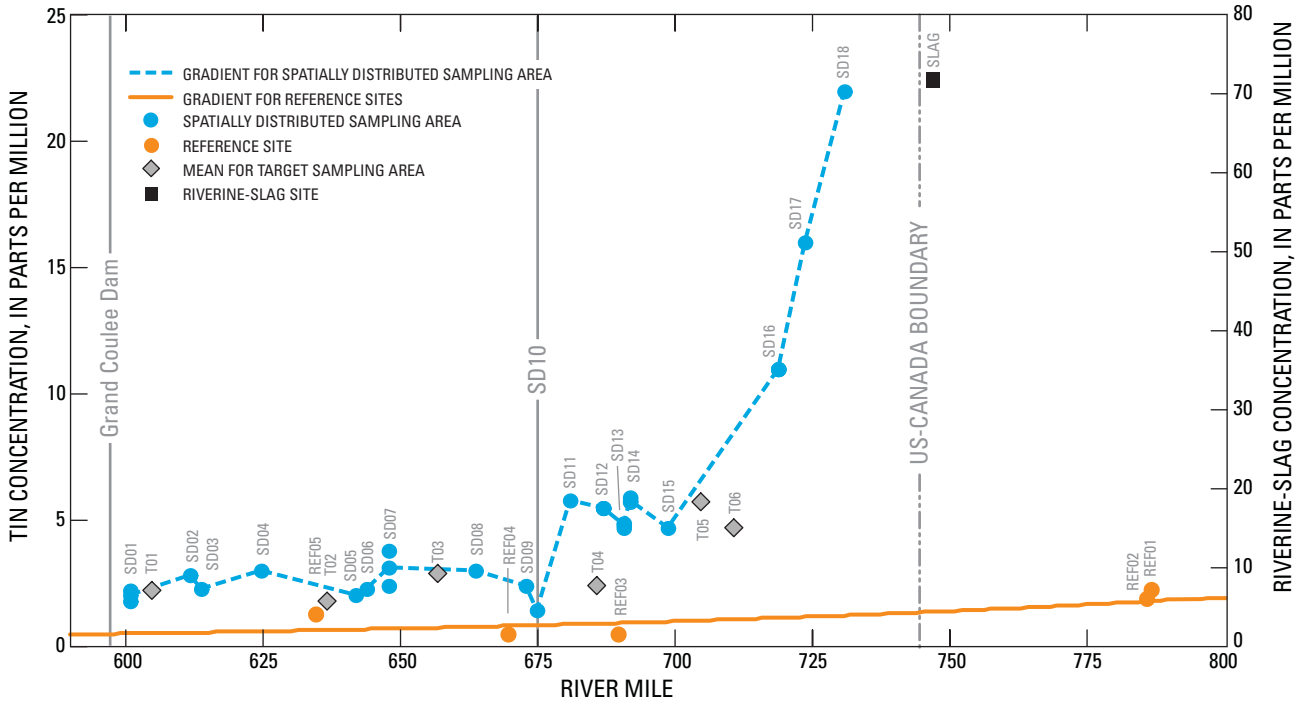


Figure 7. Gradient in concentration of tin in fine-grained sediments along Lake Roosevelt and the upper Columbia River, Washington and British Columbia, April-May 2001.

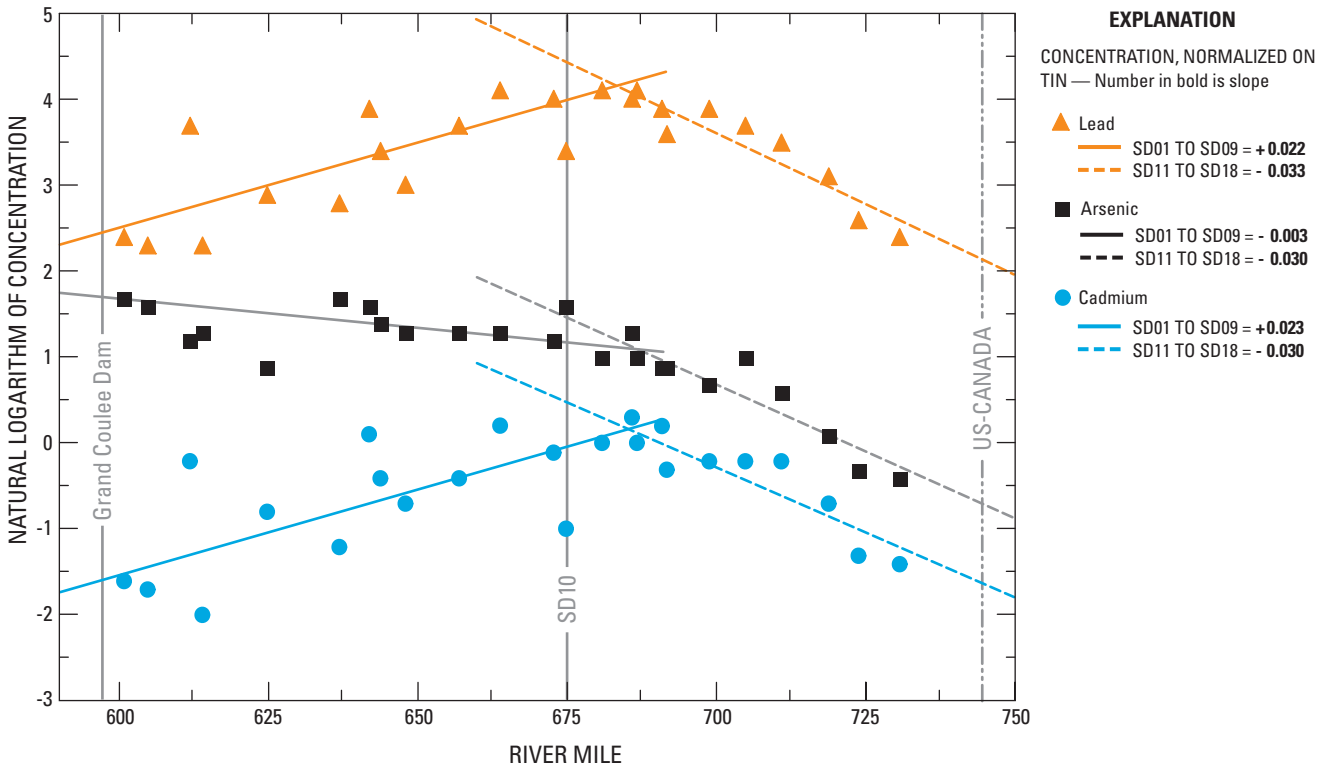


Figure 8. Natural logarithm of the tin-normalized concentrations of lead, arsenic, and cadmium in fine-grained sediments with respect to river mile along Lake Roosevelt and the upper Columbia River, Washington and British Columbia, April-May 2001.

Comparison of Concentrations of Slag-Related Trace Elements with Sediment-Quality Guidelines

Concentrations of slag-related trace elements at the T and SD sampling areas were compared with the sediment-quality guidelines for freshwater environments developed by the Water Resources Branch of the Ontario Ministry of Environment and Energy (Persaud and others, 1991; Jaagumagi, 1993) and updated in 2002 (Canadian Council of Ministers of the Environment, 2002). These sediment-quality guidelines provide scientific benchmarks, or reference points, for evaluating the potential for observing adverse biological effects in aquatic systems. The guidelines are derived from the available toxicological information according to the formal protocol established by the Canadian Council of Ministers of the Environment (1995).

The guidelines are based on two assessment levels of toxicity, the threshold effect level (TEL) and the probable effect level (PEL). The TEL is defined as the level below which adverse biological effects are expected to occur rarely, i.e., fewer than 25 percent. The PEL is defined as the level above which adverse biological effects are expected to occur frequently, i.e., greater than 50 percent. Interim sediment-quality guidelines (ISQG) are used in place of TEL when there is insufficient toxicological information available (Canadian Council of Ministers of the Environment, 2001). For the trace elements discussed in this report, only ISQG and PEL values have been issued.

Concentrations of cadmium, copper, lead, zinc, and mercury at the reference sites were all generally below the ISQG. Lead and zinc concentrations at REF01, however, were slightly above the ISQG values. Concentrations at most of the T and SD areas, however, were consistently above the ISQG values (figs. 4*B*, 4*C*, 4*D*, 4*E*, and 4*F*). The mean concentrations of arsenic at the reference sites (6.5 ppm) was slightly above the ISQG (5.9 ppm), as were the concentrations at all T and SD sites (fig. 4*A*).

Copper concentrations exceeded the PEL guidelines (table 5) at only one site—SD18 (fig. 4*C*). Cadmium, lead, zinc, and mercury exceeded the PEL guidelines (table 5) at nearly all sites above SD10, and nearly one-half of the sampling areas below SD10 exceeded PEL guidelines for lead and zinc (figs. 4*B*, 4*D*, 4*E*, and 4*F*).

Canadian toxicity guidelines are based on the bioavailability of trace metals to the benthic organisms. While treated slag, primarily an iron silicate matrix, is reported to be inert and therefore not bioavailable (William Duncan, Teck Cominco Metals Ltd., written commun., April 2003), several laboratory studies have reported toxicity and reproductive depression for several test species (Bortleson and others, 1992; Godin and Hagen, 1992; Nener, 1992) when exposed to slag from the Trail, B.C. smelter. The results from a field study of benthic invertebrate communities (Bortleson and others, 1992) in three erosional habitats between SD18 and the International Border showed relatively low total abundance, diversity, and number of individuals that compose the EPT index. In addition, the communities resembled those commonly associated with a chemical or physical disturbance. The EPT index refers to the number of distinct taxa within the insect orders *Ephemeroptera*, *Plecoptera*, and *Trichopetera*. These groups are considered pollution-sensitive taxa.

Implications to Airborne Trace Metal Concentrations

The Clean Air Act, which was last amended in 1990, requires EPA to set National Ambient Air Quality Standards (NAAQS) for pollutants considered harmful to public health and the environment (http://www.epa.gov/airs/criteria.html). The Clean Air Act established two types of national air-quality standards—Primary and Secondary. Primary standards set limits to protect public health, including the health of "sensitive" populations such as asthmatics, children, and the elderly. Secondary standards set limits to protect public welfare, including protection against decreased visibility and damage to animals, crops, vegetation, and buildings.

The EPA Office of Air Quality Planning and Standards (OAQPS) has set NAAQS for six principal pollutants, which are called "criteria" pollutants. These are carbon monoxide, nitrogen dioxide, ozone, lead, particulate matter with diameters of 10 and 2.5 µm or less (PM10 and PM2.5), and sulfur dioxide.

The second phase of this study will sample air in the study area for concentrations of particulate matter with diameters of 10 µm or less and most of the trace elements listed in table 2, with the exception of mercury. These data will be provided to interested health-related organizations. The inhalation threat from airborne trace elements in the ambient atmosphere, slag related or otherwise, is largely unknown. The health effects and routes of exposure, such as acute and chronic inhalation, of reference concentrations for the trace elements listed as hazardous air pollutants can be viewed at http://www.epa.gov/ttn/atw/hapindex.html.

On the basis of the measured concentrations and areal distribution of the slag-related and other trace elements at the T and SD sites, the air samples are expected to contain a similar suite of trace elements. Concentrations in the air are expected to increase up-lake, based on the direction of the prevailing winds. The Washington State Department of Ecology has an active air-quality monitoring program throughout the State. This program monitors for ozone, PM10, and PM2.5, but does not monitor for any associated toxic chemical or trace elements in the Lake Roosevelt area.

SUMMARY

Concern about the potential exposure to contaminated sediment from inhalation of airborne sediment particles along Lake Roosevelt during reservoir drawdown periods prompted a cooperative study by the U.S. Geological Survey, the Confederated Tribes of the Colville Reservation, the Lake Roosevelt Water-Quality Council, the Bureau of Reclamation, and the National Park Service of concentrations and distribution of trace elements in the fine-grained fraction of beach and bed sediments. The principal contaminants of interest in this study were trace elements associated with slag discharge (arsenic, cadmium, copper, lead, and zinc) and smelting effluent discharge (mercury). Each year, from about January through April, the water level in Lake Roosevelt is decreased substantially, primarily for flood-control purposes. Given the right exposure, drying, and wind conditions, significant amounts of contaminated sediment can be entrained into the lower atmosphere

along Lake Roosevelt. For this study, the fine-grained sediments were defined as those smaller than 63 micrometers for use as a screening method. This study is the first of a two-part study to assess the contributions from trace elements in exposed bed sediments to elemental concentrations of airborne particles.

In order to determine the concentrations and distribution of trace elements in the fine-grained fraction of exposed sediments, 24 areas along Lake Roosevelt and the upper Columbia River were sampled between April 23 and May 4, 2001. Surficial samples of exposed beach and bed sediments were collected using two different sampling designs—targeted (T) and spatially distributed (SD). Six T sampling areas were selected because they contained large areas of exposed, fine-grained material known to be sources for airborne particulate matter during high wind events and their proximity to downwind communities and recreational areas. Because several of the T sites were extremely large, a sampling strategy was designed to determine the variation in the trace-element concentrations over the large depositional areas, and to determine if concentration gradients were present from the shoreline to the 1,290-foot contour of full-pool elevation. Selection of SD sampling areas was based largely on location and size of the exposed bed-sediment areas. Eighteen SD areas were selected between Northport and Grand Coulee Dam to provide a broad assessment of the distribution of trace elements in exposed beach and bed sediments along Lake Roosevelt. These concentrations were compared with concentrations at reference sites above lake level and upstream of contamination sources, with concentrations in riverine slag deposits, and with concentrations measured in previous studies.

The results of this study show that trace elements associated with treated slag and metallurgical waste are present in the fine-grained fraction (less than 63 micrometers) of exposed beach and bed sediments along the length of Lake Roosevelt. As such, it is possible that these trace elements will be a component of the wind-blown dust resulting from the drying and entrainment into the lower atmosphere of the sediments exposed annually during the drawdown of the reservoir for flood-control measures.

Trace-element concentrations showed a gradient from water to shore at some of the targeted (T) areas. Of the slag-related trace elements, concentrations of cadmium, copper, lead, and zinc decreased from the water line to the bank at T01, T02, and T03, at the lower part of the reservoir. At area T04, the gradients for concentrations for lead and mercury were reversed. Areas T05 and T06, at the upper reach of the lake, showed no gradient trends for any of the trace elements analyzed for.

The mean concentrations of the slag-related trace elements at the targeted areas (the averaged concentration of the three composite samples) showed a gradient of decreasing concentration downstream, from the International Border to Grand Coulee Dam. The trace-element concentrations at the spatially distributed (SD) areas varied, but the slag-related trace elements showed generally pronounced decreases in concentration from near the International Border to Grand Coulee Dam. Concentrations of all trace elements analyzed for varied greatly between SD15 (RM 699) and SD10 (RM 675). The large variations in this area were attributed to the addition of natural sediments from streams and creeks in the area draining into the lake, as well as from erosive slumping of bank deposits. The subsequent downstream areas showed a gradual decrease in concentration following the general gradient trend.

Concentrations of all slag-related trace elements generally were greater than the Canadian ISQG for trace metals. Cadmium, lead, zinc, and mercury, however, exceeded the Canadian PEL guidelines for trace metals at most of the sampling areas upstream from SD10. Both lead and zinc concentrations also exceeded PEL values at nearly 50 percent of the sampling sites downstream from SD10 as well.

Based on the measured concentrations and areal distribution of slag-related and other trace elements at the T and SD areas, it is possible that the air samples collected during the second phase of this study will contain a similar suite of trace elements. It also is expected that the concentrations of trace elements in the air will increase up lake, based on the results of the sediment phase of the study and the predominant wind direction.

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Appendix 1. Analytical results and relative standard deviations for duplicate samples and National Institute of Standards Technology reference material for quality control

[**Duplicates**: REF, reference site; SD, spatially distributed area; T, targeted area and sample number; DUP, duplicate sample; RSD, relative standard deviation. **Standard reference material**: NIST, National Institute of Standards and Technology; USGS, U.S. Geological Survey. Values in parentheses are uncertified values and are included for reference only. ppm, parts per million in micrograms per gram; %, percent; NA, not applicable; ND, not detected; <, less than]

Duplicates	Silver	Copper	Lead	Zinc	Cadmium	Mercury	Chromium	Cobalt	Nickel	Barium	Vandium	Lithium	Beryllium	Molybdenum
	(ppm)													
REF02	<0.5	8.8	25	73	0.2	0.02	110	9	34	830	96	18	2.1	<1
DUP REF02	<0.5	8.5	25	71	0.3	0.01	110	9	33	820	96	18	2.1	<1
RSD	NA	0.2	0	1	0.1	0.01	0	0	1	7	0	0	0	NA
SD08	0.7	46	180	460	3.4	0.37	87	13	35	1,000	110	29	2.1	1.2
DUP SD08	<0.5	47	180	440	3.5	0.35	85	13	35	1,000	100	29	2.1	1.1
RSD	NA	1	0	14	0.1	0.01	1	0	0	0	7	0	0	0.1
SD16	1.9	130	220	1,200	5.3	0.61	80	11	28	1,200	92	23	1.8	2.1
DUP SD16	1.6	120	220	1,200	5.5	0.55	79	11	28	1,300	91	22	1.8	2.1
RSD	0.2	7	0	0	0.1	0.04	1	0	0	71	1	1	0	0
T0310	<0.5	54	170	420	3.3	0.36	93	14	41	1,200	110	34	2.2	1.4
DUP T0310	0.5	54	170	450	3.4	0.40	94	15	43	1,200	110	33	2.3	1.6
RSD	NA	0	0	21	0.1	0.03	1	1	1	0	0	1	0.1	0.1
T0620	2.8	140	310	990	6.9	0.68	82	12	32	1,400	89	30	2.1	2.4
DUP T0620	2.6	150	310	980	7.1	0.64	81	12	31	1,400	89	30	2.0	2.3
RSD	0.1	7	0	7	0.1	0.03	1	0	1	0	0	0	0.1	0.1

Standard reference material	Silver	Copper	Lead	Zinc	Cadmium	Mercury	Chromium	Cobalt	Nickel	Barium	Vandium	Lithium	Beryllium	Molybdenum
	(ppm)													
NIST 2709	<0.5	35±1	19±1	106±3	0.4±0.01	1.40±0.08	130±4	13±1	88±5	970±40	112±5	ND	ND	(2)
Reported value														
Found	<0.5	34	18	100	0.3	1.3	120	13	85	940	110	58	5.0	2
Found	<0.5	34	18	100	0.3	1.4	120	13	84	990	110	56	5.3	2
NIST 2711	4.6±0.4	114±2	1,162±30	350±5	41.7±0.3	6.25±0.19	(47)	(10)	21±1	730±40	82±3	ND	ND	(2)
Reported value														
Found	4.6	110	1,200	350	41.0	6.3	49	10	21	710	80	29	2.1	1
Found	4.5	110	1,200	350	40.0	6.1	48	10	21	760	80	28	2.1	2
NIST 1646A	<0.5	10±0.3	12±1	49±2	0.15±0.07	0.04	41±2	5	23	210	45±1	17	<1	1.8
Reported value														
Found	<0.5	10	11	50	0.1	0.03	43	5	26	210	46	17	0.9	2
Found	<0.5	10	10	48	<0.1	0.02	44	5	25	230	45	16	0.9	2
USGS MAG-1	0.08±0.02	30±3	24±3	130±6	0.2±.03	(0.02)	97±8	20±2	53±8	480±41	140±6	79±4	3.2±0.4	2±1
Reported value														
Found	<0.5	27	27	130	0.1	0.05	110	21	52	480	140	84	2.9	1
Found	<0.5	27	27	140	<0.1	0.04	110	21	52	500	140	85	2.9	1
USGS RGM-1	<0.5	12±2	24±3	32±6	0.1	0.02	4±1	2±1	4±2	807±46	13±2	57±8	2.4±0.2	2±1
Reported value														
Found	<0.5	10	25	32	0.1	0.01	5	2	2	850	12	62	2.3	2
Found	<0.5	11	24	36	<0.1	<0.01	5	2	2	880	12	65	2.4	3
USGS SDO-1	0.2	60±10	28±5	64±7	<2-<10	0.19±0.08	66±8	47±6	100±10	ND	160±20	29±6	3.3±0.6	130±20
Reported value														
Found	<0.5	57	23	66	0.1	0.19	74	46	100	ND	160	32	3.0	140
Found	<0.5	57	25	64	<0.1	0.14	79	49	100	ND	160	31	3.0	150

Appendix 1. Analytical results and relative standard deviations for duplicate samples and National Institute of Standards Technology reference material for quality control—*Continued*

[**Duplicates**: REF, reference site; SD, spatially distributed area; T, targeted area and sample number; DUP, duplicate sample; RSD, relative standard deviation. **Standard reference material**: NIST, National Institute of Standards and Technology; USGS, U.S. Geological Survey. Values in parentheses are uncertified values and are included for reference only. ppm, parts per million in micrograms per gram; %, percent; NA, not applicable; ND, not detected; <, less than]

Duplicates	Phosphorus (ppm)	Strontium (ppm)	Arsenic (ppm)	Antimony (ppm)	Selenium (ppm)	Tim (ppm)	Iron (%)	Manganese (ppm)	Aluminum (%)	Titanium (%)	Total organic carbon (%)	Total carbon (%$)	Total sulfur (%)	Total nitrogen (%)
REF02	1,700	530	2.9	0.5	0.1	2.4	3.4	790	6.5	0.54	0.4	0.5	<0.1	<0.1
DUP REF02	1,700	530	3.4	0.7	0.1	1.3	3.4	810	6.4	0.55	0.7	0.4	<0.1	<0.1
RSD	0	0	0.4	0.1	0	0.8	0	14	0.1	0.01	0.2	0.1	NA	NA
SD08	1,300	370	11	2.6	0.4	3.6	3.7	1,700	7.2	0.44	1.0	1.1	<0.1	0.1
DUP SD08	1,300	370	11	2.8	0.5	3.2	3.7	1,800	7.1	0.43	1.0	1.1	<0.1	0.1
RSD	0	0	0	0.1	0.1	0.3	0	71	0.1	0.01	0	0	NA	0
SD16	1,500	390	11	12	1.0	11	4.0	710	5.7	0.33	1.4	2.8	0.4	0.2
DUP SD16	1,500	390	13	14	1.0	11	4.0	680	5.6	0.33	1.4	2.7	0.3	0.2
RSD	0	0	1	1.4	0	0	0	21	0.1	0	0	0.1	0.1	0
T0310	1,300	370	14	3.0	0.6	3.3	3.9	1,500	7.5	0.42	0.9	0.9	<0.1	0.1
DUP T0310	1,300	390	14	3.4	0.7	3.7	4.0	1,500	7.5	0.43	0.9	0.9	<0.1	0.2
RSD	0	14	0	0.3	0.1	0.3	0.1	0	0	0.01	0	0	NA	0
T0620	1,500	370	14	12	1.2	8.7	3.7	610	6.3	0.32	2.3	2.9	0.1	0.3
DUP T0620	1,400	360	14	12	1.2	7.5	3.7	610	6.2	0.32	2.4	3.0	0.1	0.3
RSD	71	7	0	0	0	0.8	0	0	0.1	0	0.1	0.1	0	0

Standard reference material	Phosphorus (ppm)	Strontium (ppm)	Arsenic (ppm)	Antimony (ppm)	Selenium (ppm)	Tim (ppm)	Iron (%)	Manganese (ppm)	Aluminum (%)	Titanium (%)	Total organic carbon (%)	Total carbon (%)	Total sulfur (%)	Total nitrogen (%)
NIST 2709	620±50	230±2	18±1	7.9±.6	1.6±0.1	ND	3.5±0.1	540±20	7.5±0.1	0.34±0.02	1.2	1.2	0.1	ND
Reported value														
Found	620	230	19	7.7	1.8	1	3.6	550	7.6	0.33	1.0	1.1	0.1	0.1
Found	610	230	18	7.3	1.7	<1	3.5	550	7.4	0.33	1.0	1.2	0.1	0.1
NIST 2711	860±70	245±1	105±8	19±2	1.5±0.1	ND	2.9±0.1	640±30	6.5±0.1	0.31±0.02	2.0	2.0	0	ND
Reported value														
Found	790	240	100	20	1.5	4	2.9	660	6.6	0.29	1.8	1.7	<0.1	0.1
Found	800	250	100	21	1.5	4	2.9	630	6.6	0.29	1.7	1.7	<0.1	0.2
NIST 1646A	270±10	68	6.2±0.2	0.30	0.2±0.1	1	2.0±0.1	234±3	2.3±0.02	0.46±0.02	ND	ND	0.3±0.1	ND
Reported value														
Found	300	74	6.3	0.3	0.2	1	2.0	220	2.3	0.47	0.5	0.6	0.3	<0.1
Found	290	76	6.2	0.3	0.3	1	2.0	240	2.3	0.45	0.5	0.6	0.3	<0.1
USGS MAG-1	700±100	146±15	9.2±1.2	1.0±0.1	1.2±0.1	3.6±1	4.8±0.2	760±70	8.7±0.2	0.45±0.04	2.15±0.4	2.15±0.4	0.4±0.1	0.08
Reported value														
Found	700	140	9.8	0.9	1.4	3	4.8	740	8.7	0.42	2.2	2.2	0.2	0.3
Found	700	140	9.7	0.9	1.6	3	4.8	710	8.6	0.41	2.2	2.2	0.2	0.3
USGS RGM-1	210±15	108±10	3.0±.4	1.3±0.1	<0.1	4.1±0.4	1.3±0.1	282±30	7.3±0.1	0.16±0.02	<0.1	<0.1	<0.1	ND
Reported value														
Found	190	100	2.4	1.0	<0.1	3	1.3	280	7.2	0.17	<0.1	<0.1	<0.1	<0.1
Found	190	110	2.7	1.3	<0.1	3	1.3	290	7.3	0.17	<0.1	<0.1	<0.1	<0.1
USGS SDO-1	480±30	75±11	69±9	4.1-4.8	1.9-6.8	3.7±1.2	6.5±0.2	320±40	6.5±0.1	0.43±0.02	10±0.4	10±.4	5.4±0.4	0.35
Reported value														
Found	470	78	70	3.7	2.3	2	6.4	300	6.3	0.40	9.7	9.5	4.8	0.4
Found	470	82	65	5.0	1.6	3	6.4	290	6.5	0.40	9.4	9.5	4.8	0.4

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