US Army Corps of Engineers®
Portland District

BUREAU OF RECLAMATION

SEDIMENT QUALITY REPORT

GRAND COULEE, LAKE ROOSEVELT
COLUMBIA RIVER BASIN
COLUMBIA RIVER, WASHINGTON

Grand Coulee, Lake Roosevelt

Sediment Quality Report
August 2020

EXECUTIVE SUMMARY

The scope of this evaluation includes the reach of the Columbia River from the Grand Coulee Dam upstream to the U.S.-Canada border, a reach length of about 150 miles. This appendix provides an analysis of the existing sedimentation conditions for Lake Roosevelt and the Grand Coulee Dam along the upper Columbia River. The analysis of existing conditions in this appendix is limited to physical and chemical parameters of sediment and sediment-related concerns within the reach. It should be noted that ongoing sediment analysis by Teck Resources Limited (Teck) under U.S. Environmental Protection Agency (EPA) oversight continues past the time of this report's publication, and conclusions made regarding slag-associated contamination in this report may not reflect the current status of the projects analysis.

CONTENTS

EXECUTIVE SUMMARY i
CONTENTS ii
ACRONYMS iv

SECTION 1 - INTRODUCTION 1-1

1.1 SCOPE OF STUDY 1-1
1.2 SEDIMENT EVALUATION FRAMEWORK GUIDANCE 1-1

SECTION 2 - WATER QUALITY 2-1

2.1 GENERAL DESCRIPTION 2-1
2.1.1 Geology 2-2
2.1.2 Sediment Loading in the Reservoir 2-3
2.1.3 Past Dredging 2-4
2.1.4 Land Use 2-4
2.1.5 Management Area 2-4
2.2 EXISTING DATA 2-5
2.2.1 Sediment Characterization Studies 2-5
2.2.2 Existing 303(d), 305(b) and Total Maximum Daily Loads 2-1
2.2.3 Physical Data 2-2
2.2.4 Chemical Data 2-2
2.2.5 Biological Data 2-20
2.2.6 Elutriate Data 2-20
2.3 CHEMICALS OF CONCERN 2-20
2.4 CONCEPTUAL SITE MODEL 2-21
2.4.1 Secondary Media and Release Mechanisms 2-21
2.4.2 Exposure Routes 2-22

SECTION 3 - REFERENCES 3-1

TABLES

Table 2-1. Porewater Concentration of Select Analytes Throughout Lake Roosevelt .. 2-6
Table 2-2. Distribution of Particle Sizes by Grain Size Percent within Lake Roosevelt 2-2
Table 2-3. Percent Weight Composition of Slag in Sediment Samples by River Mile .. 2-4
Table 2-4. Percent Distribution by Size Class of Slag in Sediment Samples by River Mile 2-5
Table 2-5. Average Content of Metals in Sediments as Sampled from the U.S-Canada Border to Grand Coulee Dam 2-6
Table 2-6. Total Trace Element Concentrations at Select Sites 2-7

FIGURES

Figure 2-1. Map Displaying Management Areas Within and Surrounding Lake Roosevelt 2-2
Figure 2-2. Site Locations Sampled in 1992 2-8
Figure 2-3. Lead Concentration by River Mile from RM 745 to 596 in the Mainstem of Lake Roosevelt 2-9
Figure 2-4. Zinc Concentration by River Mile from RM 745 to RM 596 in the Mainstem of Lake Roosevelt 2-10
Figure 2-5. Distribution of Sediment Particle Size Within Lake Roosevelt by River Mile 2-12
Figure 2-6. Map of Locations of Core Samples Collected 2-13
Figure 2-7. Zinc Concentration from Core Samples 2-14
Figure 2-8. Lead Concentration from Core Samples 2-15
Figure 2-9. Copper Concentration from Core Samples 2-16
Figure 2-10. Arsenic Concentration from Core Samples 2-17
Figure 2-11. Cadmium Concentration from Core Samples 2-18
Figure 2-12. Mercury Concentration from Core Sample 2-19

ACRONYMS

Acronym	Description
% w/w	Percent Weight by Weight
µg/L	Micrograms Per Liter
EPA	U.S. Environmental Protection Agency
mg/kg	Milligrams Per Kilogram
mg/L	Milligrams Per Liter
PCBs	Polychlorinated Biphenyls
Reclamation	Bureau of Reclamation
RM	River Mile
SEF	Pacific Northwest Sediment Evaluation Framework
Teck	Teck Resources Limited
USGS	U.S. Geological Survey

SECTION 1 - INTRODUCTION

1.1 SCOPE OF STUDY

The scope of this evaluation includes the reach of the Columbia River from the Grand Coulee Dam upstream to the U.S.-Canada border, a reach length of about 150 miles. This appendix provides an analysis of the existing sedimentation conditions for Lake Roosevelt and the Grand Coulee Dam along the upper Columbia River. The analysis of existing conditions in this appendix is limited to physical and chemical parameters of sediment and sediment-related concerns within the reach. It should be noted that ongoing sediment analysis by Teck Resources Limited (Teck) under U.S. Environmental Protection Agency (EPA) oversight continues past the time of this report's publication, and conclusions made regarding slag-associated contamination in this report may not reflect the current status of the projects analysis.

1.2 SEDIMENT EVALUATION FRAMEWORK GUIDANCE

The Sediment Evaluation Framework for the Pacific Northwest (SEF) (Northwest Regional Sediment Evaluation Team Agencies 2016), was applied to this analysis to help guide the scope of analysis for characterizing existing conditions. The purpose of the SEF guidance is to provide a framework for assessing and characterizing sediment associated with dredging activities, including disposal, post-dredge surfaces, and water quality. The SEF guidance was specifically used to guide data acceptability and identification of contaminants of interest when evaluating existing data.

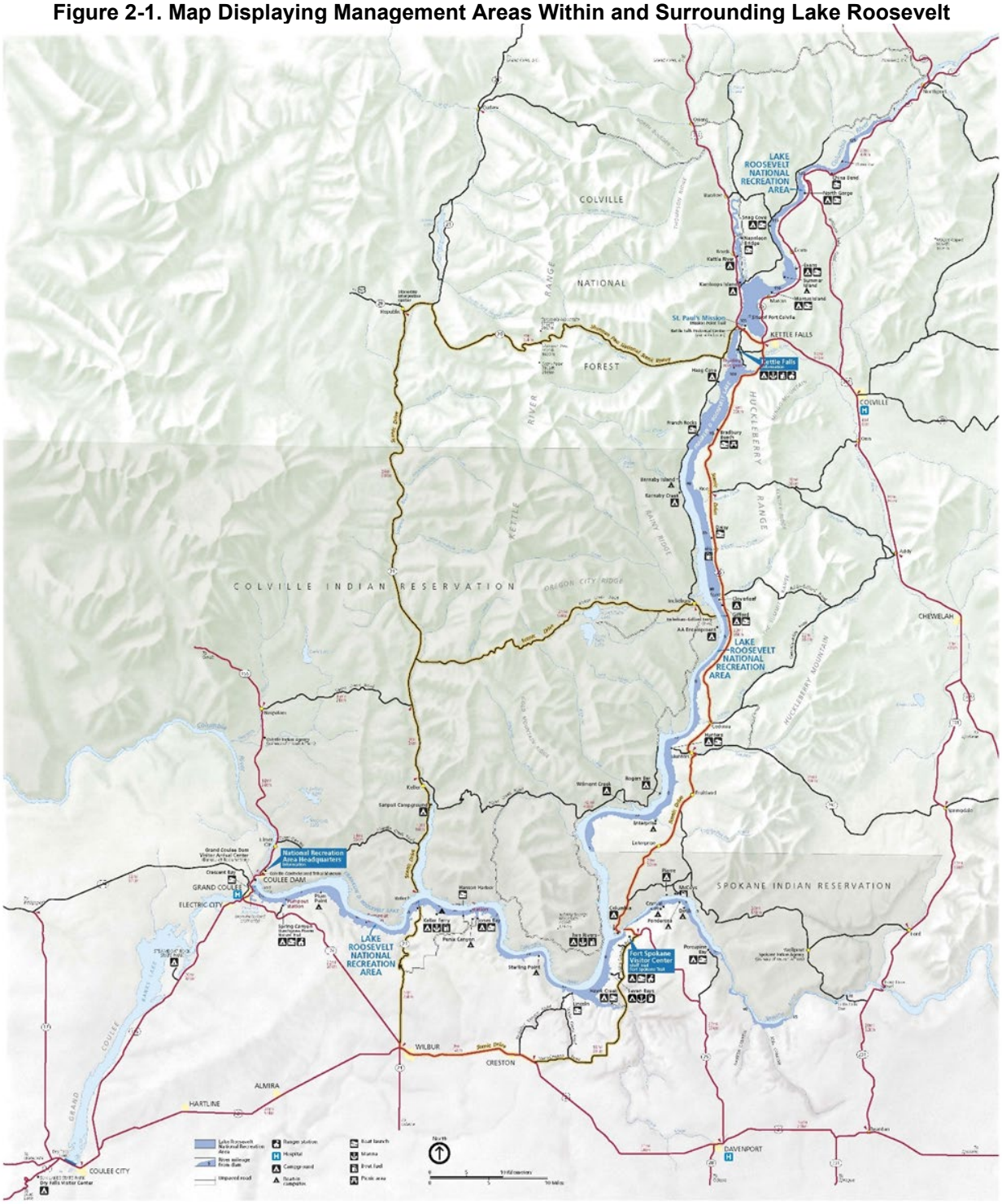
SECTION 2 - WATER QUALITY

2.1 GENERAL DESCRIPTION

The Columbia River between the U.S.-Canada border and Grand Coulee Dam is divided into four reaches based on geomorphic characteristics: (1) the Northport Reach, which extends from the U.S.-Canada border (River Mile [RM] 745) to Onion Creek (RM 730); (2) Lake Roosevelt Upper Reach between Onion Creek and Marcus Island (RM 708); (3) Lake Roosevelt Middle Reach, between Marcus Island and the Spokane River confluence (RM 639); and (4) Lake Roosevelt Lower Reach, between the Spokane River confluence and Grand Coulee Dam (RM 597) (Bortleson et. al 2001; Cox et al. 2005; Magirl et al. 2014). These reaches have been impacted by the Columbia River's impoundment at Grand Coulee Dam, approximately 148 river miles downstream of the U.S.-Canada border (Magirl et al. 2014). The Northport Reach is generally a free-flowing riverine segment; the intermediate transitional reach stretches from approximately Onion Creek to Marcus Flats (Figure 2-1), below which is the long lacustrine reach formed by the reservoir. The length of the transitional zone varies in hydraulics between riverine and lacustrine based on Columbia River streamflow and water surface elevation of Lake Roosevelt (Magirl et al. 2014).

Grand Coulee Dam was constructed between 1933 and 1942; closure of the dam created Lake Roosevelt, which is approximately 150 miles long, including 29 miles of inundation along the Spokane River (Reidel 1997). With a shoreline of more than 600 miles and covering approximately 125 square miles at full pool, it is the largest lake in Washington State. The reservoir provides multiple benefits to local communities including hydroelectric power, flood control, recreation opportunities, and water supply for irrigation. Lake Roosevelt functions as a sediment sink for the majority of incoming sediment load due to the slow velocity water conditions created by Grand Coulee Dam.

Figure 2-1. Map Displaying Management Areas Within and Surrounding Lake Roosevelt



Source: National Park Service (2016)

2.1.1 Geology

The geologic history of Lake Roosevelt has been largely shaped by (1) the uplift of the Cascade Range (ca. 15 to 36 million years ago) and the Rocky Mountains (ca. 55 to 80 million years ago) due to subduction of the Farallon Plate (Reiners et al. 2002; English

and Johnston 2004); (2) the eruption of the Columbia River Basalt Group between 17 and 6 million years ago (Hooper 1982), and (3) Quaternary glaciations (McMacken 1937; Alden 1953). The Columbia River Basalt Group forms high mesas above portions of the Lake Roosevelt rim, often overlain by loess. The geology of the riverine and lacustrine reaches of Lake Roosevelt are dominated by Quaternary glacial, glaciofluvial, and glaciolacustrine deposits that have been deposited on highly dissected bedrock, typically intrusive and metamorphic rocks of various age (Washington Division of Geology and Earth Resources [WDGER] 2016; Washington Geological Survey [WGS] 2017)). In addition, volcanic ash from eruptions associated with Mount Mazama, Glacier Peak, and Mount St. Helens have deposited large plumes of ash into the reservoir (Reidel 1997).

The geomorphology of the study reach was extensively shaped by glaciations, as the extent of the Cordilleran ice sheet blocked portions of the Columbia River in eastern Washington, and alpine glaciers and the Cordilleran ice sheet filled much of the Columbia River Basin above Grand Coulee (Alden 1953; Easterbrook 1992). The Okanogan Lobe of the Cordilleran ice sheet formed an ice dam, leading to the formation of Glacial Lake Columbia located near Spokane, Washington (Waitt 1985; Bureau of Reclamation [Reclamation] 2015). Sediment deposits from Glacial Lake Columbia of sand, gravel, and clay can be as much as 1,000 feet thick (Pardee 1918; Flint 1935; Flint 1939) and likely record a history of periodic filling and draining of Lake Columbia and inflows from Lake Missoula floods (Atwater 1984; Waitt 1985). Further evidence for multiple outburst floods from Glacial Lake Missoula exist in the Channeled Scablands and other floodways with large water-eroded cuts and flood gravel deposits (Waitt 1985).

Following deglaciation (ca. 13 thousand years ago), terraces remain that mark the previous extent of glacial lakes. Slopes descending from the terraces are steep and can drop as much as 1,000 feet in elevation to Lake Roosevelt (Reidel 1997). Approximately 10 percent of the shoreline along Lake Roosevelt is composed of bedrock, while the remaining 90 percent is composed of ice age deposits (Jones et al. 1961). Large landslides are documented along terraced slopes (Jones et al. 1961; Schuster 1979; Kiver and Standling 1995). Further investigations are needed to determine the potential for continued mass movement along the slopes; these landslides provide a potential sediment source for Lake Roosevelt.

2.1.2 Sediment Loading in the Reservoir

Sediment is primarily contributed to Lake Roosevelt from sediment loads transported by the Columbia and Spokane Rivers, sediment loads from other tributaries entering the reservoir, landslides, and bank erosion. Sediment grain size within Lake Roosevelt “include gravel, sand and silt located at the mouths of major tributaries and beneath the large landslides” (Reidel 1997). A portion of the historical sediment load in Lake Roosevelt includes slag from a smelt plant operated upstream of the U.S.-Canada border (Reidel 1997). The Lake Roosevelt shoreline is composed of approximately 10 percent bedrock and 90 percent erodible Pleistocene sediment deposits (Jones et al. 1961). Landslides are part of the natural sediment delivery to the Columbia River (Jones

et al. 1961), but can be induced more frequently by reservoir operations. Of 500 landslides studied by Jones et al. (1961), 49 percent occurred during the initial filling of Lake Roosevelt, and 30 percent occurred during subsequent reservoir drawdowns ranging from 33 to 66 feet during 1942 to 1953 (Schuster 1979). Reclamation began a formal landslide surveillance program in the 1960s along portions of the reservoir shoreline (Schuster 1979). Additional landslide activity occurred from 1969 to 1975 that may be attributed to large reservoir drawdowns in 1969 and 1974 of 131 feet to allow construction of the third power plant at Grand Coulee Dam (Schuster 1979). Areas particularly prone to numerous landslides in the past include “the north shore of the lower reach of the reservoir near the Sanpoil River, and in the middle reach near Ninemile Creek Cedonia, and the mouths of the Kettle and Colville Rivers” (Reidel 1997).

Reidel (1997) suggests “risk of landslides is a moderate concern for 30-50 ft drawdowns, and a major concern for drawdowns of more than 50 ft. Bureau of Reclamation management of reservoir levels has attempted to avoid these conditions for the past 20 years.” Reclamation uses rates of drawdown that do not exceed 1.5 feet per day to minimize occurrence of landslides (Reclamation 1993). Reclamation also uses a landslide monitoring program during significant drawdown operations to adaptively manage rates and extent of drawdown.

2.1.3 Past Dredging

No records of significant dredging of Lake Roosevelt exist.

2.1.4 Land Use

Early settlers in the late 1800s through early 1900s used the land for timber harvest, gold mining, and livestock grazing. Upon construction of Grand Coulee Dam, approximately 70,500 acres became inundated by Lake Roosevelt. In the decades following completion of Grand Coulee Dam, land use included agriculture and continued operation of lumber mills (Jones et al. 1961). Land use also included historical lead, zinc, gold (cyanidation process), and uranium mining and mineral processing (Reidel 1997). Upstream of the U.S.-Canada border, one of the world’s largest lead and zinc smelters has been in operation since 1890 (Reidel 1997). This plant is estimated to be the largest source of heavy metal pollution in the watershed (Reidel 1997). Small communities, recreation areas, roads, and railroads are currently located along Lake Roosevelt. Recreation is a popular land use in the area by residents and tourists. Visitor use in the Lake Roosevelt National Recreation Area increased from 250,000 in 1965 to more than 1.5 million by 1990 (Reidel 1997).

2.1.5 Management Area

Lake Roosevelt is managed between multiple interested organizations (Figure 2-1). Lake Roosevelt and the surrounding lands are managed through a cooperative effort consisting of five agencies: Reclamation, the National Park Service, the Bureau of Indian Affairs, the Confederated Tribes of the Colville Reservation, and the Spokane

Tribe of Indians (Reidel 1997). These five partners work closely with state and county agencies to meet fishery, wildlife, emergency response, and other needs. Additionally, the Bonneville Power Association and state and local governments have interests in the reservoir and surrounding area.

2.2 EXISTING DATA

The sediments in Lake Roosevelt have been analyzed by a number of studies, primarily with the purpose of studying the trace element concentrations from more than a century of smelting and other mining-related wastes being released into the Columbia River upstream of the waterbody. This report focuses on the larger and more recent studies that have been conducted within Lake Roosevelt. The more recent studies give a more accurate picture of what is currently found throughout the reservoir.

2.2.1 Sediment Characterization Studies

The primary source for data on the metal contamination of the sediments the reservoir is developed from studies by Teck, which are continuing at the time this report is written. Teck (2017) studied the sediment and porewater of the upper Columbia River from September 5 to October 25, 2013, from the U.S.-Canada border to Grand Coulee Dam. In one study alone, approximately 250 graphs display the concentration of a given analyte organized by the river mile the sample was collected at (Table 2-1). Due to the number of graphs and data, not all of the sample results will be described in depth here and will only be summarized. Currently, the data available only represents the findings of the Phase I and Phase II analysis; this analysis is a partial product in the ongoing study, and Phase III is in development.

Table 2-1. Porewater Concentration of Select Analytes Throughout Lake Roosevelt

Type	Analyte	Number of Results	Number of Detected Values	Minimum Detected	Mean Detected	Maximum Detected
Conventional	Alkalinity (mg/L)	81	81	54.8	130	384
Conventional	DOC (mg/L)	84	84	1.63	9.22	57.4
Conventional	Hardness as calcium carbonate (mg/L)	83	83	62.2	1.27127	545
Conventional	pH	82	82	7.17	7.89	9.19
Conventional	Sulfate (mg/L)	82	82	0.39	9.78	104
Conventional	Total chloride (mg/L)	82	82	0.5	3.08	30.1
Conventional	Total organic carbon (µg/L)	84	84	2.25	10.6	47.9
Metals (µg/L)	Aluminum	91	39	54.6	143	1040
Metals (µg/L)	Antimony	91	84	0.14	3.74	29.8
Metals (µg/L)	Arsenic	91	91	0.51	8.38	90.4
Metals (µg/L)	Barium	91	91	16.8	99.1	417
Metals (µg/L)	Beryllium	91	11	0.009	0.0211	0.07
Metals (µg/L)	Cadmium	91	63	0.007	0.244	1.21
Metals (µg/L)	Calcium	91	91	17400	39700	157000
Metals (µg/L)	Chromium	91	80	0.11	0.312	1.75
Metals (µg/L)	Cobalt	91	80	0.136	0.733	3.25
Metals (µg/L)	Copper	91	63	0.75	13	126
Metals (µg/L)	Iron	91	90	35.1	2010	20100
Metals (µg/L)	Lead	91	84	0.066	6.85	101
Metals (µg/L)	Magnesium	91	91	1130	7040	37400
Metals (µg/L)	Manganese	91	90	5.06	2110	12800
Metals (µg/L)	Nickel	91	25	2.5	5.66	14.3
Metals (µg/L)	Potassium	91	91	655	1940	5430
Metals (µg/L)	Selenium	91	25	0.3	0.516	1.2
Metals (µg/L)	Silver	91	39	0.007	0.133	0.672
Metals (µg/L)	Sodium	91	91	1710	3260	12500
Metals (µg/L)	Thallium	91	19	0.03	0.0602	0.172
Metals (µg/L)	Vanadium	91	80	0.529	4.21	50.9
Metals (µg/L)	Zinc	91	1	540	540	540

Note: mg/L = milligrams per liter; µg/L = micrograms per liter.
Source: Teck (2017)

Teck (2014), with EPA oversight, sampled 43 beaches along the upper Columbia River for metal contamination. In areas that exceeded acceptable tolerances and posed an exceptional exposure risk, Teck conducted remediation actions. In addition to sampling beach soils for metals, Teck studied the sediment particle size, smelting byproducts typically associated with a given river mile, and the percent weight of slag in sediment samples. Teck (2014) found that the concentration of slag decreases with downstream distance from the U.S.-Canada border.

Cox (2002) characterized sediment core samples collected at six locations in Lake Roosevelt for trace element concentration in the vertical profile. Elevated concentrations of arsenic, cadmium, copper, lead, mercury, and zinc were found in many of the samples. Wide variations of trace element concentrations were observed among core samples, often covering a concentration range of fivefold to tenfold with highest concentrations typically observed in the lower half of each profile below the 1964 horizon (Cox et al. 2005). This indicates that sediments older than 1964 tend to be associated with higher concentrations of heavy metals, and sediments deposited after 1964 tend to be associated with lower concentrations of heavy metals.

In another study, the U.S. Geological Survey (USGS) analyzed potential for sediment transport mobility within Lake Roosevelt for seven future hydro-regulation scenarios (Magirl et al. 2014). Magirl et al. (2014) on page 2 concluded that in “the riverine reach of the main-stem Columbia River, alluvial deposits are armored and likely are resistant to disturbance for discharge values up to 300,000 [cfs]. Some analyses indicated that riverine deposits could be stable for flows as large as 500,000 [cfs], but it was beyond the scope of the study to determine sediment transport of specific riverine deposits for flows between 300,000 and 500,000 [cfs].” Shoreline sediment composed of lacustrine alluvial deposits was noted to have potential for mobility during drawdowns where the sediment would be exposed to higher velocity river flows. In June 2012, during a large post-regulation discharge of 280,000 cfs, USGS observations with an acoustic doppler current profiler indicated that little fine-grained sediment was suspended in the water column (Magirl et al. 2014, page 13). “Relatively small acoustic backscatter from directly above the riverbed indicated that the armored bed had remained largely immobile during these high flows” (Magirl et al. 2014).

2.2.2 Existing 303(d), 305(b) and Total Maximum Daily Loads

Past water quality investigations determined that Lake Roosevelt was not meeting beneficial uses; it was found to be impaired with respect to various pollutants. In 1994, the lake and waters immediately downstream of the dam were listed on the Washington State’s Clean Water Act 303(d) list as impaired for polychlorinated biphenyls (PCBs), sediment bioassay, mercury, total dissolved gas, pH, fecal coliforms, water temperature, and dissolved oxygen. Due to the difficulties of establishing environmental regulations across the U.S.-Canada border, it took more than a decade to curtail pollution into the lake, and the effort continues to be a challenge. However, in 2004, Teck (current owners of the Trail smelter), which discharged mining waste biproducts into the Columbia River approximately 10 miles north of the U.S. Canada border, agreed to

comply with a 2003 EPA Unilateral Administrative Order under Superfund (Comprehensive Environmental Response, Compensation, and Liability Act) law. The agreement has resulted in remediation, restoration, and pollution controls, as well as continued study and analysis (EPA 2009).

2.2.3 Physical Data

Lake Roosevelt's river channel is governed by the underlying bedrock as the riverbed does not have a deep layer of alluvial sediments. Alluvial deposits are widely spaced and are generally small in volume in both the riverine and lacustrine reaches of the reservoir (Magirl et al. 2014). A comparison of riverbed elevations between bathymetry measurements taken in 2011 and 1947 indicates that sediment accumulation in the thalweg is minor. No large, expansive delta has been documented at the upstream end of Lake Roosevelt. The majority of sediment deposition in the lake occurs at the margins (Ferrari 2012). The sediments that accumulate in the reservoir are primarily silt, with a lesser composition of clay, sand, and gravel (Table 2-2) (Teck 2017). Qualitative observations by USGS personnel, using subaqueous imaging equipment, indicated the armor layer that controls sediment mobility (D90) area of the upper Columbia riverbed is likely 20 centimeters or thicker (Magirl et al. 2014).

Table 2-2. Distribution of Particle Sizes by Grain Size Percent within Lake Roosevelt

Analyte	Number of Results	Minimum Value (mm)	Maximum Value (mm)	Mean Value (mm)
Clay	120	0	67.7	17.5
Silt	120	0.1	81.53	35.8
Very fine	120	0.02	26.97	4.62
Fine sand	120	0.18	63.4	13.2
Medium sand	120	0.03	63	9.09
Coarse sand	120	0	78.77	13.8
Very coarse sand	120	0	42.45	4.05
Fine gravel	120	0	27.55	1.6
Medium gravel	120	0	2.87	0.0569

Note: mm = millimeter.
Source: Teck (2017)

2.2.4 Chemical Data

Lake Roosevelt sediments are widely known to be contaminated by heavy metals. In addition, past studies have identified other compounds of concern. These compounds include polycyclic aromatic hydrocarbons, PCBs, organochlorine pesticides, and polychlorinated dibenzo-p-dioxins, and polychlorinated dibenzofurans. Elevated metal concentrations are highest in the upper reaches of the reservoir, but elevated concentrations of heavy metals are found throughout the basin while concentrations of other compounds of potential concern are found in both the upper and lower reaches of the reservoir (EPA 2011; MacDonald et al. 2012).

Slag associated with reservoir sediments has been found to be concentrated toward the U.S.-Canada border at RM 745. The concentration of the slag was found with a

decreasing presence to approximately RM 675. From RM 675 to 599 (Grand Coulee Dam), sediments were found to either have very low amounts or be below detection limits for slag-associated deposits (Teck 2017). However, elevated concentrations of metals typically associated with slag deposits, such as zinc and lead, have been observed near Grand Coulee Dam (Bortleson et al. 2001).

2.2.4.1 *pH*

Upland sediments are moderately to slightly acidic with pH ranging from 4.69 to 6.79. The range of mean pH within each individual reach is 5.59 to 6.27 percent, while the lower 10th percentile concentrations range from 5.21 to 6.11 percent (McGinnis and Bailey 2013).

2.2.4.2 *Organics*

Biological uptake and biological accumulation of dioxins, furans, and PCBs can be an important process affecting the fate and distribution of these constituents in the food web. The less-chlorinated PCBs are moderately volatile and can undergo biodegradation processes, while PCBs that are more highly chlorinated biodegrade very slowly. Like highly chlorinated PCBs, dioxins and furans also tend to be persistent in the aquatic environment (CH2M Hill 2012).

Organic constituents such as dioxins, furans, and PCBs have a relatively low solubility in water and show a strong affinity for sorption to solid-phase particulates, especially those containing elevated concentrations of organic carbon. Because organic compounds are suspended in water more easily, these constituents are more likely than heavy metals to be transported downstream into the middle and lower reaches of the reservoir (Magirl et al. 2014).

Total organic carbon concentration in the lake sediments range from 1.2 to 23.4 percent and primarily reflect the amount of decomposed organic matter in the samples. The total organic carbon mean concentration in each reach ranges from 3.8 to 9.7 percent, and the 90th percentile concentrations range between 6.3 and 14.5 percent (McGinnis and Bailey 2013).

2.2.4.3 *Metals*

Movement of sediments carrying trace metals is a major concern in Lake Roosevelt. These trace metals, originating primarily from 10 to 15 million tons of slag dumped into the Columbia River north of the U.S.-Canada border, have significantly altered the sediment chemistry in the reservoir. Metal concentrations in sediment within the sampled areas generally are highest closest to the U.S.-Canada border and along the Columbia River Valley corridor. Concentrations of five smelter-related metals decline with increasing lateral (generally east-west) distance away from the river valley corridor, and downstream from the U.S.-Canada border, but are still found on Lake Roosevelt's beaches and near the dam (Bortleson et al. 2001; EPA 2011; McGinnis and Bailey 2013).

Surface soils on both banks of the river, along the lateral limits of the study area, show strong evidence of widespread metal contamination. From a spatial perspective, metal contamination is broadly evident in surface soils on the banks of the reservoir. Metals that have been found to be especially elevated include arsenic, cadmium, lead, mercury, and zinc (Johnson, Norton, and Yake 1989). The range of these metals has been compared to normal background concentration; arsenic was found to be between 1 to 11 times higher than normal, cadmium was 2 to 135 times higher, lead was 3 to 171 times higher, mercury was 1 to 33 times higher, and zinc was found to be 1 to 23 times higher than normal background concentrations (McGinnis and Bailey 2013). Due to the contamination along the banks of the reservoir, Bossburg Flat Beach was closed in 2012, contaminated sediments were removed and replaced with clean fill at Black Sand Beach in 2010, and ongoing studies and remediation work continue to present day (EPA 2011).

Chemical analyses of slag samples obtained from the Teck lead-zinc smelter show that the material is enriched by several metals including cadmium, copper, iron, lead, manganese, and zinc. These metals were identified as potential indicators of slag in the reservoir (MacDonald et al. 2012). The Teck study modeled slag sediment deposition below the plant in the Columbia River. The study used sediment size, slag concentration, and the metal indicators noted above to approximate concentration in the river from the U.S.-Canada border all the way down to Grand Coulee Dam. Study data is displayed in Table 2-3, Table 2-4, and Figure 2-5.

Table 2-3. Percent Weight Composition of Slag in Sediment Samples by River Mile

River Mile	% w/w	River Mile	% w/w
(Border) 745	31.1	722	76
745	16.8	722	3.6
743	33	722	50.5
738	27	721	46.6
738	13.6	716	66.3
735	48.9	711	47
735	10.9	711	52.5
735	29	709	60.2
733	0.319	709	59.8
733	22.9	709	61.4
733	12.3	709	59.8
732	3	707	35.4
729	71.3	705	37.1
728	23.6	705	0.234
727	5.4	692	0.024
726	48.7	689	0.0005
725	72.4	678	0.003
724	26.4	673	0.013
724	60.4	664	0
724	66.7	652	0
723	44	645	0
723	62.7	604	0
723	52.9	(Dam) 599	0

Note: RM 745 is near the U.S.-Canada border. RM 599 is near the Grand Coulee Dam. % w/w = percent weight by weight, i.e., X grams of slag in 100 grams of water.
Source: Teck 2017

Table 2-4. Percent Distribution by Size Class of Slag in Sediment Samples by River Mile

River Mile	15 to 44 (µm)	44 to 124 (µm)	125 to 349 (µm)	350 to 999 (µm)	1,000 to 2,829 (µm)	2,830 to 4,000 (µm)	>4,000 (µm)
745	0.1	1.6	21.4	76.7	0	0	0
745	0.2	1.7	25.1	72.9	0	0	0
745	0.5	3.7	58.7	37.1	0	0	0
743	0.2	2	33.7	64.1	0	0	0
738	0.4	2.9	39.9	56.8	0	0	0
738	0.3	4.5	68.1	27	0	0	0
735	0.1	0.8	5.5	93.5	0	0	0
735	0.9	7.2	73.5	18.5	0	0	0
735	0.3	2.1	32.1	65.3	0	0	0
733	0.7	14.9	38.8	45.6	0	0	0
733	8.3	17.6	73.4	0	0	0	0
733	0.4	3.2	62.2	34.1	0	0	0
732	2	36.5	61.4	0	0	0	0
729	0.1	0.6	4.7	93.4	1.2	0	0
728	0.2	1.7	18.5	75.8	3.7	0	0
727	4.2	31.4	64.2	0	0	0	0
726	0.1	1.7	19.9	78.1	0	0	0
725	0	0.7	3.8	83.8	11.6	0	0
724	0.2	0.9	8.8	84.1	5.9	0	0
724	0.2	1.2	11.6	83.1	3.8	0	0
724	0.4	1.3	10.7	84.8	2.7	0	0
723	0.2	1.3	14.2	80.5	3.8	0	0
723	0.3	1.3	24.3	74	0	0	0
723	0.3	1.2	12.7	81.1	4.8	0	0
722	0.3	0.4	3	87.1	9.1	0	0
722	1.6	11.7	83.2	3.4	0	0	0
722	0.1	0.9	9.3	89.7	0	0	0
721	0.3	2.9	41	55.6	0	0	0
716	0.3	1.2	11.2	85.8	1.4	0	0
711	0.1	1	11.3	84.9	2.5	0	0
711	0.2	0.9	10.6	85.1	3.2	0	0
709	0.1	1.4	21	75.9	1.5	0	0
709	0.2	1.4	20.4	76.6	1.5	0	0
709	11.3	8.9	0	78.5	0	0	0
709	0.2	1	18.9	78.3	1.6	0	0
707	0.2	1.4	27.9	70.4	0	0	0
705	0.1	0.6	5.4	93.7	0	0	0
705	20.6	79.3	0	0	0	0	0
692	93.4	0	0	0	0	0	0
689	0	0	0	0	0	0	0
678	100	0	0	0	0	0	0
673	33.5	66.5	0	0	0	0	0

Note: River Mile 745 is near the U.S-Canada border. River Mile 673 is toward the Grand Coulee Dam.
µm = micrometers.
Source: Teck (2017)

In sediment samples from the U.S.-Canada boundary in which slag was estimated to compose 48 percent of sediment grains, the average concentration of copper and zinc was 3,000 and 15,000 milligrams per kilogram (mg/kg), respectively. Slag in bed sediments 15 miles (RM 730) further downstream was estimated to comprise 5 percent

of the sand-sized fraction, and the average concentration of copper and zinc was 670 and 4,100 mg/kg, respectively (Cox et al. 2005). Near the dam, Bortleson et al. (2001) reported elevated zinc concentrations at 1,100 mg/kg) within about 10 miles of Grand Coulee Dam. The concentrations reported by Bortleson et al. (2001) are displayed in Table 2-6 and sample locations are shown in Figure 2-2. The elevated concentrations of zinc and lead reported by Bortleson et al. near the dam have been similarly observed in the Teck studies; some of these results are displayed in Figure 2-3 and Figure 2-4. Because slag deposits have not been reported near the dam (Table 2-5) (Teck 2017), but metals commonly associated with the slag deposits have been observed, either other sources are responsible for the reported metal contamination (such as other mining activities in the basin), metals are being mobilized from the slag deposits through pathways such as leaching, or a combination of the two.

Table 2-5. Average Content of Metals in Sediments as Sampled from the U.S-Canada Border to Grand Coulee Dam

Analyte	Concentration Units	Number of Acceptable Analyses	Number of Detected Values	Minimum Value	Mean Value	Maximum Value
Aluminum	mg/kg	120	120	4670	16800	29500
Antimony	mg/kg	120	119	0.0185	12.9	98
Arsenic	mg/kg	120	120	0.91	11.1	36.8
Barium	mg/kg	120	120	37.5	523	2390
Beryllium	mg/kg	120	120	0.133	0.605	1.2
Cadmium	mg/kg	120	120	0.07	3.4	13.1
Calcium	mg/kg	120	120	1840	19400	85200
Chromium	mg/kg	120	120	2.28	42.7	146
Cobalt	mg/kg	120	120	2.74	17.8	70.4
Copper	mg/kg	120	120	3.88	445	3370
Iron	mg/kg	120	120	10100	59900	291000
Lead	mg/kg	120	120	2.9	235	1080
Magnesium	mg/kg	120	120	1940	9320	23300
Manganese	mg/kg	120	120	148	1340	5710
Mercury	mg/kg	120	119	0.001	0.399	1.9
Nickel	mg/kg	120	120	2.38	22.2	38.8
Potassium	mg/kg	120	120	861	2620	5090
Selenium	mg/kg	120	119	0.1	1.21	5
Silver	mg/kg	120	120	0.042	1.43	7.32
Sodium	mg/kg	120	118	23.3	591	2740
Thallium	mg/kg	120	110	0.0215	0.441	1.23
Vanadium	mg/kg	120	120	14.9	39.4	57.1
Zinc	mg/kg	120	120	32.1	3870	28200

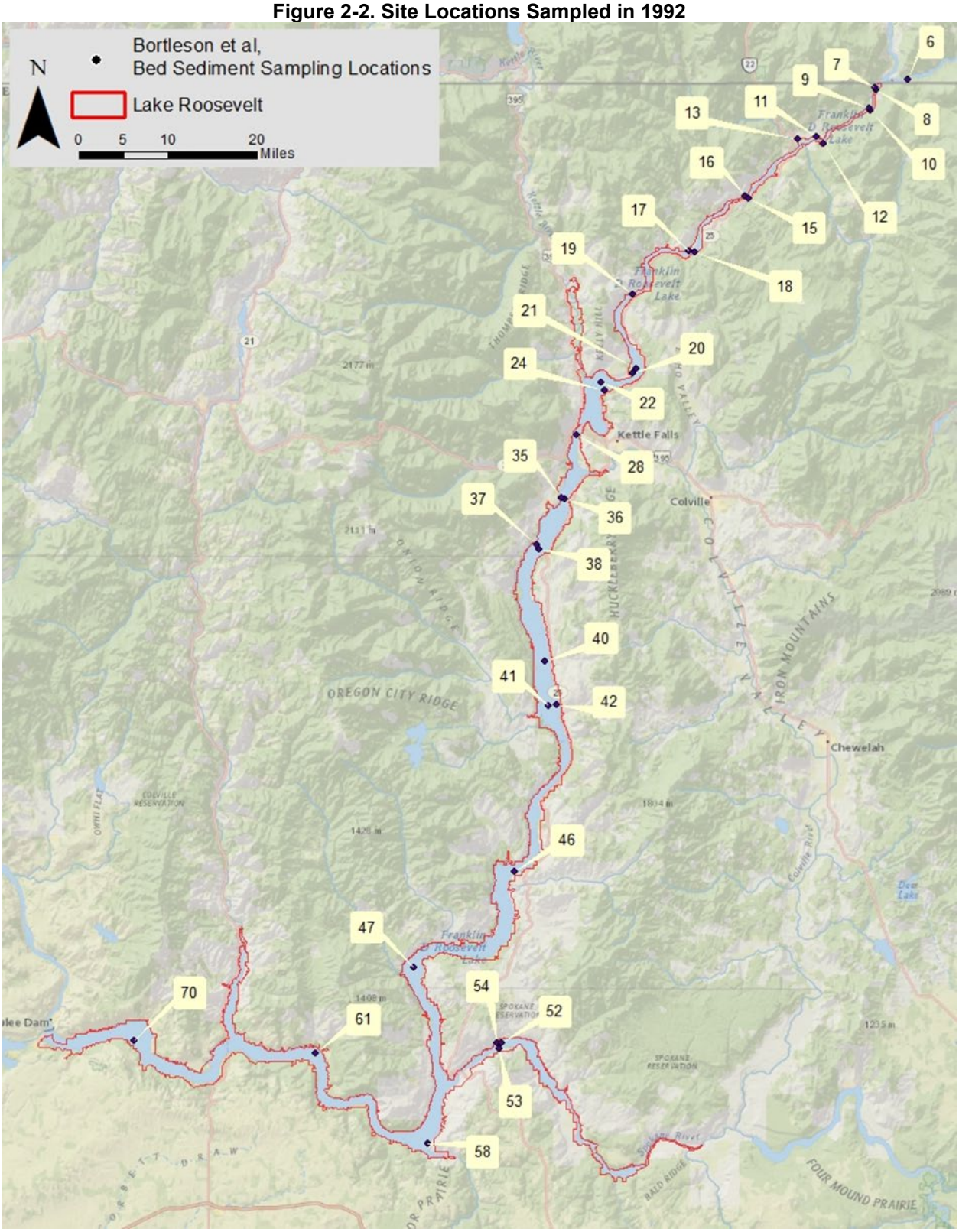
Source: Teck (2017)

Table 2-6. Total Trace Element Concentrations at Select Sites

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 (820mg/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

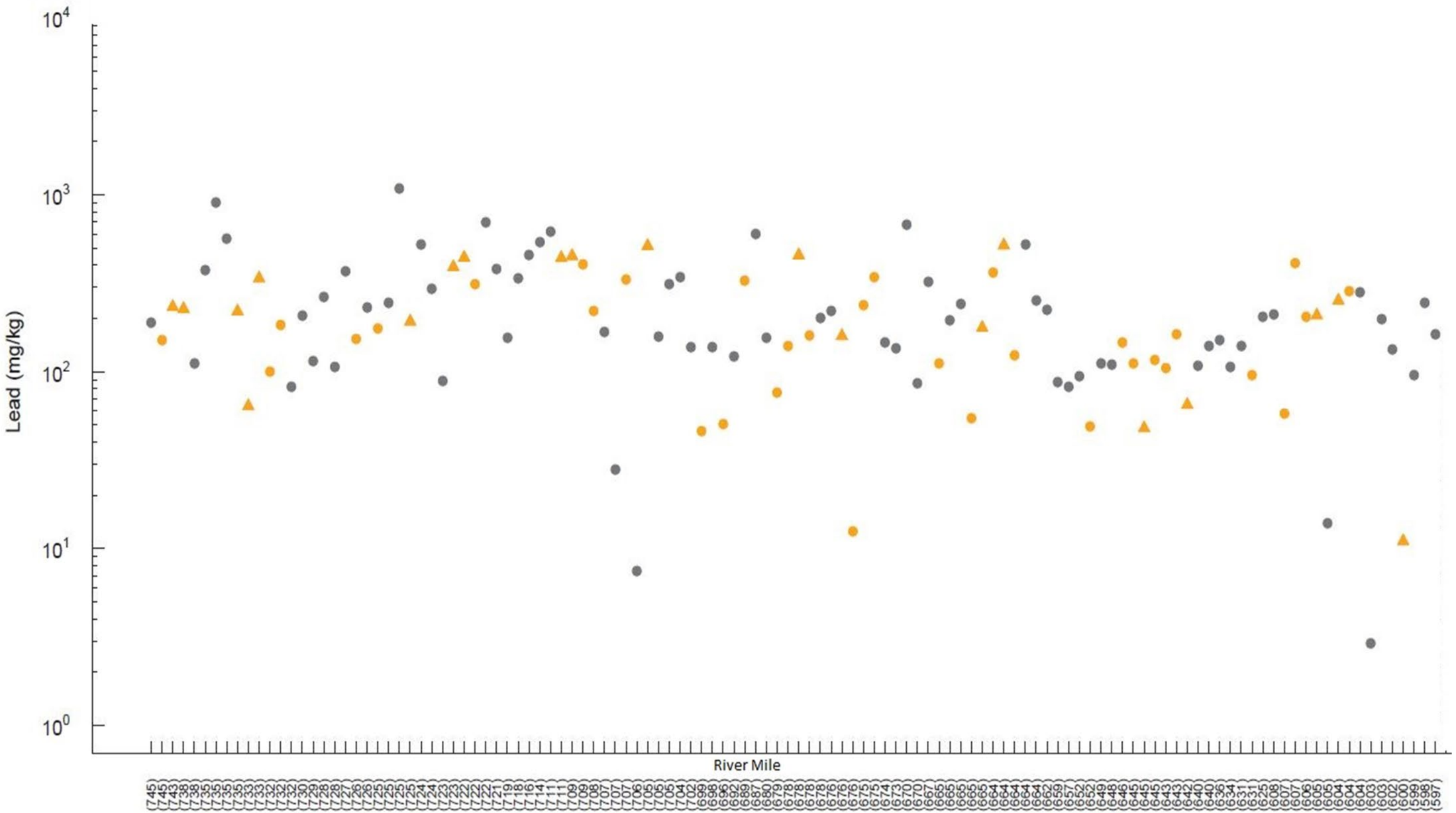
Note: Lower number sites are closer to the U.S.-Canada border, higher number sites are closer to Grand Coulee Dam. Site types detail the site location with "T" being tributaries, "C" Columbia River, "D" delta deposits, "R" Lake Roosevelt. Name endings in LB, RB, or MS were collected near the left bank, right bank, or mid-channel, respectively. Concentrations in the column header under the analyte name are trace element sediment quality guidelines for benthic organisms developed by the Ontario Ministry of Environment and Energy (Persaud, Jaagumagi, and Hayton 1991). All values displayed exceed these guidelines; all values in bold exceed these guidelines by at least 100 percent. Site locations can be referenced with the locations displayed by their corresponding site numbers on the map in Figure 2-2.
Source: Bortleson et al. 2001

Figure 2-2. Site Locations Sampled in 1992



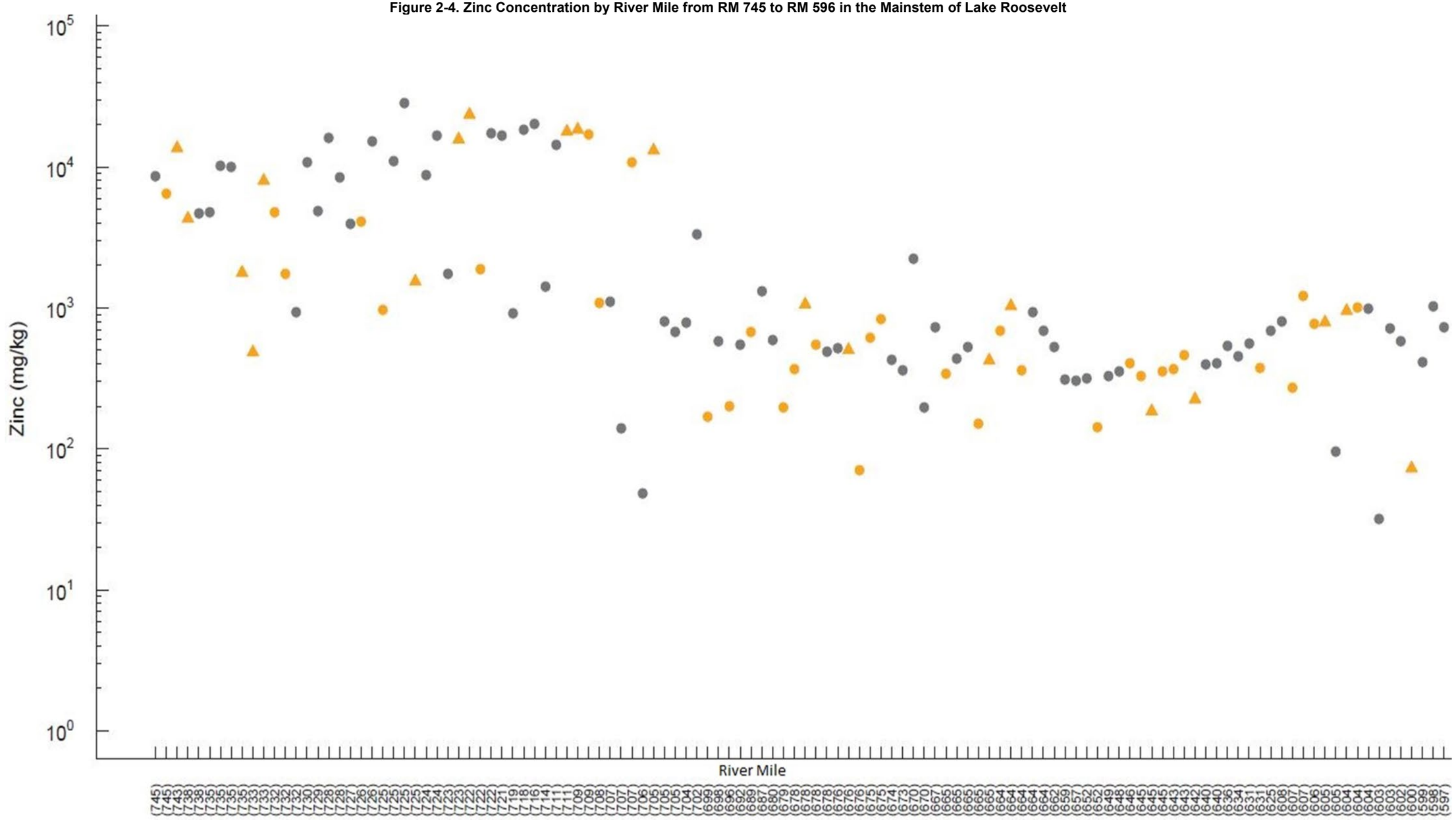
Note: Trace metal concentrations correlated to these sample locations are displayed in Table 2-6.
Source: Bortleson et al. (2001)

Figure 2-3. Lead Concentration by River Mile from RM 745 to 596 in the Mainstem of Lake Roosevelt



Note: RM 745 is near the U.S.-Canada border, and RM 597 is near the Grand Coulee Dam.
Source: Teck (2017)

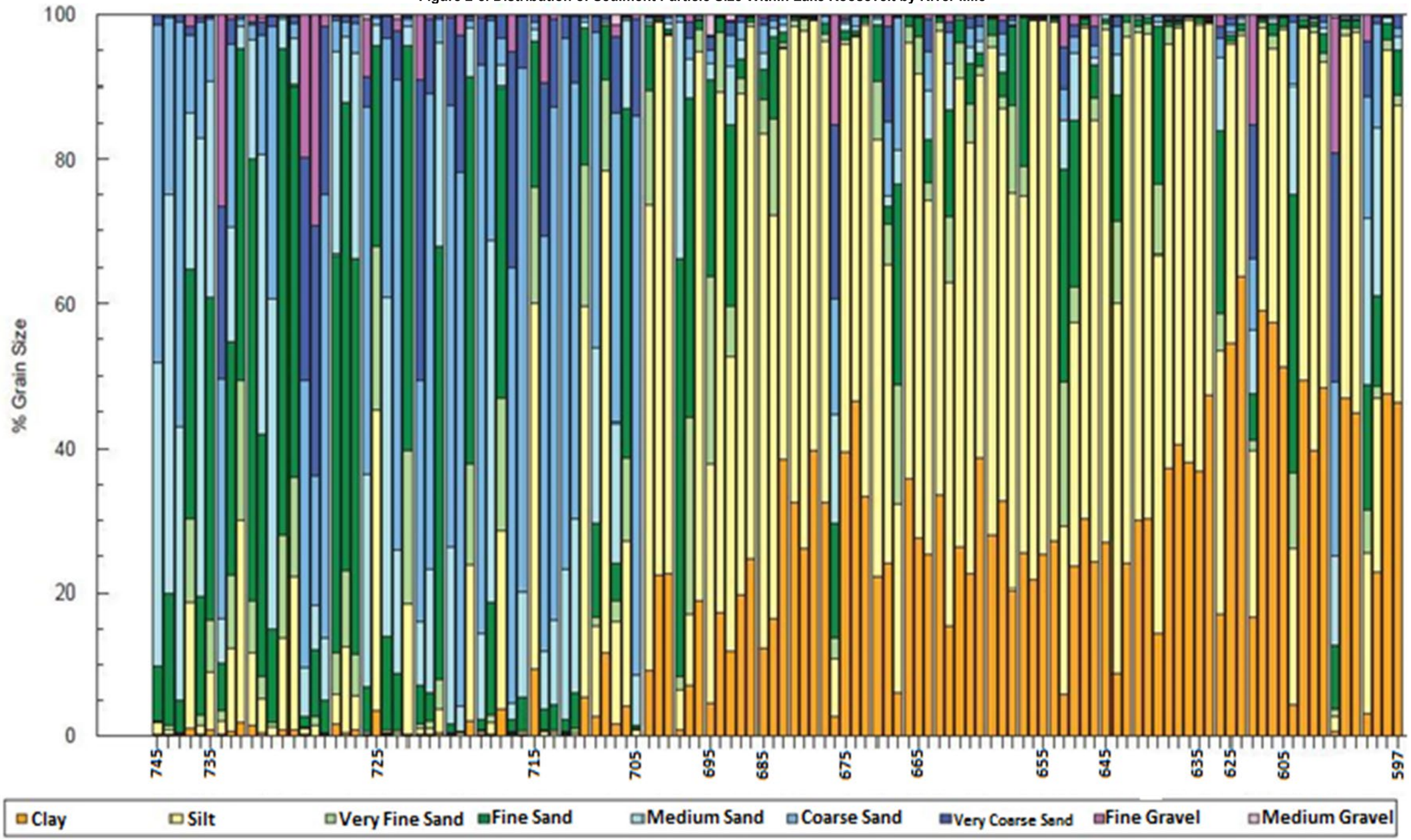
Figure 2-4. Zinc Concentration by River Mile from RM 745 to RM 596 in the Mainstem of Lake Roosevelt



Note: RM 745 is near the U.S.-Canada border, and RM 597 is near the Grand Coulee Dam.
Source: Teck (2017)

Metals can occur as dissolved ions, be sorbed to suspended organic or inorganic particulates or colloids, be present in small floating mats of slag, or be present in coarse-grained slag that is transported via saltation and/or bed transport (MacDonald et al. 20120). The presence of these trace elements in bed sediments of Lake Roosevelt was attributed to the sorption of trace elements from the water column onto suspended-sediment particles, which are subsequently deposited in the downstream quiescent waters of the mid- and lower reaches of Lake Roosevelt. Because sorption is related to the surface area of particles, a proportionally greater mass of trace elements is sorbed to smaller-sized sediment particles. Partially due to the ability of smaller particles to proportionally sorb more contaminants than larger particles concentrations of some trace elements were larger in the downstream reaches of Lake Roosevelt that are dominated by fine colloidal silt and clay-sized lacustrine sediments (Cox et al. 2005). A leaching experiment indicated that most of the mass of trace elements associated with the contaminated sediments is associated with the surface of the sediment particle where it is more accessible to physical, chemical, and biological processes that can remobilize trace elements into the overlying water column (Cox et al. 2005).

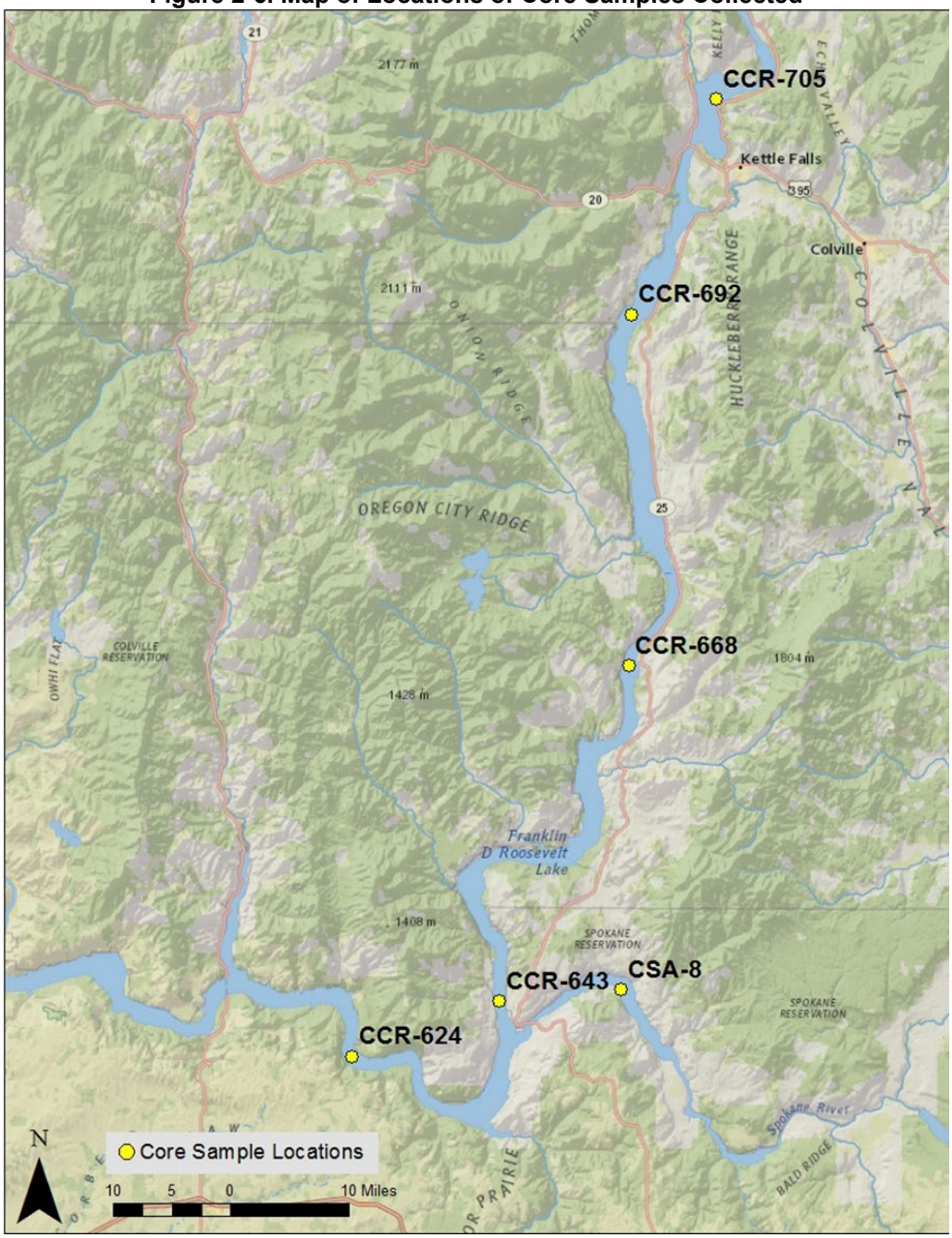
Figure 2-5. Distribution of Sediment Particle Size Within Lake Roosevelt by River Mile



Note: River miles are marked approximately every 10 miles for general location reference only; spacing is uneven to reflect the number of samples gathered, which was variable for each river segment (to determine an exact location of sample, the original report should be referenced). RM 745 is near the U.S.-Canada border, and RM 597 is near the Grand Coulee Dam.
Source: Teck (2017)

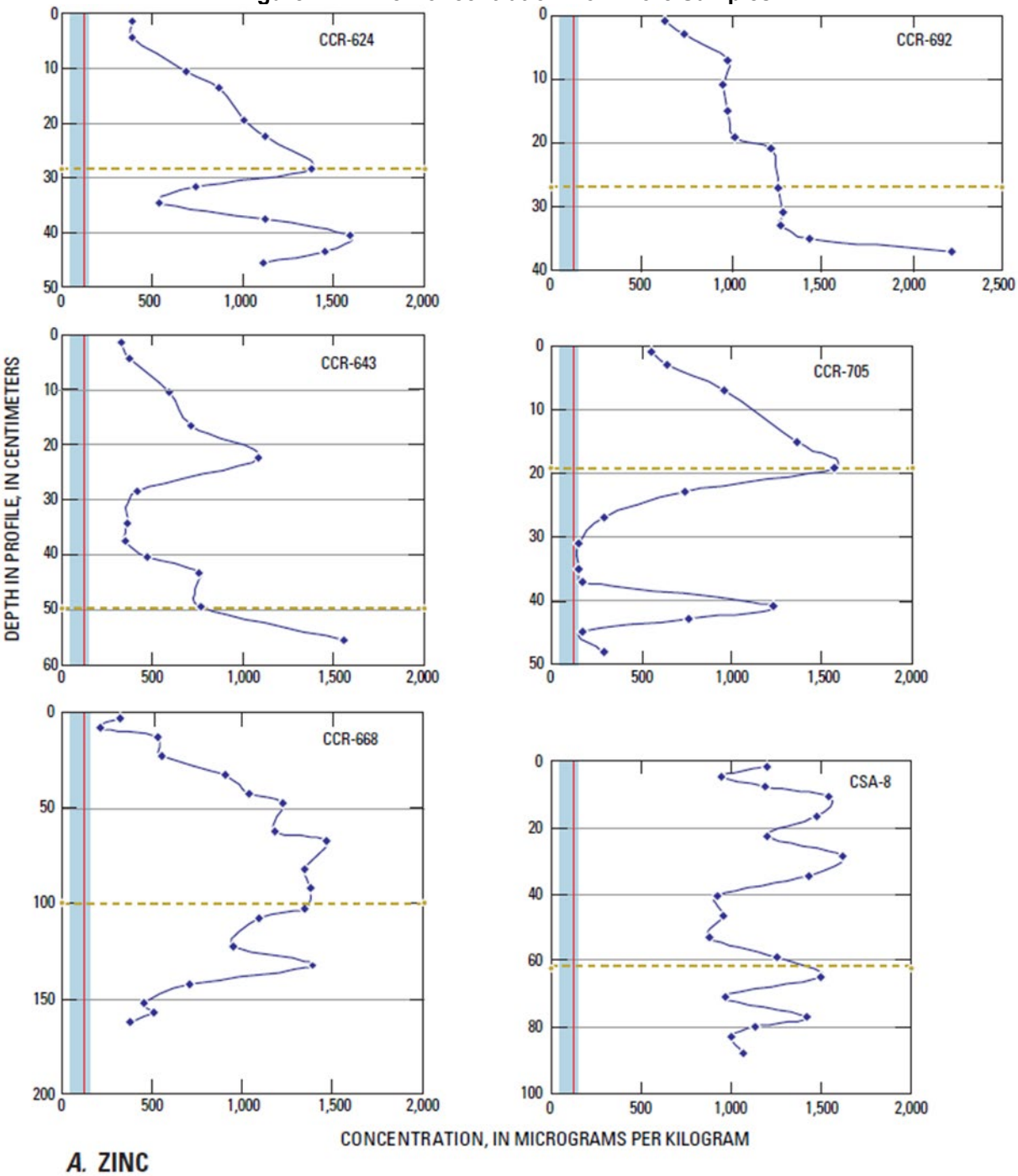
Overall, the depth concentration profiles in the lake sediments typically show that concentrations of arsenic, cadmium, lead, mercury, and zinc often were highest in the lower to mid-sections (closer to the bottom), and the concentration of copper often was highest closer to the surface in the trace-element profiles. Trends of decreasing concentrations of arsenic, lead, zinc, and to a lesser degree, cadmium, were observed in the upper sections of cores corresponding to sedimentation that occurred since the 1964 horizon. Core sample locations are marked on Figure 2-6, and data from this analysis is displayed in Figure 2-7 through Figure 2-12 (Cox et al. 2005).

Figure 2-6. Map of Locations of Core Samples Collected



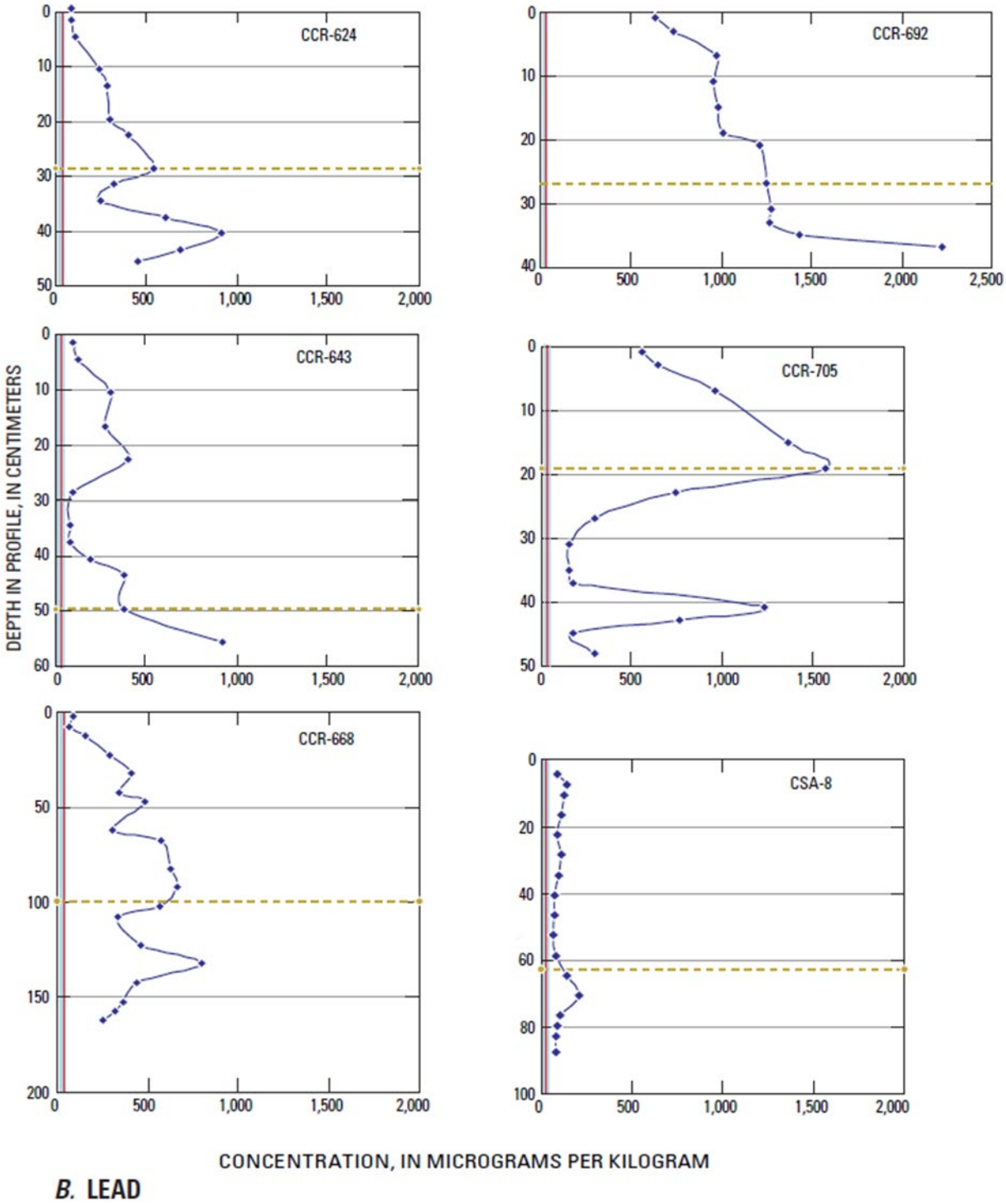
Source: Cox et al. (2005)

Figure 2-7. Zinc Concentration from Core Samples



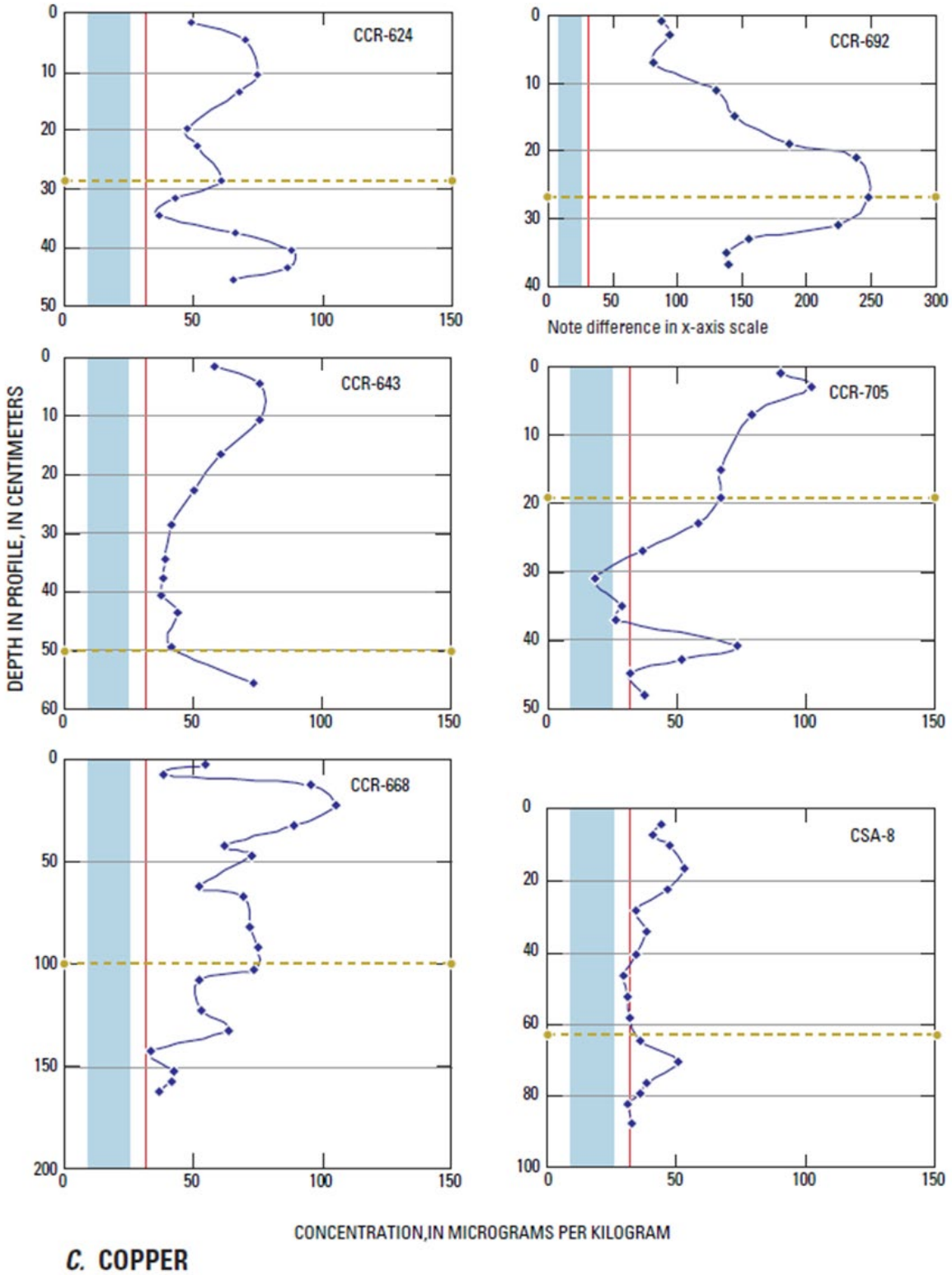
Note: Blue vertical and red vertical lines indicate range and average of normal background concentration. Yellow dashed horizontal line indicates the 1964 horizon.
Source: Cox et al. (2005)

Figure 2-8. Lead Concentration from Core Samples



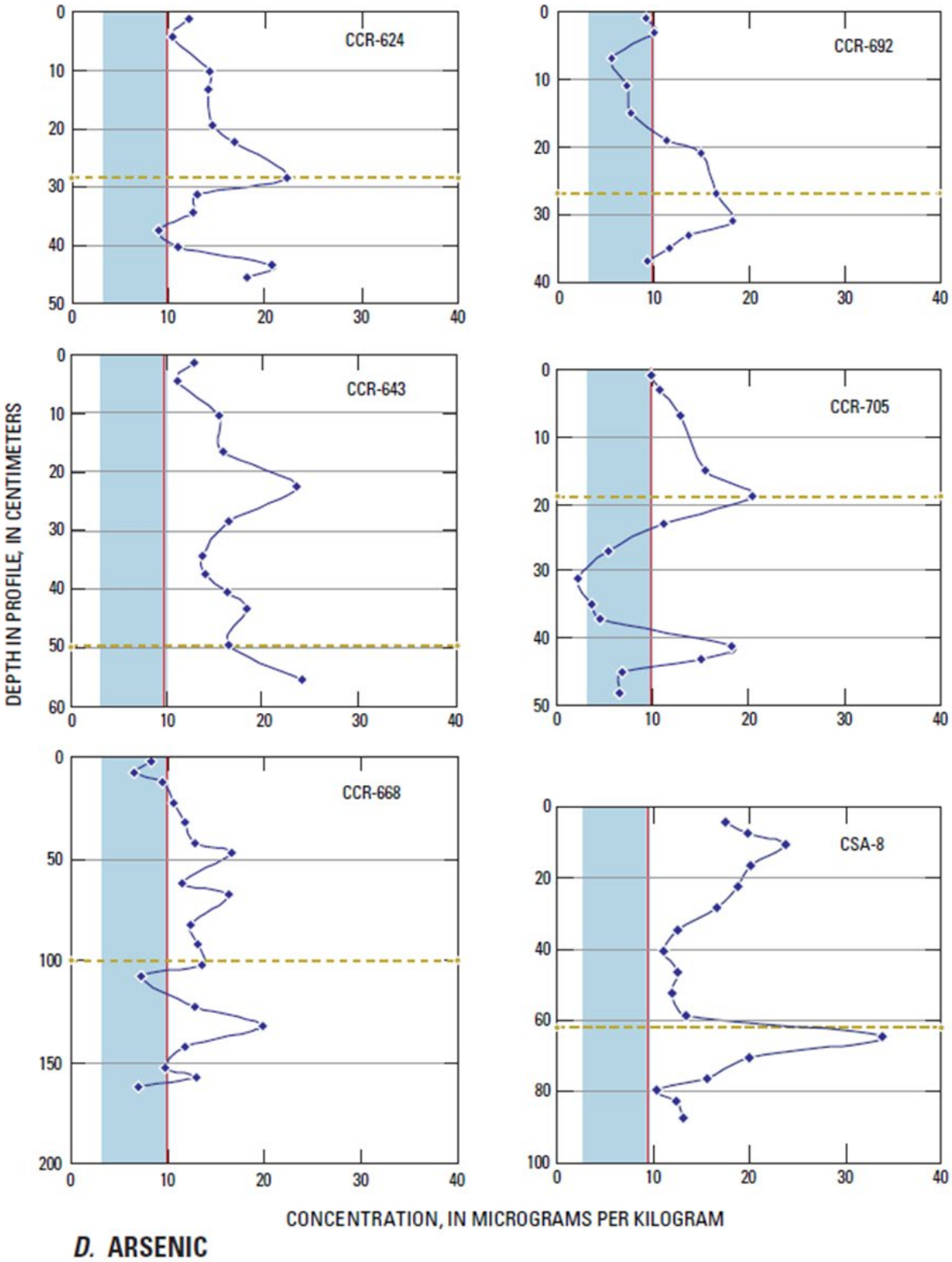
Note: Blue vertical and red vertical lines indicate range and average of normal background concentration. Yellow dashed horizontal line indicates the 1964 horizon.
Source: Cox et al. (2005)

Figure 2-9. Copper Concentration from Core Samples



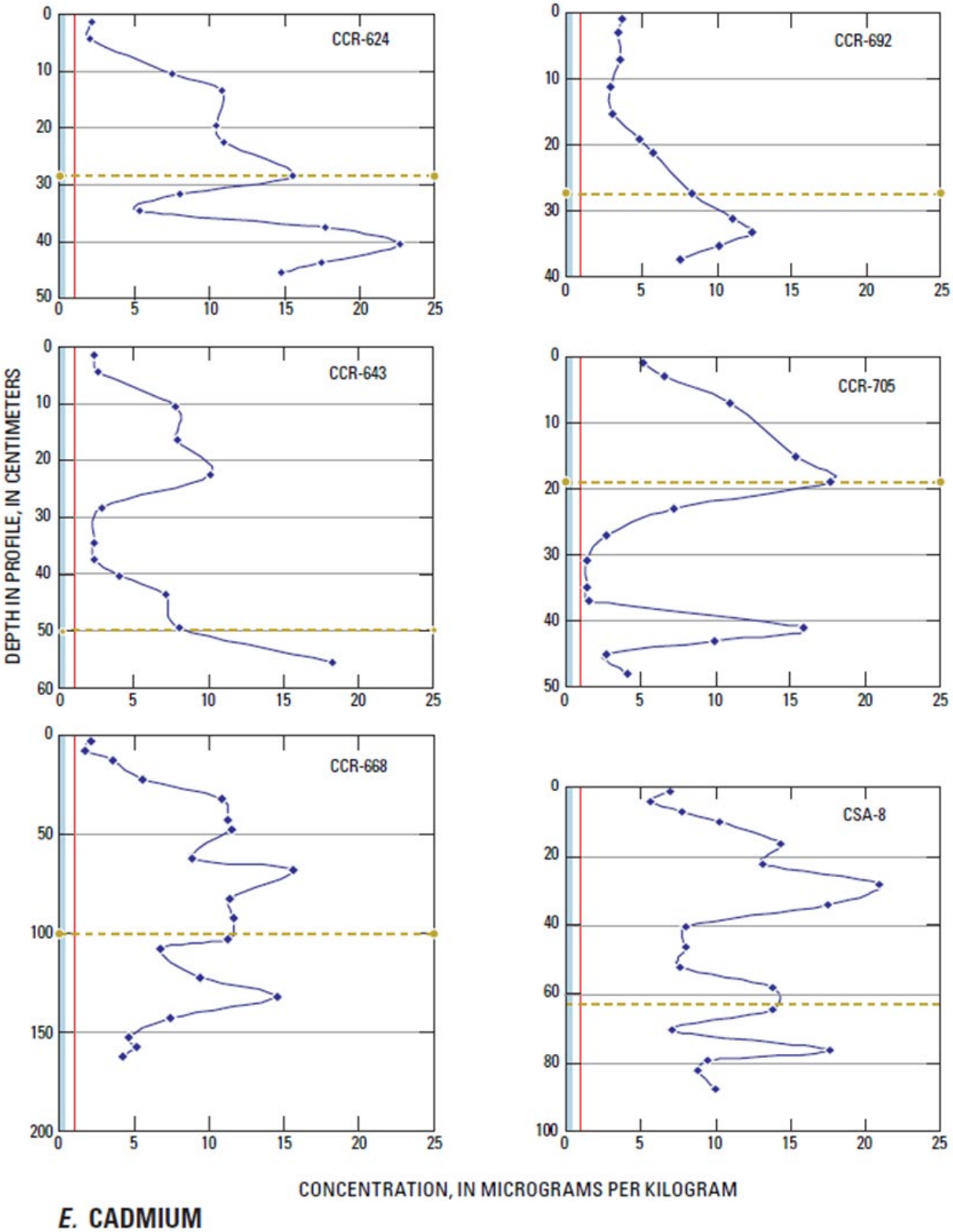
Note: Blue vertical and red vertical lines indicate range and average of normal background concentration. Yellow dashed horizontal line indicates the 1964 horizon.
Source: Cox et al. (2005)

Figure 2-10. Arsenic Concentration from Core Samples



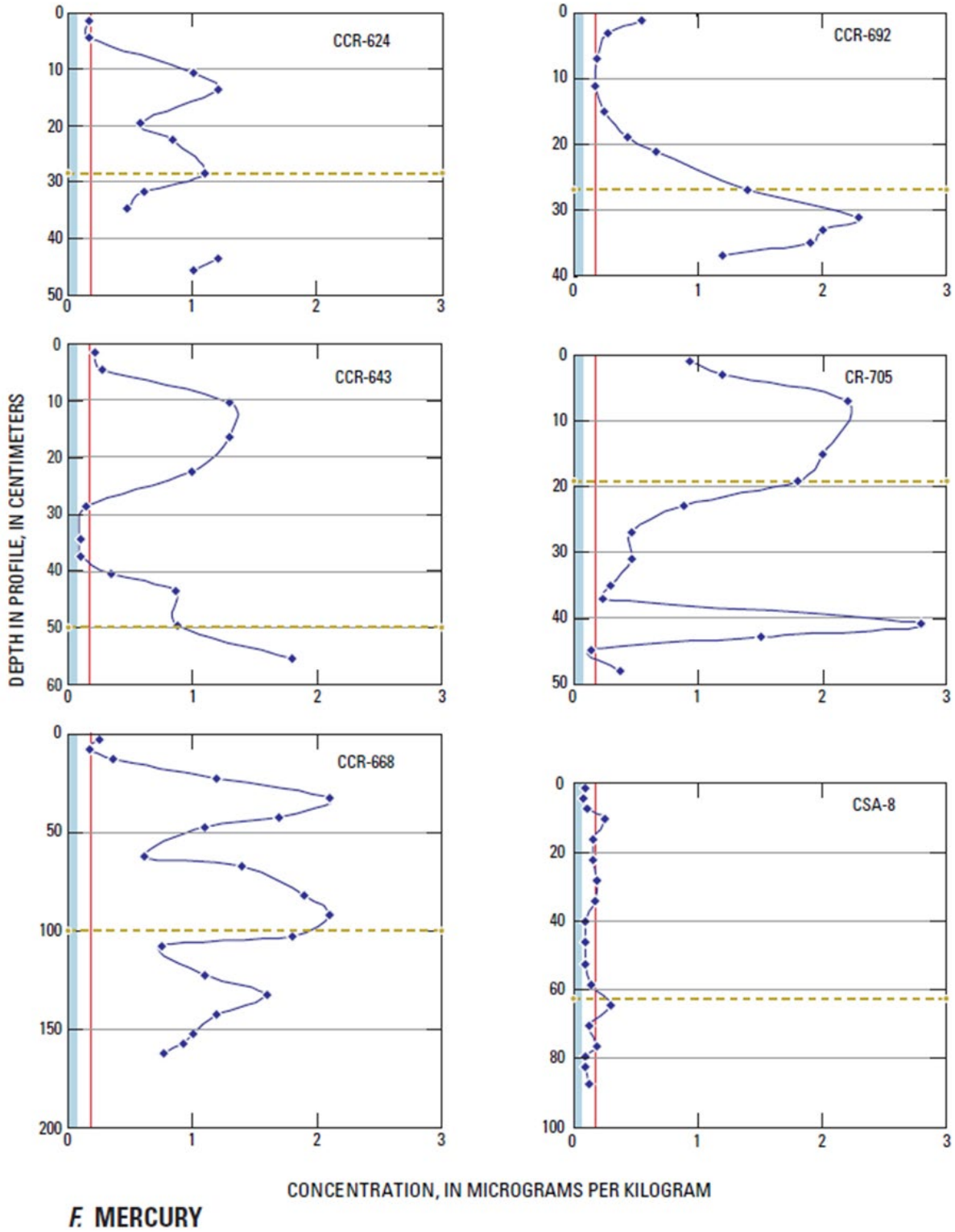
Note: Blue vertical and red vertical lines indicate range and average of normal background concentration. Yellow dashed horizontal line indicates the 1964 horizon.
Source: Cox et al. (2005)

Figure 2-11. Cadmium Concentration from Core Samples



Note: Blue vertical and red vertical lines indicate range and average of normal background concentration. Yellow dashed horizontal line indicates the 1964 horizon.
Source: Cox et al. (2005)

Figure 2-12. Mercury Concentration from Core Sample



Note: Blue vertical and red vertical lines indicate range and average of normal background concentration. Yellow dashed horizontal line indicates the 1964 horizon.
Source: Cox et al. (2005)

2.2.5 Biological Data

The results of 28-day whole-sediment toxicity tests with amphipods indicated that 19 to 53 percent of the sediment samples from Lake Roosevelt were toxic. Additionally, the study found that 18 to 81 percent of the sediment samples from the reservoir were found to be toxic to midges. Reservoir sediments tended to be less toxic to the order of small crustaceans, cladocerans, which indicated that 16 to 25 percent of the sediment samples were designated as toxic to this order. Exposure to contaminated sediments are likely to pose risks to biologic communities, especially benthic communities, in and around Lake Roosevelt. Overall, 58 of the 71 (82 percent) sediment samples from the reservoir that were evaluated using the reference envelope approach were found to be toxic to amphipods, midges, or cladocerans. The differences in toxicity among the upper reaches was generally small. These reaches all displayed elevated toxicity when compared to the lower reaches of the reservoir less than 70 river miles above Grand Coulee Dam. The sediment samples closer to Grand Coulee Dam indicated significantly lower trace element concentrations. Little information has been reported in regards to toxicity and bioaccumulation in vertebrates, and further research should be undertaken in this area (MacDonald et al. 2012).

While toxicity was found to be closely related to trace element concentrations sorbed to sediments, no significant relationship was found between porewater concentrations and toxicity (CH2M Hill 2012). The consistent conclusion drawn from the toxicity studies is that cationic metals such as chromium, copper, lead, and zinc are bioavailable when sorbed to sediments, and if elevated above threshold levels, these metals found in sediments originating from activities in the upper Columbia River watershed have the potential to cause toxicity in biological resources (Besser et al. 2007).

2.2.6 Elutriate Data

Variability in porewater concentrations of trace elements may occur seasonally due to the changing water levels, temperature, and redox conditions in the reservoir. However, further study is needed on the possible seasonal variation in porewater concentration as a function of these factors in the reservoir (Cox et al. 2005). Porewater samples have been collected and analyzed in a study funded by Teck (Teck 2017); the concentration values throughout the reservoir are displayed in Figure 2-6. If more detail for a given analyte at a given river mile within the reservoir is needed, the original report should be referenced. In general, though, the concentration of contaminants decreases in correlation with the amount of slag in the sediment as displayed in Figure 2-2.

2.3 CHEMICALS OF CONCERN

Primary chemicals of concern are those associated with smelting operations. The highest metal concentrations of concern found in the reservoir are cadmium, copper, iron, lead, manganese, and zinc. However, a variety of other trace metals are also present: dioxins, furans, PCBs, and other constituents have also been observed in the reservoir.

Likely primary sources of metals within the reservoir include chemical discharges via stacks, liquid effluent and slag discharges from smelter operations, drainage from closed mines within the basin, and other metal deposits naturally transported by ground and surface water. As previously mentioned, the primary historical source of elevated metals is attributed to the Teck Cominco Smelter Complex. Additionally, lesser quantities of slag likely originated from the Le Roi Smelter in Northport, Washington, and the Young American Mine (EPA 2012). The primary source of historical loading of dioxins and furans to the reservoir was the pulp mill in Castlegar, British Columbia. Although PCBs have been detected in fish tissue analyses, PCBs have been found in a limited number of sediment samples (CH2M Hill 2012)

2.4 CONCEPTUAL SITE MODEL

In regard to sediment transport in Lake Roosevelt, the reservoir can be separated into riverine (above Onion Creek) and lacustrine (below Marcus Island). Riverine sediment deposits are generally armored and require a certain sheer stress to initiate movement; sediment transport can be estimated by calculating the shear stress needed to initiate movement. Lacustrine deposits, which are more easily mobilized than riverine deposits, may be more easily transported with increased river flow and are difficult to model (Magirl et al. 2014). The majority of slag-contaminated sediment mass is located near the U.S.-Canada border in riverine areas. Because this reach of the river is armored with large boulders, it is less likely to mobilize sediments in response to Grand Coulee Dam operational changes. While some sand and silt alluvium can be mobilized from these bed and bank deposits with local disturbance, most of the alluvium will remain stable unless the armor layer is mobilized, which is estimated to require discharges at Grand Coulee Dam of over 300,000 cfs (Magirl et al. 2014).

The primary contaminant of concern associated with sediments in the reservoir is the trace metal deposits resulting from dumping of slag metals and wastewater effluent from smelting plants in the basin, especially the Trail smelter now operated by Teck. Other contaminants, such as PCBs, are an issue in the reservoir sediments, but the concern for trace metal contamination and bioaccumulation is much greater.

Sediments in the reservoir are typically deposited from natural inflows and landslides. Major sediment-carrying tributaries to the reservoir include the Columbia, Pend Orielle, Sanpoil, and Spokane Rivers. Landslides in the basin have been well documented (Jones et al. 1961; Kiver and Strandling 1995). Landslides are especially likely when reservoir water levels are lowered 30 to 50 feet and are a high concern if the reservoir is lowered in excess of 50 feet (Reidel 1997).

2.4.1 Secondary Media and Release Mechanisms

Slag deposited in the sediments of Lake Roosevelt shows signs of having undergone hydration and chemical weathering. When inspected using a scanning electron microscope, fourteen of eighteen slag grains gathered from the reservoir showed signs of exfoliation flakes, an indication of surficial weathering. The distribution of these indicators is consistent with the weathering processes. Calcium and iron are often

removed during chemical weathering while silicon, aluminum, and oxygen are more recalcitrant elements whose concentrations become larger in the residual weathered material. Further evidence of slag weathering included the presence of weathering rinds, typically about 20 to 100 microns thick, present in the samples (Cox et al. 2005). Better information than that in the current literature will be required to effectively assess seasonal pore concentration variations that may be affected by changes to pool elevations in the reservoir.

2.4.2 Exposure Routes

Direct exposure from bulk sediment or porewater contamination is the most prominent contaminant pathway for invertebrates, fish, and wildlife. Through this pathway, bioaccumulation of sediment constituents into higher trophic forms such as birds, mammals, fish, amphibians, and reptiles are most likely. However, bioaccumulation in Lake Roosevelt is poorly understood and should be further studied and quantified if it is to be properly understood in the area (MacDonald et al. 2012).

Generally speaking, exposure risk is dependent on suspension and transport of contaminants associated with reservoir sediments. Due to the lack of specific quantifiable information, exposure related to suspension and transport of contaminants is difficult to determine (Magirl et al. 2014). More data is required to accurately describe the effects of water management on sediment transport in the reservoir. Transport of reservoir sediment is contemplated in the River Mechanics Appendix (River Mechanics Appendix x ref).

Soil exposure due to reservoir drawdown is another route of possible biological exposure to contaminants in Lake Roosevelt. Reservoir operations may result in seasonal reservoir fluctuations in excess of 80 feet in the spring for flood control purposes during years of high precipitation. Bed and bank sediments are exposed along the length of the reservoir during these spring drawdown periods (EPA 2003). Many of these banks and beds also carry elevated levels of trace elements from smelting and mining operations, which creates a possible pathway for direct exposure to human populations who use Lake Roosevelt’s shores and beaches (CH2M Hill 2012).

SECTION 3 - REFERENCES

Alden, W. C. 1953. Physiography and Glacial Geology of Western Montana and Adjacent Areas, a Study of Glacial Features in the Intermontane Valleys and the Drainage Area of the Upper Missouri and Columbia Rivers. Professional Paper 231. U.S. Department of the Interior, U.S. Geological Survey.

Atwater, B .F. 1984. “Periodic Floods From Glacial Lake Missoula into the Sanpol Arm of Glacial Lake Columbia, Northeastern Washington.” Geology 12:464–467. U.S. Geological Survey.

Besser, J. M., W. G. Brumbaugh, C. D. Ivey, C. G. Ingersoll, and P. W. Moran. 2007. “Biological and Chemical Characterization of Metal Bioavailability in Sediments from Lake Roosevelt, Columbia River, Washington, USA.” Archives of Environmental Contamination and Toxicology 54:557¬–570. DOI 10.1007/s00244-007-9074-5.

Bortleson, G. C., S. E. Cox, M. D. Munn, R. J. Schumaker, and E. K. Block. 2001. Sediment-Quality Assessment of Franklin D. Rooselevelt Lake and the Upstream Reach of the Columbia River, Washington 1992. Water-Supply Paper 2496. U.S. Geological Survey.

CH2M Hill. 2012. Summary and Evaluation of Phase 1 (2005) Sediment Toxicity Tests Upper Columbia River Site. U.S. Environmental Protection Agency, Region 10.

Cox, S. E., P. R. Bell, J. S. Lowther, and P. C. VanMetre. 2005. Vertical Distribution of Trace-Element Concentrations and Occurrence of Metallurgical Slag Particles in Accumulated Bed Sediments of Lake Roosevelt, Washington, September 2002. Scientific Investigations Report 2004-5090. U.S. Geological Survey.

Easterbrook, D. J. 1992. “Advance and Retreat of Cordilleran Ice Sheets in Washington, U.S.A.” Geographie Physique et Quaternaire 46(1)51–68. DOI:10.7202/032888ar. Les Presses de l'Universite de Montreal.

English, J. M., and S. T. Johnston. 2004. “The Laramide Orogeny: What Were the Driving Forces?” International Geology Review 46:833¬–838.

EPA (U.S. Environmental Protection Agency). 2003. Upper Columbia River Expanded Site Inspection Report: Northeast Washington. TDD: 01-02-0028, Contract:68-S0-01-01, START-2. Region 10.

———. 2009 Columbia River Basin: State of the River Report for Toxics. EPA 910-R-08-004. Region 10.

———. 2011. Upper Columbia River Site Update 2011 EPA. Region 10 Superfund Records Center.

———. 2012. Young American Mine Removal Assessment Trip Report, Evans, Stevens County, Washington. TDD: 11-06-0011, Contract EP-S7-06-03, START-3. Prepared by TechLaw, Inc.

Ferrari, R. L. 2012. Franklin D. Roosevelt Lake-Grand Coulee Dam 2010-2011 Survey. Technical Report No. SRH-2012-06. Bureau of Reclamation, Sedimentation and River Hydraulics Group.

Flint, R. F. 1935. “Glacial Features on the Southern Okanogan Region.” Geological Society of America Bulletin 46:169–194.

———. 1939. “Glacial Geology of the Grand Coulee Dam, Washington.” Geological Society of America Bulletin 50:661–680.

Hooper, P. R. 1982. “The Columbia River Basalts.” American Association for the Advancement of Science 215(4539)1463–1468.

Johnson, A., D. Norton, and W. Yake. 1989. An Assessment of Metal Contamination in Lake Roosevelt. Washington State Department of Ecology Toxics Investigations/Ground Water Monitoring Section, 89-e26 Water Body No. WA-CR-9010.

Jones, F. O., D. R. Embody, W. L. Peterson, and R. M. Hazelwood. 1961. Landslides Along the Columbia River Valley, Northeastern Washington. Geological Professional Paper 367. U.S. Geological Survey.

Kiver, E. P., and D. R. Strandling. 1995. Geology of the Franklin D. Roosevelt Reservoir Shoreline: Glacial Goelogy, Terraces, Landslides, and Linements: Grand Coulee, Washington. Bureau of Reclamation.

MacDonald, D. D., J. A. Sinclair, M. A. Crawford, H. J. Prencipe, and M. R. Coady. 2012. Evaluation and Interpretation of the Sediment Chemistry and Sediment Toxicity Data for the Upper Columbia River. MacDonald Environmental Sciences Ltd.

Magirl, C. S., R. S. Dinicola, S. E. Cox, M. C. Mastin, C. P. Konrad, and J.A. Czuba. 2014. Sediment Transport in the Upper Columbia River to Support Columbia River Treaty 2014/2024 Review. U.S. Geological Survey.

McGinnis, R., and M. J. Bailey. 2013. Upper Columbia River Upland Soil Sampling Study, Stevens County, WA. Hart Crowser 17800-36.

McMacken, J. G. 1937. Geology of the Grand Coulee. Eastern Washington University.

National Park Service. 2016. https://www.nps.gov/laro/planyourvisit/upload/LAROmap1.pdf.

Pardee, J. T. 1918. Geology and Mineral Deposits of the Colville Indian Reservation Washington. U.S. Geological Survey Bulletin 677.

Persaud, D., R. Jaagumagi, and A. Hayton. 1991. The Provincial Sediment-Quality Guidelines. Ontario Ministry of Environment and Energy, Water Resources Branch.

Reclamation (Bureau of Reclamation). 1993. Memorandum on Guideline Considerations for Daily Drawdown Limits, FDR Lake.

———. 2015. Geology of the Grand Coulee Dam Area

Reidel, J. L. 1997. Lake Roosevelt National Recreation Area Water Resources Scoping Report. National Park Service.

Reiners, P. W., T. A. Ehlers, J. I. Garver, S. G. Mitchell, D. R. Montgomery, J. A. Vance, and S. Nicolescu. 2002. “Late Miocene Exhumation and Uplift of the Washington Cascade Range.” Geology 30(9)767–770.

Northwest Regional Sediment Evaluation Team Agencies. 2016. Sediment Evaluation Framework for the Pacific Northwest.

Schuster, R. L. 1979. “Reservoir Induced Lanslides.” Bulletin of the International Association of Engineering Geology 20:8–15.

Teck (Teck Resources Limited). 2014. Final Beach Sediment Study Field Sampling and Data Summary Report. Integral Consulting Inc.

———. 2017. FINAL Phase 2 Sediment Study Data Summary and Data Gap Report. Windward Environmental, Exponent, Parametrix, and HDR.

Waitt, R. B., Jr. 1985. “Case for Periodic, Colossal Jokulhlaups from Pleistocene Glacial Lake Missoula.” Geological Society of America Bulletin 96:1271–1286.

WDGER (Washington Division of Geology and Earth Resources). 2016. Surface Geology, 1:100,000–GIS data. Digital Data Series DS-18, version 3.1, previously released June 2010.

WGS (Washington Geological Survey). 2017. Surface geology, 1:24,000–GIS data. Digital Data Series DS-10, version 3.0, previously released November 2016.