PAKOOTAS ET AL. V.
TECK COMINCO METALS LTD.
(NHC Report 35240)

Opinion on the transport of metallurgical slag by the Columbia River, Trail, B.C. to International Boundary

Expert Report prepared for
The Confederated Tribes of the Colville Reservation
and the State of Washington

September 17, 2010

nhc
northwest hydraulic consultants
water resource specialists

Opinion on the Transport of Metallurgical Slag by the Columbia River, Trail B.C. to International Boundary

Prepared For:

The Confederated Tribes of the Colville Reservation
and the State of Washington

David G McLean

David G. McLean, Ph.D., P.Eng.

September 15, 2010
35240

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EXECUTIVE SUMMARY

This report assesses the transport and fate of metallurgical slag material that was discharged into the Columbia River by the Teck Cominco smelter operations at Trail B.C. during the period 1930 to 1995. In particular, the study assessed whether any slag material has been transported by the river downstream across the International Border into Washington State.

Teck Cominco has operated a smelter in Trail, BC since 1896. Starting in 1929, blast furnace slag was reprocessed in a slag fumer from which the final slag by-products were discharged into the Columbia River. The slag material has a granular texture, with dominantly sand-sized particles. The estimated total discharge between 1929 and 1995 (including the stockpiled material from the 1920s) is approximately 12 million tonnes. If all of the slag that was discharged into the river remained within 1 km of the discharge point, the deposited slag would cover the river bed from bank to bank to a depth of 37 m (approximately 120 feet). If all of the slag that was discharged into the river was deposited in the 18 km reach from Trail down to the International Boundary, the deposited slag would cover the river bed from bank to bank to a depth of 2.1 m (7 feet). Field inspections and surveys indicate only local deposits of slag occur along the shoreline and in some pools. Therefore, most of the slag has been transported downstream of the International Boundary.

The free-flowing reach of the Columbia River from Birchbank, BC to Northport had a very low sediment supply prior to flow regulation from upstream hydro power developments since most of the sediment generated in the upstream watershed was trapped by lakes. Construction of dams on the Arrow Lakes (Hugh Keenleyside Dam), on the upper Columbia (Mica and Revestoke Dam) and Kootenay River (Brilliant Dam) further reduced the sediment supply. The suspended sediment transport in this reach is “supply limited”, meaning that the river’s transport capacity far exceeds the rate of sediment supply and the river can transport all of the suspended sediment that is supplied.

Several independent methods have been used to assess the transport and movement of granular slag discharged into the Columbia River at Trail, including:

- Reviewing previous results of suspended sediment sampling along the Columbia River and comparing its sediment supply to its sediment transport capacity;
- Computing the initiation of motion, initiation of suspension and transport capacity of slag using analytical sediment transport equations and long-term hydrometric measurements made by Water Survey of Canada at Trail and the International Boundary (with USGS);
- Computing the initiation of motion and initiation of suspension of slag using sediment transport equations and a one-dimensional hydraulic model (HEC-RAS) from Birchbank down to Northport, Washington;
- Computing slag transport, erosion and deposition using a one-dimensional sediment model (SRH-1d) from Trail down to the International Boundary;
- Sediment sampling and assessing the distribution of slag and metals commonly associated with slag along the river from Birchbank down to Northport, Washington;

- Developing a mass balance of slag distributed in the channel of the Columbia River from Trail down to the International Boundary using results of sediment sampling and comparison of bathymetric surveys from 1948, 1989 and 2010.

The results from all of these methods are consistent and demonstrate that slag discharged from the Teck Cominco smelter was transported downstream as bed load and in suspension across the International Boundary.

A small fraction of the slag that was discharged has remained in Canada. This slag has deposited locally in slack water areas (behind obstructions or in back eddies), or has sifted into the pore space of the gravel and cobble sediments that form most of the river bed or has infilled some of the large pools such as at the Waneta eddy near the confluence of the Columbia River and Pend d'Oreille River. We estimate only 10% of the total slag discharged to the river between 1930 and 1995 remains upstream of the International Boundary. The remaining 90% has been transported downstream to Northport.

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GLOSSARY

Cobbles: sediment particles having a size between 256 mm and 64 mm

Gravel: sediment particles ranging in size between 64 mm and 2 mm

Sand: sediment particles ranging in size between 2.00 mm to 0.063 mm

Silt: sediment particles ranging in size between 0.063 mm to 0.004 mm

Clay: sediment particles less than 0.004 mm

Bed Load: sediment particles moving in direct contact with the bed by rolling, sliding and saltating. Bed load is usually measured by trap samplers placed on the river bed;

Suspended Load: sediment particles maintained in the water column by the turbulence of the flow. The suspended load is normally measured with depth integrating samplers and may consist of clay, silt and sand-sized particles;

Bed Material: sediments that compose the river channel deposits, shoals and bedforms.

Bed Material Load: The transport rate of sediments derived from entrainment and erosion of the bed material deposits in the channel. The bed material load can be transported both as “bed load” and as “suspended bed material”. The bed material load is governed by the local velocities and shear stresses in the river channel, not the upstream supply. The bed material load also has a major influence on the stability of the channel, since changes in bed material load affect aggradation and degradation.

Wash Load: Fine sediment load that can be maintained in suspension by the turbulence of the flow and consequently is not found in appreciable quantities in the river channel bed material. The rate of wash load transport is governed by the supply of fine sediment erosion in the watershed, not by the local hydraulic conditions in the river channel.

One Dimensional Hydraulic Model: A model that solves the equations of water movement and conservation of mass by dividing the reach into cross sections at intervals along the reach and representing the channel geometry and hydraulic properties at each location using cross section averaged values such as the mean depth and mean velocity.

1 INTRODUCTION

1.1 PURPOSE

Northwest Hydraulic Consultants Ltd. (NHC) was retained by the Confederated Tribes of the Colville Reservation and the State of Washington to provide an expert opinion on the transport and fate of metallurgical slag material that was discharged into the Columbia River by the Teck Cominco smelter operations at Trail B.C. during the period 1930 to 1995. In particular, the study assessed whether any slag material has been transported by the river downstream across the International Border into Washington State.

1.2 QUALIFICATIONS

This report was prepared by Dr. David McLean, P.Eng. of Northwest Hydraulic Consultants Ltd. Dr. McLean was the senior hydraulic engineer /sedimentation engineer for the investigation. Dr. McLean is a Principal of NHC and has 33 years of experience in hydraulic engineering and sedimentation. He has conducted research on sediment transport and sedimentation processes on gravel-bed rivers and investigated the physical and morphological impact of major engineering projects such as dams and water diversions on river processes. A declaration statement and resume for Dr. McLean are attached in Appendix A of this report.

Mr. Peter Brooks, P.E. was project hydraulic engineer for the investigations. Mr. Brooks has a MS degree in Civil Engineering (Hydraulics) from the University of Minnesota and has 10 years of experience in river hydraulics and sediment transport. He has conducted numerous hydraulic modeling investigations in Washington State for determining flood levels, for assessing river erosion and developing design parameters for river stabilization and habitat enhancement projects.

Dr. Darren Ham was the senior geomorphologist and GIS specialist for the investigations. Dr. Ham implemented the field investigation program, prepared digital terrain models of the bathymetric survey data and assessed historic channel changes. Dr. Ham has a Ph.D. in physical geography and has 15 years experience in the field of fluvial geomorphology and GIS analysis. His expertise includes river sedimentation and erosion, analysis and interpretation of geomorphic processes, topographic modelling, and application of remote sensing technologies for mapping and measuring landform dynamics.

Dr. André Zimmermann. P.Geo. was project geo-scientist for the investigation. Dr. Zimmermann participated in the field sampling program, assessed the slag content and grain size distribution of the sedimentary units along the river. Dr. Zimmermann completed his Doctoral research in physical geography and has 10 years of experience in sedimentology and geomorphology. He has conducted detailed field studies and physical modelling programs, and published papers on sediment sampling techniques in gravel-bed rivers similar to the Columbia. He is an adjunct Faculty member in the Department of Geography at the University of British Columbia.

1.3 METHOD OF APPROACH

This investigation used several different methods and analytical techniques to assess the transport and fate of granular slag discharges into the Columbia River. These methods included hydraulic computations based on available hydrometric data collected by government agencies (Water Survey of Canada and US Geological Survey), hydraulic modeling and hydraulic computations, sediment transport modeling, field sampling of river bed materials and sediments, and analysis of historic channel changes to the river bed using geomorphic interpretation. My opinions expressed in the conclusions of this report are based on a review and an overall assessment of all these results. This multi-level approach is appropriate because sedimentation processes on large rivers is complicated and there are always limitations associated with any single analytical technique. For example, numerical models always involve some degree of simplification of the actual physical processes and are limited by the availability of data for calibration and verification. Direct field-based observations are generally more reliable than model predictions but may be limited in terms of time and spatial extent. Using several independent methods to develop our assessment overcomes these limitations and provides a more robust opinion than relying on any single method or technique.

The following tasks were conducted during the investigation:

- A review of previous studies and data sources related to river hydraulics, sediment transport and water quality on the Columbia River between the Arrow Lakes and the town of Northport, Washington;
- Site inspections, sediment sampling and field surveys to characterize the composition of the sediments in the bed of the Columbia River and to assess localized topographic changes in some reaches of the river. Table 1 summarizes when these field investigations were conducted and their primary purpose;
- Detailed assessment of hydrologic, hydraulic and sediment data collected by agencies such as the Water Survey of Canada, BC Ministry of Environment, US Geological Survey at various gauging stations on the river located between Birchbank, B.C. and the International Border. These historic data were used to characterize the hydraulic properties (mean velocity and water depth) and sediment transport characteristics of the slag at specific locations on the river for a range of discharge conditions;
- Development of a one-dimensional hydraulic model of the Columbia River from Birchbank, B.C. to Northport Washington using the program HEC-RAS 4.0 to assess water levels and hydraulic parameters (mean velocity, water depth and shear stress) along the river under a range of discharge conditions. The model was used to estimate hydraulic parameters and sediment transport characteristics of the slag at various sections between Trail and Northport;
- Development of a one-dimensional sediment model using the program SRH-1D to assess sediment transport and deposition along the Columbia River.

Table 1: Summary of field investigations conducted by NHC

Date	Purpose	Section of River Visited
January 21-22 2010	Reconnaissance site visit	River between Trail and Canadian/US border
April 24-28 2010	Detailed sampling program including collecting material for target analyte and measuring surface and sub-surface grain size distributions. Collected side scan sonar and samples in two pools.	River from the Hugh Keenleyside Dam to the Canadian/US border
June 23-28, 2010	Collect updated bathymetry data and underwater video in two large pools	Pools at Pend d'Oreille confluence and upstream of Fort Sheppard.
May 4, 2010	Reconnaissance site visit	River between the International Boundary and Northport, Washington.
July 30-31, 2010	Collected updated bathymetry and substrate sampling in four pools	River between the International Boundary and Northport, Washington

1.4 REPORT OUTLINE

In addition to this brief introduction, the report contains six chapters and two appendices. Chapter 2, *Data Sources* lists the key data sources that were used in the investigation. Chapter 3, *Background Information*, describes the hydrological and sediment transport characteristics of the Upper Columbia River from Birchbank B.C. to Northport, Washington. Chapter 4, *Transport of Slag in the Columbia River*, summarizes the history of slag discharges from the Teck-Cominco smelter at Trail, and assesses the sediment transport and fate of slag sediments under varying discharge conditions in the Columbia River from Trail downstream to Northport. Chapter 5, *Observed Distribution of Slag in Columbia River Sediments*, characterizes the distribution of slag in the river bed sediments between Trail and the International Boundary in order to estimate the amount of slag remaining upstream of the border and the amount of slag that has been transported downstream across the border into Washington State. Chapter 6, *Assessment of Results* summarizes and compares the assessments from the different analytical techniques. Chapter 7, *Conclusions*, provides a summary of the key findings from the investigations.

Appendix A, includes a declaration statement, detailed resume and list of publications. *Appendix B, Hydraulic Model Development*, summarizes the development and calibration of the one dimensional hydraulic and sediment transport models that were used in study. Appendix C. *Quality Assurance Plan*, provides details on the methods of sediment sampling.

2 DATA SOURCES

This chapter summarizes the published data that were used in this investigation

2.1 HYDROMETRIC DATA

Water Survey of Canada (WSC) has operated four key hydrometric stations in the study area (Figure 1).

Daily water levels and discharge have been published at three sites on the Columbia River and at the Pend d'Oreille River at the International Boundary. Table 2 summarizes the period of record for each station.

Table 2: Period of record of key hydrometric stations

Gauge	**Gauge ID**	**Period of Record**	**Distance From International Boundary (km)**	**Drainage Area (km^2)**
Columbia R. at Birchbank	08NE049	1937 – 2008	27.5 upstream	88,100
Columbia R. at Trail	08NE003	1913-1969	18.0 upstream	88,100
Columbia R. at International Boundary	08NE058	1938 – 2008		155,000
Pend d'Oreille R. at International Boundary	08NE010	1913-1991	----	65,300

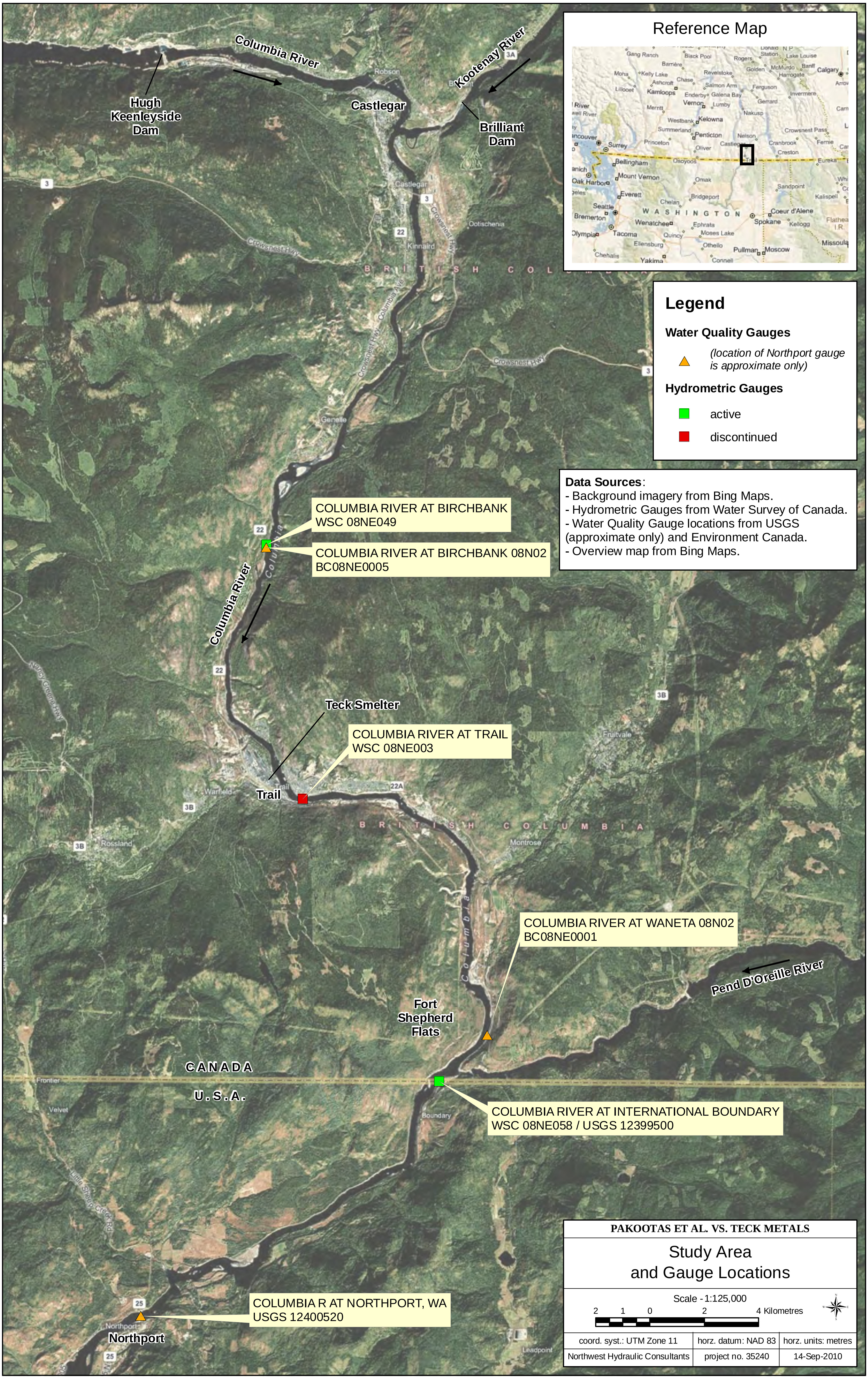
Daily values were obtained in digital format from Environment Canada at www.wsc.ec.gc.ca/hydat/H2O.

In addition to the published daily records the actual discharge measurement notes were obtained for the three stations on the Columbia River. These discharge measurements are made periodically (typically 10 to 20 times per year) by WSC technicians and document the actual measurement of velocity, depth and width of the river at each site.

2.2 SEDIMENT TRANSPORT DATA

Sediment data in Canada were originally published in the Water Survey of Canada's annual reports and are now available in digital form at www.wsc.ec.gc.ca/hydat/H2O. Table 3 summarizes the period of record for the two sampling stations on the Columbia River. The suspended sediment concentration and suspended load were measured periodically on the river near Trail between 1965 and 1982. The sediment station is labeled as the "Columbia River at Birchbank" (08NE049). However, according to WSC records, the suspended sediment samples were actually collected in Trail, at the bridge, downstream of the Teck Cominco smelter (Lynne Campo, Water Survey of Canada, pers. com.). The discharges from the Birchbank gauge

(08NE049) were then used to convert the measured suspended sediment concentrations to sediment loads. This could introduce some confusion on interpretation of the data. For the purposes of this report, we have continued to use the WSC title “Columbia River at Birchbank”, even though it is understood the actual samples were collected in Trail. After further analysis and interpretation of the data, it was found that the actual location of the sampling did not fundamentally affect any of our opinions or conclusions.



Legend

Water Quality Gauges

▲ *(location of Northport gauge is approximate only)*

Hydrometric Gauges

🟩 active

🟥 discontinued

Data Sources:
- Background imagery from Bing Maps.
- Hydrometric Gauges from Water Survey of Canada.
- Water Quality Gauge locations from USGS (approximate only) and Environment Canada.
- Overview map from Bing Maps.

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Study Area
and Gauge Locations

Scale - 1:125,000

2 1 0 2 4 Kilometres

coord. syst.: UTM Zone 11	horz. datum: NAD 83	horz. units: metres
Northwest Hydraulic Consultants	project no. 35240	14-Sep-2010

MSN, 35240 Columbia River Slag\GIS\35240_MSN_Fig_BaseMap1.mxd

Figure 1

Table 3: Period of record of sediment stations

Gauge	Gauge ID	Period of Record	Distance From International Boundary (km)	Drainage Area (km^2)
Columbia R. at Birchbank	08NE049	1965 – 1981	27.5	88,100
Columbia R. above Steamboat Rapids	08ND011	1967 – 1976	305	26,400

Suspended sediment concentrations and sediment loads were also recorded much further upstream above Steamboat Rapids, prior to the construction of Revelstoke Dam. This site is too far upstream to be directly used in this study, but does provide an indication of the sediment yield in the Columbia basin in areas not directly affected by lakes or reservoirs.

2.3 WATER QUALITY DATA

Miscellaneous water quality measurements have been published by Environment Canada and the USGS at three stations on the Columbia River. The period of record is summarized in Table 4.

Table 4: Period of record of water quality stations

Gauge	Gauge ID	Period of Record	Distance From International Boundary (km)	Drainage Area (km^2)
Columbia R. at Birchbank	BC08NE0005	1983 – 2006	27.5 upstream	88,100
Columbia R. at Waneta	BC08NE0001	1979 – 2006	18.0 upstream	88,100
Columbia R. at Northport, Wash.	12400520	1974 – 2000	16.0 downstream	155,900

Station BC08NE0005 is located 10 km upstream of Trail at the active WSC hydrometric station. Station BC08NE0001 is located on the left bank of the Columbia River at the Cominco environmental monitoring station upstream of the Waneta confluence. The data was primarily used to provide information on suspended sediment concentrations.

Additional miscellaneous water quality data has been collected as part of past studies and short-term monitoring programs.

2.4 BATHYMETRIC DATA

The earliest underwater survey of the river in Canada was completed in 1948 by the Department of Public Works. The mapping extends from the Canada/US border to near the headwaters of the Columbia River and depicts the Columbia River in a natural state prior to construction of any dams. This mapping was completed as an investigation of water resources within the Columbia Basin by the International Joint Commission. As part of this investigation, surveys were also completed south of the border by the U.S. Coast and Geodetic Survey from the border downstream to Grand Coulee Dam. This information is shown on NOAA chart 18553 7th edition published in April 2004.

The river was surveyed again in 1989 by the Canadian Hydrographic Service (CHS). Chart 355 extends from Hugh Keenleyside Dam to the Canada/US border near Waneta. A digital copy of spot soundings from the original field sheets and interpolated contours was supplied to NHC by the Canadian Hydrographic Service.

2.5 ONE DIMENSIONAL HYDRAULIC MODELS

Two existing one dimensional hydraulic models have been developed as part of previous investigations along the river:

- Columbia River from Hugh Keenleyside Dam to International Boundary (BC Hydro model);
- Columbia River from International Boundary to Grand Coulee Dam (Hydro-Qual model).

Both utilize the program HEC-RAS, developed by the Hydrologic Engineering Center, US Army Corps of Engineers.

The BC Hydro model was used previously for making preliminary hydraulic and sediment transport computations downstream of Trail (NHC, 2009). The river channel geometry used in this model was based on the 1989 CHS bathymetric data described in Section 2.4. There was some uncertainty in geo-referencing the cross section locations in this model. Therefore, it was decided to prepare a new model using the geo-referenced 1989 bathymetry. Further details on the development of the updated model are contained in Appendix B.

The existing Hydro-Qual HEC-RAS model extends from the International Boundary down to Grand Coulee Dam. The HEC-RAS model was provided to NHC in digital form. The cross section geometry in the model was based on bathymetric surveys from 1948. NHC subsequently reviewed the model and extracted the portion between Northport Washington and the International Boundary. This reach was then joined to the updated Canadian model so that a single model was developed extending from Birchbank B.C. downstream to Northport Washington.

Details of the model development, calibration and verification are described in Appendix B.

3 OVERVIEW OF THE COLUMBIA RIVER

3.1 THE RIVER SYSTEM

Figure 2 shows the Columbia River and its principal tributaries in Canada. The river originates at Columbia Lake and flows in a northwesterly direction in a trench bordered by the Rocky Mountains on the east and the Purcell Mountains on the west. Near its confluence with the Canoe River, the Columbia turns southward and flows in a valley bounded by the Columbia Mountains and Monashee Mountains on the west and the Selkirk Mountains on the east. The river continues southward in a relatively narrow valley until entering the Upper and Lower Arrow Lakes. The outlet of Lower Arrow Lake, is located approximately 51 km upstream of the International Boundary. The Kootenay River enters from the east at Castlegar, approximately 10 km downstream of the outlet of Lower Arrow Lake.

The Pend d’Oreille River enters from the east approximately 50 km downstream of Hugh Keenleyside Dam, and less than 1 km upstream from the International Boundary. Both the Kootenay and Pend d’Oreille River basins lie partly in the USA, where the river names are spelled differently (Kootenai and Pend Oreille, respectively).

Columbia River flow regulation began with the construction of Grand Coulee Dam in north eastern Washington in the late 1930s for hydropower, irrigation and flood control. Reservoir filling was completed in 1941. Several dams were constructed in the Columbia River watershed upstream of Lake Roosevelt in the 1940s and 1950s for hydropower production, chiefly on the Kootenay / Kootenai and Pend d’Oreille / Pend d’Oreille River systems. Brilliant Dam was constructed near the mouth of Kootenay River in the early 1940s. Waneta Dam, constructed near the mouth of Pend d’Oreille River approximately 1 km upstream of the International Boundary was constructed in the early 1950s.

Major hydro-electric projects on the Columbia River in Canada occurred throughout the 1960s, partly to provide storage and flood control for American hydroelectric and irrigation projects under the Columbia River Treaty between Canada and the USA. Construction of Hugh Keenleyside Dam at the outlet of Lower Arrow Lake was completed in 1968. Mica and Revelstoke Dams were constructed on the Columbia River mainstem upstream of the Arrow Lakes Reservoir in 1973 and 1984, respectively, impounding new reservoirs. Duncan Dam and Libby Dam were constructed in the Kootenay / Kootenai River sub-basin in the late 1960s and early 1970s, also impounding new reservoirs.

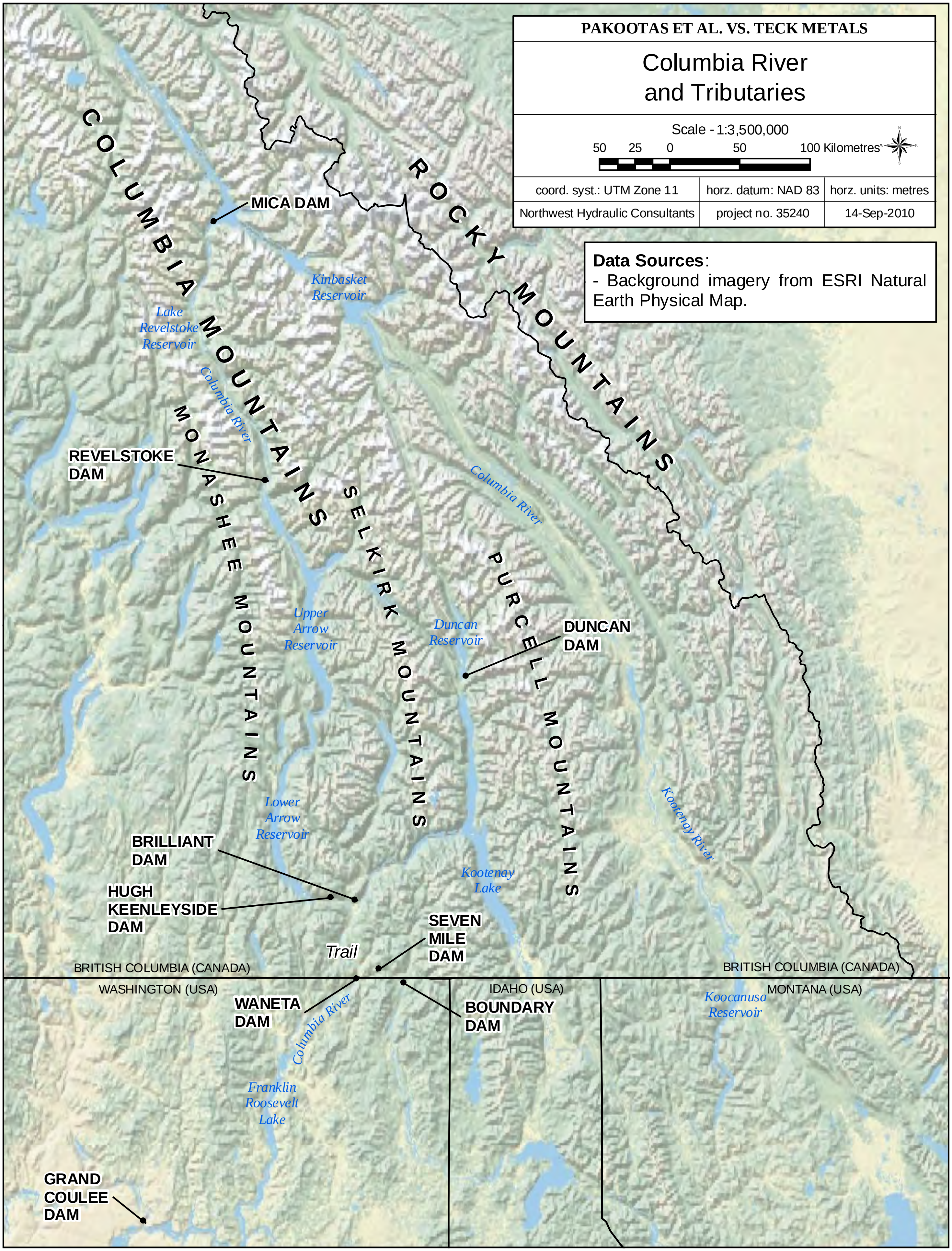
As a result, there is a 68 km, free-flowing reach from the outlet of the Arrow Lakes Reservoir (Hugh Keenleyside Dam) to Northport Washington. There are a number of small tributaries between Hugh Keenleyside Dam on the Arrow Lakes and the town of Trail including:

- Norns Creek (210 km^2)
- Blueberry Creek (149 km^2)
- Murphy Creek (79 km^2)
- Champion Creek (73 km^2)
- Trail Creek (73 km^2)
- China Creek (20 km^2)

Between the town of Trail and the International Boundary the main tributary is the Pend d'Oreille River which enters from the east (left) bank about 1 km upstream of the border. The Waneta Dam on the Pend d'Oreille River (constructed in the early 1950's on the Pend d'Oreille River about 0.5 km upstream of its confluence with the Columbia River) has intercepted and trapped most of the coarse sediment (sand and gravel) generated from the Pend d'Oreille basin. Other minor tributaries between the town of Trail and the International Boundary include:

- Bear Creek (42 km^2)
- Casino Creek (14 km^2)
- Beaver Creek (264 km^2)

On account of the naturally occurring lakes and constructed dams in the upper Columbia watershed, the potential sediment-generating watershed area between Trail and the International Boundary is very small (less than 400 km^2).



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Columbia River
and Tributaries

Scale - 1:3,500,000

coord. syst.: UTM Zone 11	horz. datum: NAD 83	horz. units: metres
Northwest Hydraulic Consultants	project no. 35240	14-Sep-2010

Data Sources:
- Background imagery from ESRI Natural Earth Physical Map.

MSN, 35240 Columbia River Slag\GIS\35240_MSN_Fig_ColumbiaRiverOverview1.mxd

Figure 2

3.2 RIVER DISCHARGES

The hydrological regime of the Columbia River in the study reach has been greatly modified by upstream dam construction and river regulation. Figure 3 shows that prior to regulation in the late 1960s and 1970s, the natural flow in the river was characterized by a winter base flow of about 1,000 m^3/s and a late-spring snowmelt freshet with a mean annual flood on the order of 9,500 m^3/s (at the International Boundary). Since regulation, the low flows in winter have been substantially increased, while the freshet peaks have been practically eliminated. As a result, the average annual daily flow has remained relatively unchanged by flow regulation. The regulated hydrograph also shows more short-term fluctuations, caused by the release of flows for hydropower generation.

Regulation has dramatically reduced the magnitude of annual floods. Annual peak flows prior to regulation typically exceeded the mean annual discharge by at least a factor of three, and sometimes up to a factor of five. Post-regulation peak flows are now typically less than twice the magnitude of the mean annual discharge. Key statistics at Birchbank/Trail and at the International Boundary are summarized in Table 5. For this analysis the data from the two hydrometric stations at Trail and Birchbank were combined to provide a continuous record of discharges for the period 1930-1972 (WSC ceased publishing daily discharges at Trail after 1969-see Table 2).

Table 5: Comparison of discharges before and after flow regulation

Location	Birchbank –Trail				International Boundary		
Period	**Mean Annual Flow**	**Mean Annual Flood**	**Maximum Daily**	**Period**	**Mean Annual Flow**	**Mean Annual Flood**	**Maximum Daily**
1930 -1972	2,050	7,020	10,600	1938 -1972	2,880	9,500	15,500
1973 -1995	1,940	3,760	5,410	1973 -1995	2,700	4,960	8,100
1996 -2008	2,075	3,580	4,520	1996 -2008	2,840	5,440	8,550

3.3 SEDIMENT LOADS

Table 6 summarizes the published suspended sediment concentration and suspended sediment load measurements on the Columbia River at Birchbank[1] made by Water Survey of Canada during the period 1966 – 1981. The sediment concentrations are very low, with the maximum daily value reaching only 109 mg/l on June 3, 1968. The annual suspended sediment load ranged from a high of 1,130,000 tonnes in 1967 to a low of 209,000 tonnes in 1977 and averaged 491,000 tonnes.

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[1] Although the official name of the station is Columbia River at Birchbank, WSC reported the samples were actually collected further downstream at Trail (see section 2.2).

Table 6: Historical suspended sediment data summary-Columbia River at Birchbank (08NE049)

Year	Maximum Concentration (mg/l)	Minimum Concentration (mg/l)	Maximum Daily Load (Tonnes/day)	Total Annual Load (Tonnes)
1966	75	2	14,300	850,000
1967	28	1	22,100	1,130,000
1968	109	3	52,600	990,000
1969	43	2	22,200	626,000
1970	19	1	4,410	278,000
1971	35	1	13,500	446,000
1972	41	1	20,800	510,000
1973	16	1	2,970	278,000
1974	51	1	15,700	428,000
1975	23	2	3,440	253,000
1976	20	0	5,630	355,000
1977	21	0	5,100	209,000
1978	16	0	3,220	371,000
1979	32	0	5,890	344,000
1980	63	1	11,800	438,000
1981	33	3	8,610	358,000

.

Based on the basin area at the Birchbank gauge (88,100 km^2) and Canada derived basin area-sediment yield relations for rivers without major lakes or dams (Church et al., 1999), an annual load of 13,000,000 tonnes per year is more typical for similarly sized watersheds.

Water Survey of Canada published results of suspended sediment measurements at only one other location - the Columbia River above Steamboat Rapids (station 08ND011) for the period 1967 to 1976. These measurements were made upstream of the town of Revelstoke and over 300 km upstream of the International Boundary. The sediment concentrations measured at Steamboat Rapids were up to ten times higher than at Birchbank, and exceeded 1,000 mg/l in 1968, 1972 and 1974. Although the drainage area at Steamboat Rapids is only about one third of the area at Birchbank, the annual sediment load was much greater than at Birchbank, reaching up to 6,360,000 tonnes in 1968 and averaging 2,920,000 tonnes (approximately six times higher than at Birchbank).

The low suspended sediment loads measured on the Columbia River at Birchbank reflect the effectiveness of the large lakes and reservoirs upstream from the site (the Arrow Lakes on the mainstem Columbia River as well Kootenay Lake on the Kootenay River) in trapping the incoming sediment load rather than an inability of the river to transport the sediment supplied.

Water Survey of Canada did not measure the size distribution of the suspended load during its monitoring program. However, some results from miscellaneous sampling in 1995 and 1999 (before and after slag discharges to the river ended) were reported in Aquatic Resources Ltd. (2001). The sampling was carried out at several locations both upstream and downstream of Teck Cominco's slag discharge site in Trail:

- Birchbank (upstream of Teck Cominco slag discharge point);
- Downstream of Stoney Creek (upstream of Teck Cominco slag discharge point);
- New Bridge in Trail (just downstream of the Teck Cominco slag discharge point);
- Old Bridge in Trail (1 km downstream of the Teck Cominco slag discharge point);
- Downstream island near Waneta (downstream of the Teck Cominco slag discharge point).

The analysis indicated the sand fraction (2.00 mm to 0.063 mm) accounted for approximately 50% of the total suspended load at Birchbank, with the silt (0.063 mm to 0.004 mm) and clay fraction (finer than 0.004 mm) accounting for the rest. The sand fraction increased to between 60% and 70% of the total suspended load in 1995 at the two bridge sampling sites (downstream from the slag discharge point). The size fraction coarser than 0.25 mm (representative of slag material discharged to the river) accounted for between 20% to 35% of the suspended load at these sites in 1995.

By comparison, the slag discharge to the Columbia River from the Teck Cominco smelter at Trail averaged approximately 170,000 tonnes/year (466 tonnes/day) during the period 1966 to 1981, or 35 % of the river's annual suspended sediment load (see Section 4 for details on historic records of slag discharges and Queneau, 2010). Using a typical mean annual discharge of 2,000 m^3/s (Table 5), this corresponds to an average concentration of 2.6 mg/l, which is very low in comparison to typical suspended sediment concentrations on the river.

3.4 RIVER CHANNEL CHARACTERISTICS

Between Birchbank and the International Boundary, the Columbia River flows in a single, gravel/cobble channel that is frequently confined by its valley walls. The river has a slightly sinuous, irregular planform. The channel width averages 180 m and ranges from 150 m in narrow confined sections near Trail to 450 m near the Pend d'Oreille River confluence and Fort Shepherd Flats. Based on published soundings shown on Canadian Hydrographic Chart 3055, the depth typically averages 4 m but exceeds 15 m at several locations, including:

- 16.4 m, just downstream of Rock Island (5.2 km downstream of Trail);
- 42 m, near Fort Shepherd Flats (13.7 km downstream of Trail);
- 15.8 m, at the International Boundary (18 km downstream of Trail).

These deep pools are all associated with bedrock that outcrops in mid- channel or projects out into the channel from the bank. These bedrock features create localized flow obstructions and generate high velocities and intense turbulence that induces channel scour. A deep pool is also located near the confluence with the Pend d'Oreille River (18.4 m). This pool has developed at the confluence zone of the Pend d'Oreille and Columbia River where intense eddying and secondary currents are produced (ASL, 2002).

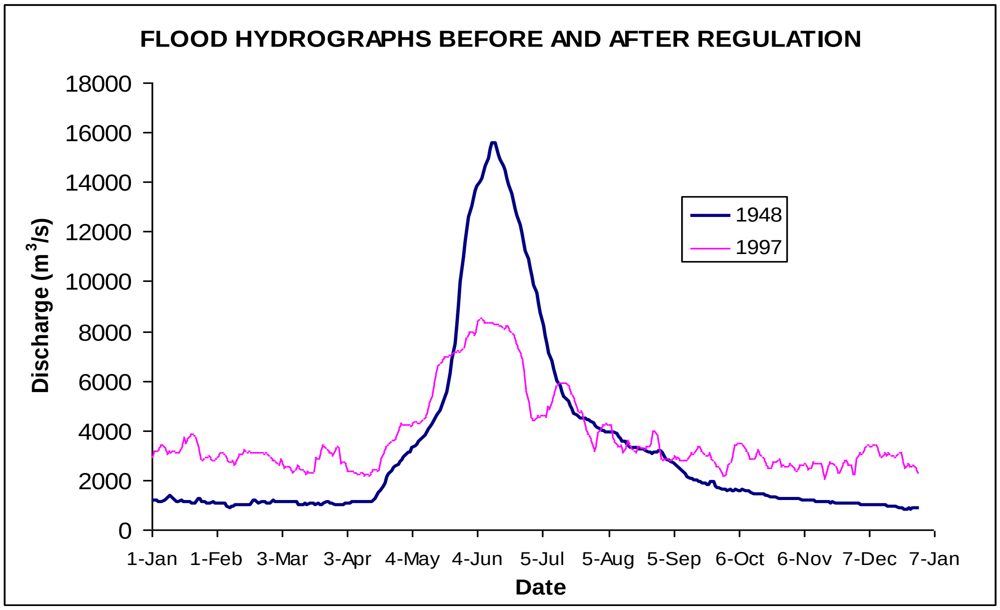

Figure 3: Columbia River hydrograph at International Boundary before and after flow regulation.

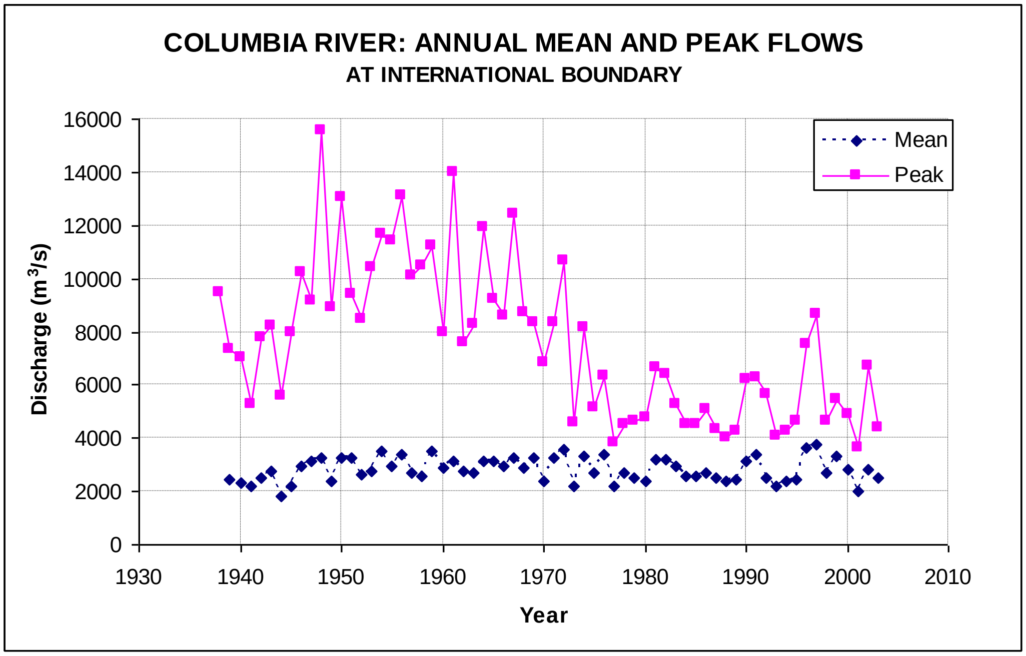

Figure 4: Variation in peak and mean annual discharges

Based on the WSC hydrometric gauge records, the Columbia River drops a vertical distance of 7.6 m between Trail and the International Boundary, which corresponds to an average gradient of 0.00046 (0.46 m per kilometer).

Channel velocities and mean depths were determined from the hydrometric measurements conducted by WSC at Trail (station 08NE003) and the International Boundary (station 08NE058). These measurements are summarized in Figure 5, along with best-fit regression equations. Table 7 summarizes estimates of mean velocity and mean depth at the two hydrometric stations for the pre-regulation (to 1972) and post-regulation (1973-1995) flow conditions.

Table 7: Hydraulic geometry at Trail and International boundary gauging stations

		Trail (08NE003)			**International Boundary (08NE058)**		
	Flow Condition	**Discharge (m^3/s)**	**Mean Velocity (m/s)**	**Mean Depth (m)**	**Discharge (m^3/s)**	**Mean Velocity (m/s)**	**Mean Depth (m)**
Pre-regulation	Mean	2,050	1.81	6.64	2,880	2.15	5.97
	MAF	7,020	3.61	9.96	9,500	3.43	10.92
	Max	10,600	4.56	11.40	15,500	4.16	13.98
Post-regulation	Mean	1,940	1.75	6.52	2,700	2.09	5.78
	MAF	3,760	2.54	8.11	4,960	2.66	7.86
	Max	5,410	3.12	9.14	8,100	3.23	10.07

Note:

- Mean = mean daily discharge during period of observations
- MAF = mean annual flood during period of observations
- Max = maximum daily discharge recorded during period of observations

These results show that the long-term mean velocity has not changed appreciably due to flow regulation. For example, the mean velocity at Trail averaged 1.81 m/s in the pre-regulation period and 1.75 m/s in the post regulation period. However, since the flood peaks have been greatly attenuated by flow regulation, the peak velocity has decreased noticeably since 1972. For example, the mean annual flood at Trail decreased from 7,020 m^3/s in pre-regulation times to 3,760 m^3/s after regulation. The corresponding velocity at Trail decreased from 3.61 m/s to 2.54 m/s.

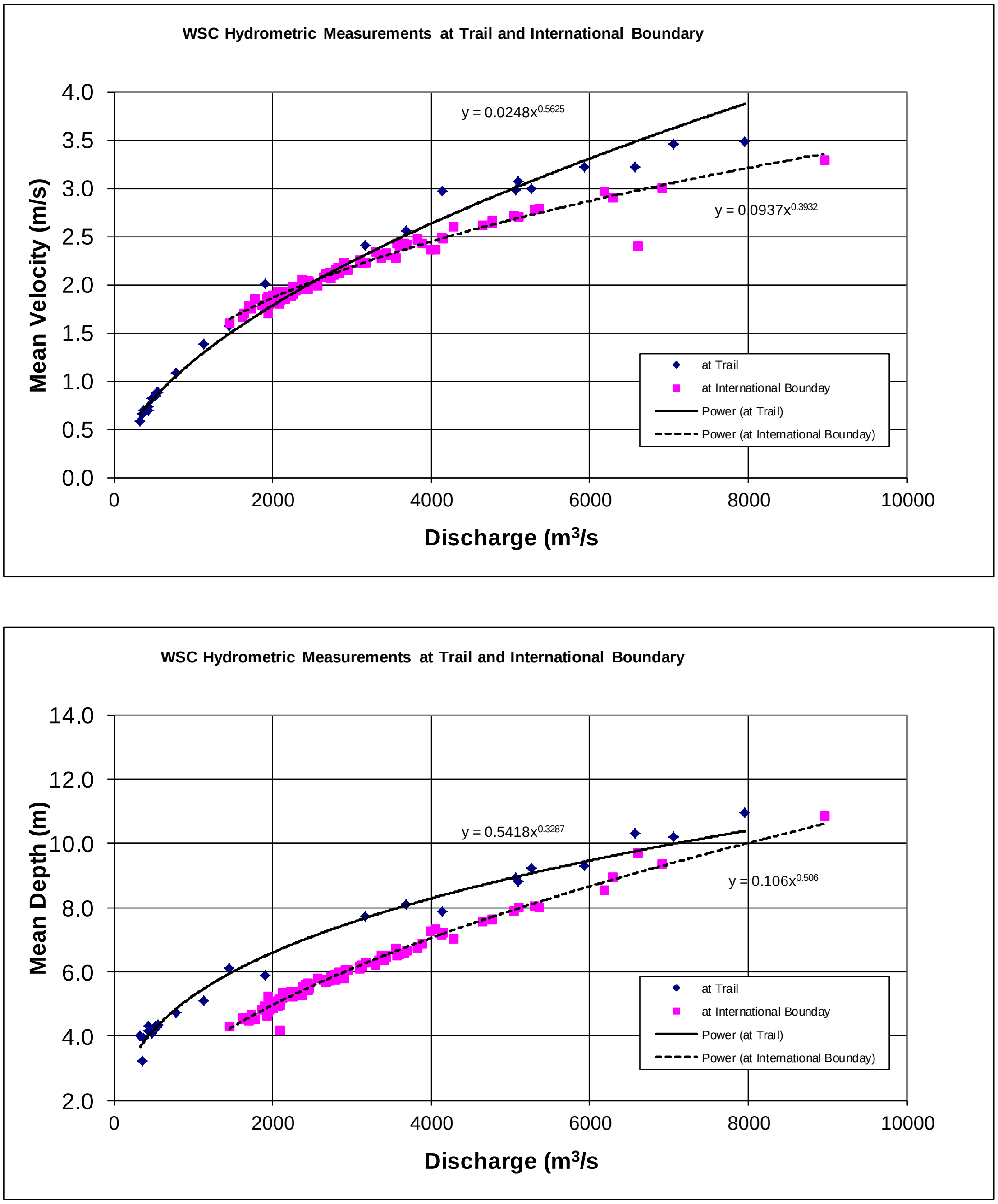

Figure 5: Hydraulic geometry measurements at Trail and International Boundary hydrometric stations.

3.5 RIVER BED MATERIAL

Table 1 summarizes the Field investigations were conducted by NHC in January and April 2010 to characterize the bed material characteristics of the Columbia River between Castlegar and the International Boundary. The surface of the river bed and exposed bars consists mainly of cobbles and coarse gravel. The surface grain size distribution of the bars along the river was determined using a variation of the Wolman (1954) pebble count technique (refer to Bunte and Abt, 2001). A 50-m long measuring tape was laid out along the bar surface roughly parallel to the prevailing flow direction, and the particle immediately below each 0.5 m increment was selected for measurement. The location of the sample sites is shown in Figure 6. Figure 7 summarizes the grain size distributions at all sites sampled and Table 8 summarizes some key statistics from the sample distributions. The values D_{10}, D_{50} (median) and D_{90} are commonly used to characterize sediment transport properties of the sediment. For example, a D_{10} value of 17 mm indicates that 10 % of the sediment in the sample was smaller than 17 mm (2/3 inch) in diameter. The D_{50} (median) grain size ranged from 60 mm (2 1/2 inch) to 200 mm (8 inch) at all sites except B2, which was anomalously finer with a D_{50} = 23 mm (1 inch). The finer sediment at this site was more representative of tributary sediments brought in from Beaver Creek immediately upstream, rather than Columbia River deposits. No surface sampling was completed at site B5 as the bar was composed entirely of sand.

Table 8: Surface grain size statistics

Site	Approximate Location	Distance to International Boundary (km)	D_{10} (mm)	D_{50} (mm)	D_{90} (mm)
A1	Birchbank	28	17	62	113
A2	Birchbank	28	20	85	140
A3	Castlegar	51	72	152	220
B2	Beaver Creek Park	7.4	7	25	52
B3	U/s Beaver Creek	9.0	29	90	160
B4	Near McAlister Creek	14.5	40	197	320
B8	Near Fort Shepherd pool	5.4	32	143	250

Samples B3, B4 and B8 are representative of the river bed between Trail and the International Boundary and an overall representative D_{50} size for the river bed material is approximately 100 mm.

Sub-surface samples were collected at three sites in accordance with standard bulk sampling techniques (Church et al., 1987). This involved removing the surface layer and then excavating a large volumetric sample (up to 800 kg) of the underlying sediment. The cumulative grain size distribution for the three bulk sampling sites is shown in Figure 8. Key grain size statistics are summarized in Table 9. The sub-surface is finest at Site B2 – which also had a finer surface grain size distribution. The D_{50} (median) sizes are very similar at A1 and B4. However, the sample at B4 contains much larger material, which was also reflected in the surface grain size distribution.

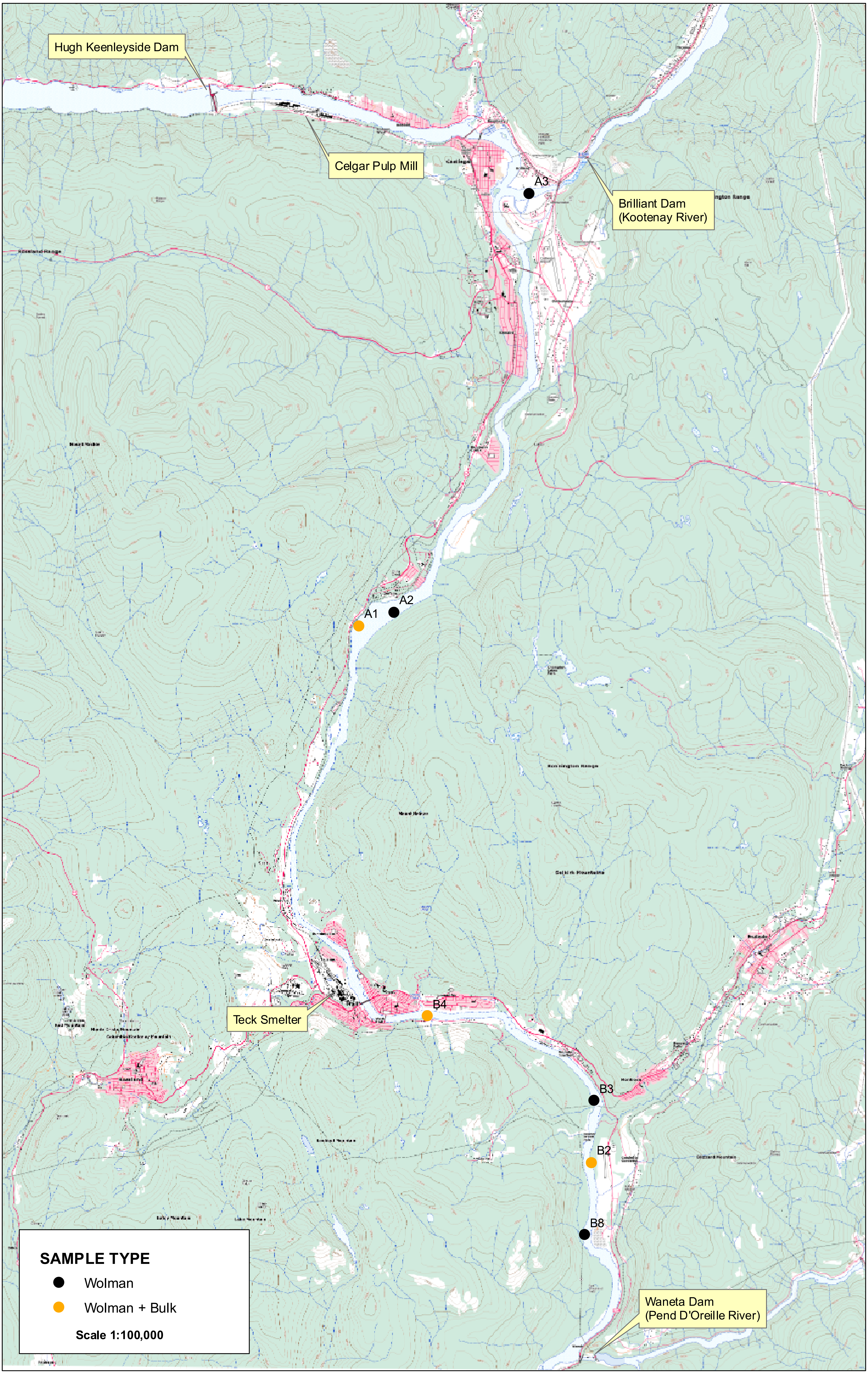
Hugh Keenleyside Dam
Celgar Pulp Mill
A3
Brilliant Dam
(Kootenay River)
A2
A1
Teck Smelter
B4
B3
B2
B8
Waneta Dam
(Pend D'Oreille River)
SAMPLE TYPE
● Wolman
● Wolman + Bulk
Scale 1:100,000

Figure 6

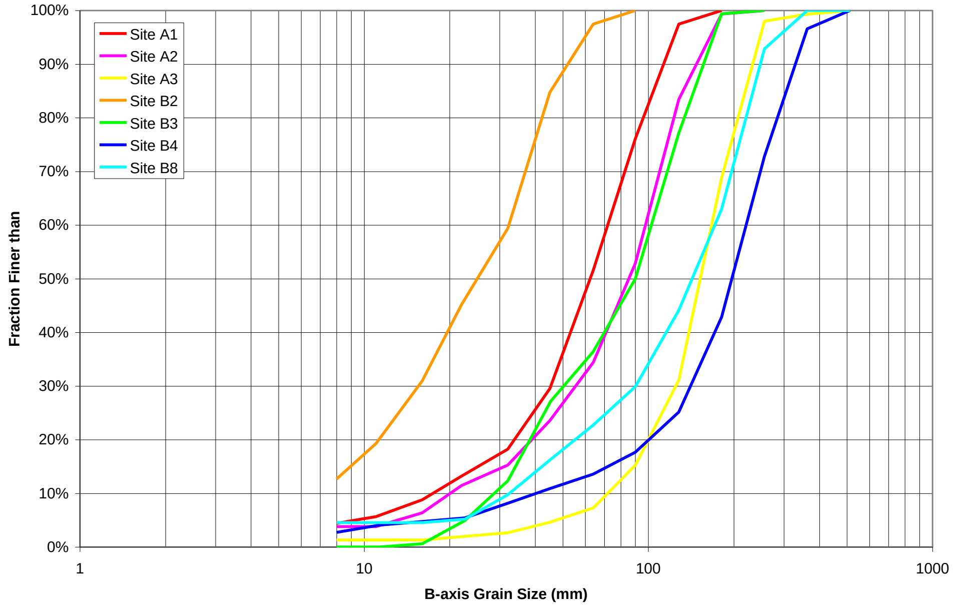

Figure 7: Surface grain size distribution of river bed sediments.

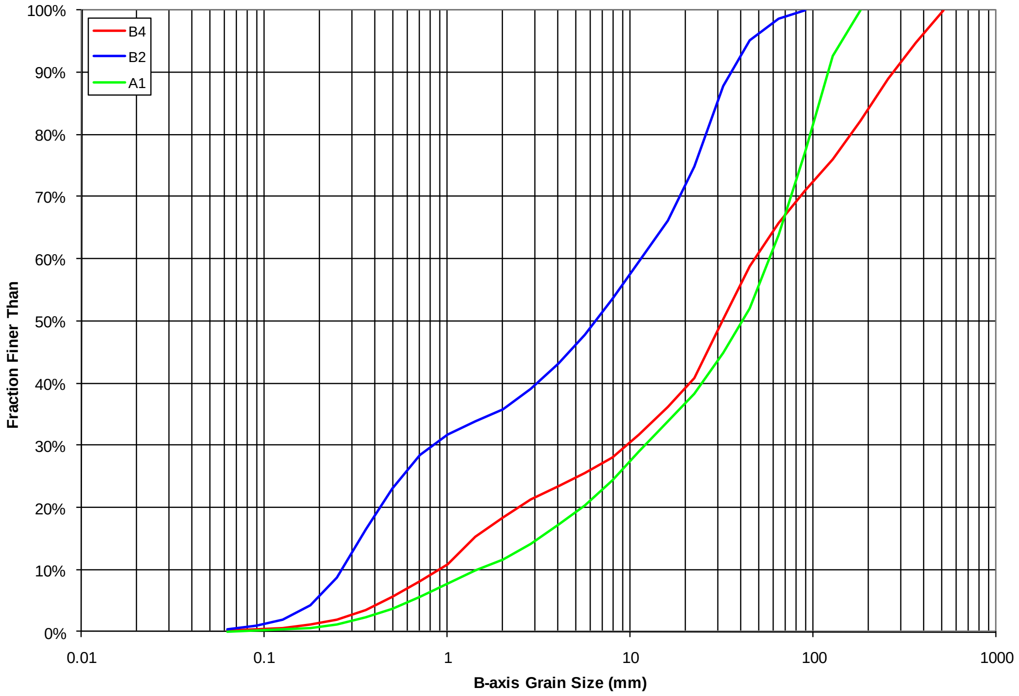

Figure 8: Sub-surface grain size distribution of river bed sediments

Table 9: Sub-surface grain size statistics

Site	Approximate Location	Distance to International Boundary (km)	D10 (mm)	D50 (mm)	D90 (mm)
A1	Birchbank	28	1.4	41	121
B2	Beaver Creek Park	7.4	0.27	6.5	36
B4	Near McAlister Cr	14.5	0.9	32	274

3.6 ASSESSMENT OF RIVER REGIME

The free-flowing reach of the Columbia River from Birchbank, BC to Northport had a very low sediment supply prior to flow regulation from upstream hydro power developments since most of the sediment generated in the upstream watershed was trapped by lakes. Construction of dams on the Arrow Lakes (Hugh Keenleyside Dam), on the upper Columbia (Mica and Revestoke Dam) and Kootenay River (Brilliant Dam) further reduced the sediment supply. The suspended sediment transport in this reach is “supply limited”, meaning that the river’s transport capacity far exceeds the rate of sediment supply and the river can transport all of the suspended sediment that is supplied.

The Columbia River between Birchbank and Northport has a predominantly gravel bed channel. Sand-sized sediment makes up only a small fraction of the total material in the channel bars and river bed material. The D_{10} bed material size is commonly used as a criterion for defining wash load (ASCE, 2007). Base on this definition, sediment in the range of 0.27 mm (medium sand) to 1.4 mm (very coarse sand) will behave mainly as wash load. Sediment that is finer than this limit will be flushed through the reach without depositing on the river bed. However, local deposition of fine wash load material may still occur in slack water areas such as on the floodplain, in back eddies, and behind local obstructions.

The surface of the gravel bars and channel bed is noticeably coarser than the underlying sub-surface deposits, which is typical of armoured channels that develop below dams or lakes, where the rate of gravel sediment supply is very low (ASCE, 2007). The point at which the sediment particles in the river bed start to be transported is defined as “incipient motion” and is commonly determined using the Shields parameter (ASCE, 2007). For coarse sediments (gravel and cobbles), the critical Shields parameter (θ_c) can be expressed as follows:

$$\theta_c = \frac{\tau}{\rho(s-1)D_{50}} = 0.03 \quad \tau = \gamma d S_f \qquad \text{and } \tau = \rho U_*^2 \qquad \text{(Eq. 1)}$$

Where τ is the critical shear stress for incipient motion, ρ is the density of water, s is the specific gravity of the sediment, D_{50} is the median sediment size, d is the water depth, S_f is the river slope and U_* is the shear velocity.

This Shields parameter expresses the ratio of hydraulic forces acting to dislodge a particle from the river bed (lift and drag forces) and the forces acting to resist particle motion (its weight and bottom friction). The shear stress was estimated directly from the WSC hydrometric measurements at Trail and the International Boundary using the relations developed in Figure 5 and the measured slope between the two stations. Based on these relations, the gravel and cobble sediment in the surface layer will begin to move at a discharge of 9,000 m3/s at Trail and 9,500 m3/s at the International Boundary. Therefore, gravel and cobble-sized sediments on the river bed were mobilized during flood conditions prior to 1973 (pre-regulation). However, these coarse-grained sediments were not mobilized under the regulated flow regime that was maintained after 1972(since the highest discharge reached only 5,400 m3/s at Trail as shown in Table 5). On account of the low sediment supply and the reduction in peak flows the main channel bars have formed a stable armour layer (Parker et al, 1982). This condition has been observed on other highly regulated gravel bed rivers below dams (ASCE, 2007). Therefore, during the regulated period of slag discharges (1973 to 1995), slag from the Teck-Cominco site was discharged onto a static, armoured river bed.

4 TRANSPORT OF SLAG IN THE COLUMBIA RIVER

4.1 HISTORY OF TECK COMINCO OPERATIONS AT TRAIL

Teck Cominco Metals Ltd (Teck Cominco) has operated a smelter on the right[2] (west) bank of the Columbia River in Trail, BC since 1896. Lead production commenced in 1901 resulting in blast furnace slag that was disposed of on land. Starting in 1929, blast furnace slag was reprocessed in a slag fumer from which the final slag by-products were discharged into the Columbia River. The slag material has a granular texture, with dominantly sand-sized particles (Sigma and Ward 1992). It is believed that slag was stockpiled for several years prior to 1929 and was reprocessed once the fumer was constructed. Blast furnace slag that was stockpiled between 1920 and 1929 was reprocessed in the slag fumer sometime after 1929 and was discharged to the river. The discharge of fumed slag to the river ceased after 1995 (Duncan 1999).

The historical quantity of fumed slag discharged to the river was not directly recorded but has been estimated on the basis of annual lead production. Figure 9 summarizes the estimated annual slag mass generated at the facility based on information provided to NHC (Queneau 2010). The estimated total discharge between 1929 and 1995 (including the stockpiled material from the 1920s) is approximately 12 million tonnes.

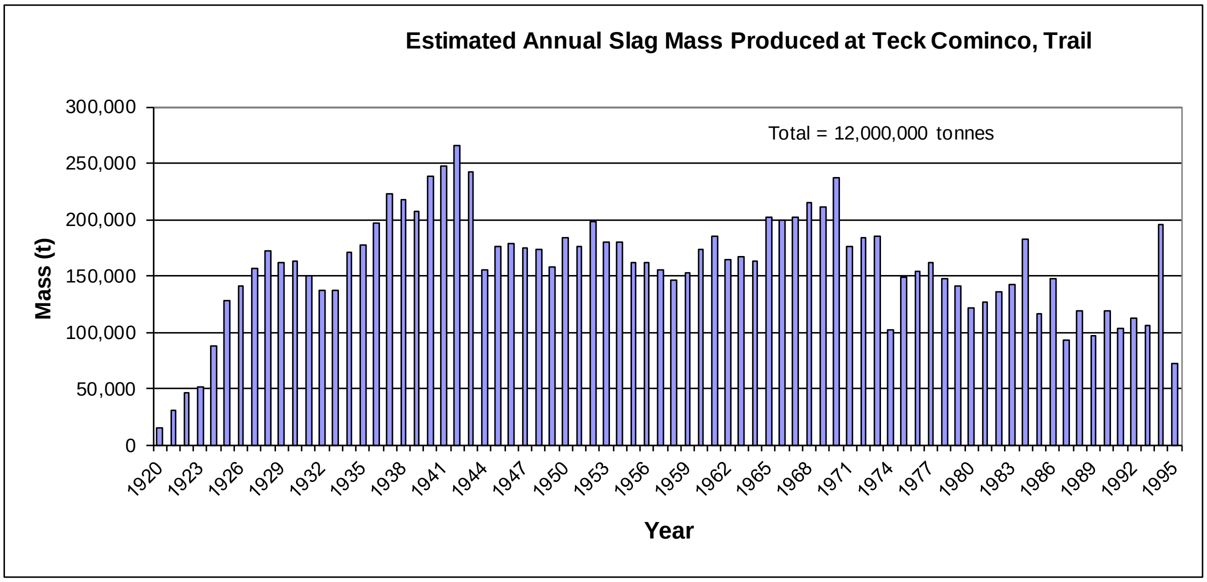

Figure 9: Estimated annual slag production at Teck Cominco smelter in Trail

Figure 10 (reproduced from Sigma and Ward, 1992) shows the slag discharge site at Trail on the bank of the Columbia River in 1992.

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[2] Throughout this report "left" and "right" bank refer to the river bank as viewed in the downstream direction

The following simplified calculation was made to illustrate the scale of the slag disposed into the Columbia River. Twelve million tonnes of slag represents a bulk deposit volume of approximately 6.7 million cubic metres (assuming a bulk density of 1.8 tonnes/cubic metres)[3]. The bank to bank width of the Columbia River downstream of Trail to the International Boundary averages approximately 180 m. If all of the slag that was discharged into the river remained within 1 km of the discharge point, the deposited slag would cover the river bed from bank to bank to a depth of 37 m (approximately 120 feet). If all of the slag that was discharged into the river was deposited in the 18 km reach from Trail down to the International Boundary, the deposited slag would cover the river bed from bank to bank to a depth of 2.1 m (7 feet). Such an extensive deposit of slag in the river would be very apparent to direct observation.

Figure 10: Slag discharge site at Trail in 1992 (from Sigma and Ward, 1992)

A site reconnaissance was made by NHC staff in April 2010 at relatively low water along the Columbia River from Trail down to the International Boundary. At that time the river bed consisted mainly of naturally occurring alluvial cobbles and gravel, although traces of slag material were found underlying the coarse surface layer of the bed material and in isolated, localized deposits along the shoreline. No surface deposits of slag, like that which is shown in Figure 10, were visible anywhere along the river. Therefore, most of the slag that was discharged into the river must have been transported downstream past the International Boundary into

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[3] Using representative slag properties (specific gravity = 2.9, sediment deposit porosity = 0.4)

Washington State. A more formalized, quantitative comparison between the total volume of slag discharged into the river and the amount of slag remaining in the channel between Trail and the International Boundary is described in Chapter 5.

4.2 PHYSICAL PROPERTIES OF SLAG

Sigma and Ward (1992) summarized particle size information on granulated slag discharged into the Columbia River at Trail using data supplied by Cominco (1991). They reported all of the material to be in the coarse to fine sand range. Medium and coarse sand accounted for 88% of the material. Slag finer than 0.15mm constituted approximately 1% of the slag discharged at that time.

Deposits of slag were identified at four locations (SL1 through SL4 on Figure 8) on the Columbia River downstream of Trail during a field inspection on June 23, 2010. Samples were collected and a particle size analysis was conducted by NHC. The grain size distribution of the slag material is illustrated in Figure 11. Inspection of the material revealed that there were some large fragments of slag in the samples that were not representative of the typical slag material discharged from Teck, but rather were rare fragments that have remained near the smelter because of their large size and relative immobility. These rare fragments can be identified by the inflection in the fractional grain size distribution curve shown in the bottom left panel of Figure 11 at a grain size of 5.6 mm. Based on the distributions from the samples at SL3 and SL4, and the observed inflection with the SL1 and SL2 samples, all SL samples were truncated at 5.6 mm to eliminate these anomalous stones. The D_{50} (median) size of the truncated SL samples ranged between 0.62 mm and 1.44 mm and averaged 0.91 mm. The D_{10} size ranged between 0.2 mm and 0.54 mm and averaged 0.33 mm. Based on the four slag samples collected by NHC in 2010 a composite grain size distribution was developed. This distribution is used to characterize the average grain size distribution of the slag material discharged into the Columbia River by the Teck Cominco smelter. This distribution was used in subsequent analysis to assess how much slag remains between the Teck smelter and the International Border. The composite distribution has a D_{50} (median) size of 0.83 mm and a D_5 and D_{95} of 0.19 mm and 3.17 mm, respectively. These results are consistent with the sizes reported in Sigma and Ward (1992).

These grain size data are similar to the data from a sample of the slag material collected at Black Sand Beach in the USA that had a D_{50} (median) size of 0.43 mm and a D_{10} of 0.25 mm (GeoEngineers, 2010). The slightly finer D_{50} observed at Black Sand Beach may be a result of selective transport, weathering and hydraulic characteristics that prevent larger grains from reaching the beach.

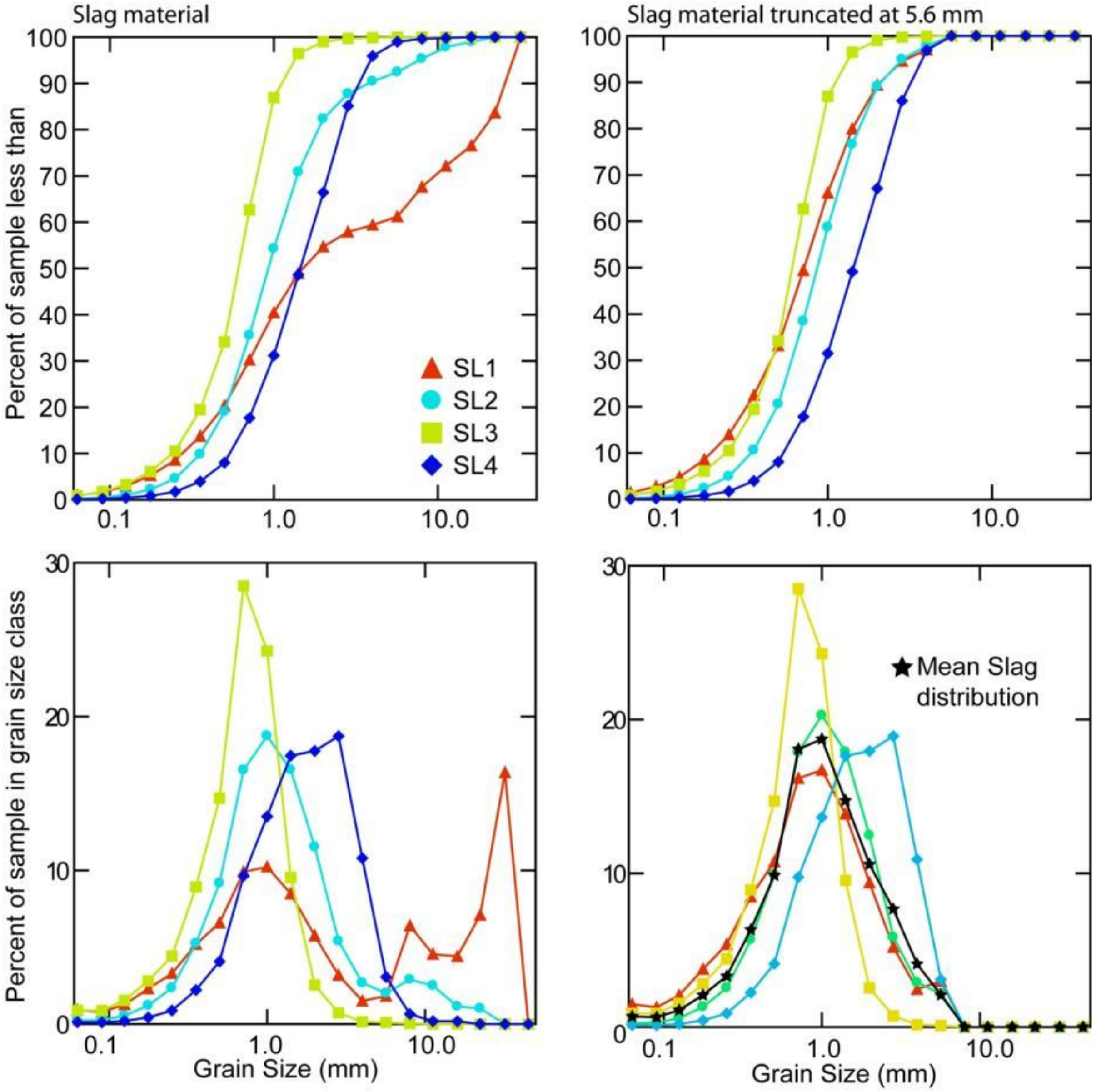


Figure 11: Grain size distribution of grab samples (SL1 through SL4) collected from the river bed below Teck Cominco. The right hand plots illustrates the distribution after truncating the sample at 5.6 mm to remove the large slag particles that are not representative of the slag material discharged by the Teck smelter.

Queneau (2010) reported blast furnace and fumed slag from Teck Cominco's Trail smelter was characterized by elevated levels of lead, zinc, copper and iron. Elevated levels of cobalt and chromium have also been associated with slag sediment (G3 Consulting Ltd., 2001).

4.3 SEDIMENT TRANSPORT CHARACTERISTICS OF SLAG PARTICLES

Initiation of slag particle transport (incipient motion) was determined using the Shields parameter θ_c , (described previously in Section 3.2.5). For coarse sediments (gravel and cobbles) the Shields parameter is a constant. However, for sand-sized sediment, the critical Shields parameter (θ_c) varies as a function of the particle Reynolds number (R_*):

$$\theta_c = f(R_*) \text{ and } R_* = \frac{U_* D}{\vartheta} \qquad \text{(Eq. 2)}$$

Where $\theta_c = \frac{\tau}{\rho(s-1)D_{50}}$, U_* is the shear velocity, D is the particle size and *v* is the water viscosity

The particle Reynolds number is a measure of turbulent conditions near the bed. When the Reynolds number is high (typical of gravel and cobble sediments), the particles project into the rougher turbulent portion of the flow. At low Reynolds numbers (typical of sand and silt sized sediment), the particles hide within the less turbulent, laminar sub-layer. Figure 12 shows the relation between the critical Shields parameter (θc) and the particle Reynolds number (R_*).

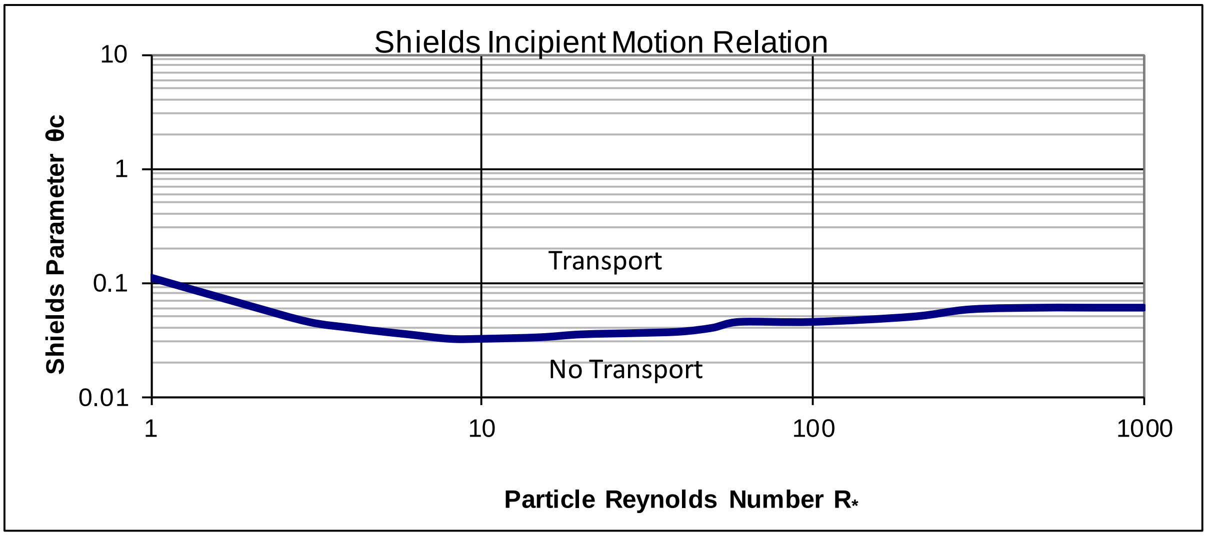


Figure 12: Shields' incipient motion relation for granular sediment subject to river currents.

Estimated values of critical shear velocity for the initiation of slag movement are summarized in Table 9.

The settling velocity of sediment in water is commonly used to determine sediment transport parameters that govern suspension and suspended sediment transport. The settling velocity is governed by the diameter, particle shape and density of the sediment as well as the viscosity of the water. The settling velocity of sediment is commonly estimated using the Rouse equation (ASCE, 2007). Estimates of settling velocity for various particle sizes of slag are summarized in Table 10. The calculations were made for slag having a specific gravity of 2.9 and a water temperature of 8 °C. Fall velocities were also measured by dropping 30 slag particles into a 1.5 m long stand tube. The time required for the particles to fall a given distance, after they had reached a terminal velocity was measured and summary numbers are provided in Table 10. The measured velocities are similar to the predicted velocities. For subsequent calculations the predicted velocities are used.

Table 10: Sediment transport characteristics of slag particles

Particle Diameter (mm)	Predicted fall Velocity (m/s)	Measured fall Velocity (m/s)	Initiation of Motion		Maintained in Suspension	
			U* (m/s)	**τ (Pa)**	**U* (m/s)**	**τ (Pa)**
0.25	0.04	0.06	0.015	0.22	0.04	1.6
0.50	0.09	0.10	0.017	0.29	0.09	8.1
0.70	0.13	0.12	0.020	0.40	0.13	16.9
1.00	0.18	0.14	0.024	0.60	0.18	32.4

Once particles begin to move along the bed by rolling and sliding, the sediment transport is characterized as bed load transport. As the flow velocity and shear stresses on the bed increase, eventually the particles are lifted off the stream bed into the boundary layer of the flow. This process is referred to as suspension and the mode of transport is termed suspended sediment transport. There is a gradual transition from predominantly bed load transport to suspension. The threshold for the commencement of suspension is approximated by the following relation (van Rijn, 1989):

$$\frac{U_*}{\omega} = 0.4 \qquad \text{(Eq. 3)}$$

Where U_* is the critical shear velocity and *w* is the sediment's settling velocity

As the flow velocity and turbulence increases further, the sediment particles will be maintained fully in suspension without re-depositing on the bed. Based on ASCE (2007) this condition is approximated by the relation:

$$\frac{U_*}{\omega} \geq 1.0 \qquad \text{(Eq. 4)}$$

The estimated shear velocity (U_*) for initiating movement and maintaining fully developed suspension of the slag particles are summarized in Table 10.

The shear velocity (U_*) characterizes the shear stress on the bed and the boundary layer of the flow and is difficult to visualize qualitatively. The actual stream velocity (speed of the water) can be related to the shear velocity using a flow resistance equation such as Manning's equation:

$$V = \frac{Y^{2/3} S^{1/2}}{n} \qquad \text{(Eq. 5)}$$

where Y is the flow depth, S is the water surface slope and n is the channel roughness.

Combining the shear velocity equation with Manning's equation gives the following expression:

$$V = \frac{U_* Y^{1/6}}{g^{1/2} n} \qquad \text{(Eq. 6)}$$

Where g is the gravitational constant (9.81 m/s^2)

This relation shows that the stream velocity required to initiate movement and suspension of the slag particles depends mainly on the shear velocity and channel roughness and is weakly dependent on the flow depth. Typical flow depths in the Columbia River range from 5 to 10 (Figure 14). The Manning's roughness value between Trail and the International Boundary was estimated from the calibrated HEC-RAS model to average 0.036 (Appendix B).

Table 11 summarizes the estimated mean channel velocity required to initiate transport and suspension of the slag particles.

Table 11: Critical velocity for initiation of slag transport and suspension

Particle Diameter (mm)	**Velocity Required to Initiate Movement (m/s)**		**Velocity Required to Maintain Suspension (m/s)**	
	Y=5m	**Y=10m**	**Y=5m**	**Y=10m**
0.25	0.17	0.19	0.46	0.52
0.50	0.20	0.22	1.04	1.17
0.70	0.23	0.26	1.51	1.69
1.00	0.28	0.32	2.09	2.34

The results show that even the coarser slag particles (1 mm diameter) will start to move when the mean velocity in the river exceeds 0.3 m/s (about 1 foot/sec). Finer slag particles (less than 0.25 mm) will stay in suspension when the velocity exceeds 0.46 m/s and the coarse slag (1 mm) will stay in suspension when the mean velocity exceeds 2.09 m/s.

4.4 SLAG TRANSPORT BASED ON HYDROMETRIC STATION DATA

4.4.1 INITIATION OF TRANSPORT AND SUSPENSION

Comparing the results summarized in Table 11 with the WSC measurements in the river (Table 6), indicates the Columbia River at Trail and at the International Boundary was capable of mobilizing and suspending slag particles even at moderate, average flows (mean annual flow). For example, at the long-term mean annual flow conditions (pre-regulation, prior to 1973) the mean velocity at Trail and the International Boundary was estimated to be 1.81 m/s and 2.15 m/s respectively. The threshold velocity for incipient movement and transport of slag as bed load ranges between 0.17 m/s to 0.32 m/s.

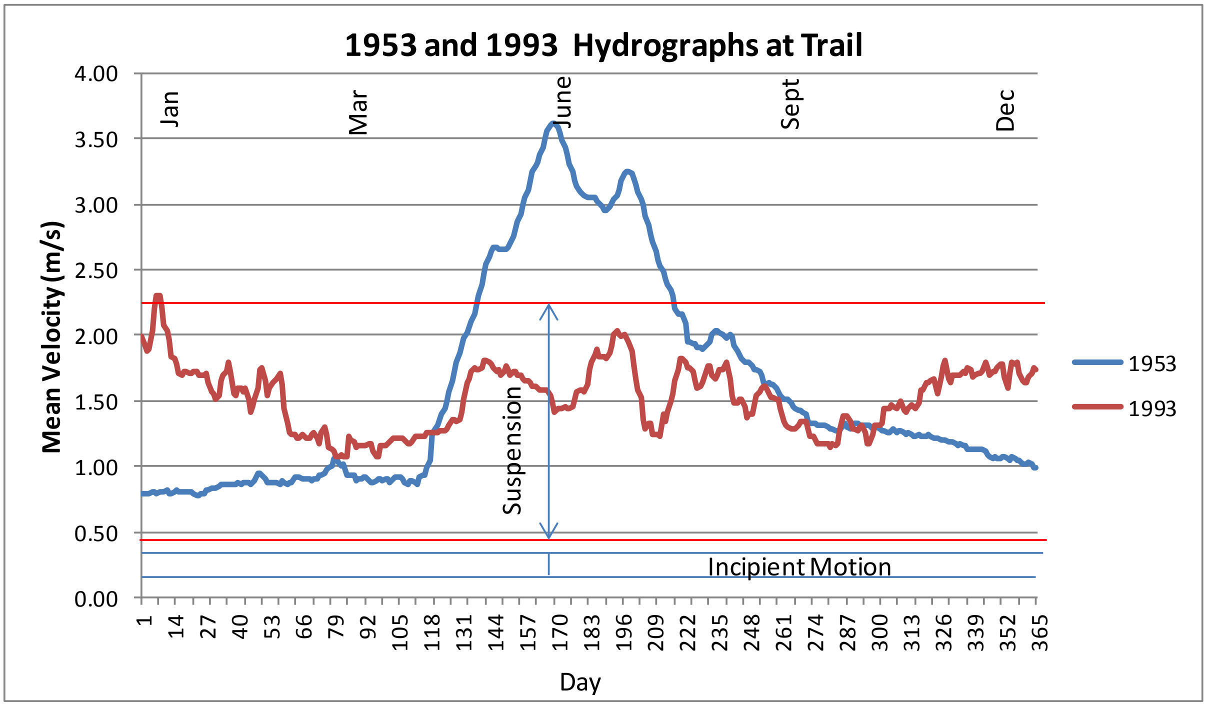
Figure 13 shows the variation in the mean velocity at the WSC hydrometric gauging stations in 1953 (a typical pre-regulation mean annual flood year) and in 1993 (a typical post-regulation mean annual flood year). The top graph shows the results at Trail; the bottom graph shows similar conditions at the International Boundary gauge. The mean velocities at the Trail site are based on the hydraulic geometry relations developed from WSC discharge measurements at

Trail. The discharges published at Birchbank in 1993 and are representative of flows at Trail since there are no major tributary inflows between the two stations.

The band of lines labeled “Incipient Motion” indicates the range of velocities required to initiate transport for slag between 0.25 mm and 1.00 mm. The wider band of lines labeled “Suspension” indicates the range of velocities required to maintain slag between 0.25 mm and 1.00 mm in suspension. The curve shows the velocity at Trail was sufficient to transport all slag in the channel downstream continuously throughout each year. Finer slag (0.25 mm or smaller) was transported downstream in suspension continuously throughout each year. The coarsest slag (1 mm) was transported downstream in suspension in 1953 during the high-flow freshet season (May – July). In 1993, the coarsest slag (1 mm) was transported downstream primarily as bed load.

Results from the hydrometric measurements at the International Boundary show very similar results as the data from Trail. However, the increased discharges due to the inflows from the Pend d’Oreille River increases the river’s competence to transport slag sediment. This means that transport of the slag by suspension is generally more frequent at the International Boundary station than at the Trail station. The results illustrate that the Columbia River at Trail and the International Boundary can easily entrain and transport slag particles under a wide range of flow conditions.

An estimate of the river’s *capacity* to transport slag sediment can be made using sediment transport equations that relate the mass rate of sediment transport to the particle characteristics (size and density) and the flow characteristics (velocity, slope and depth). The sediment transport *capacity* represents the transport rate *if* the rate of sediment supply was essentially unlimited. The Engelund-Hansen sediment transport equation was used for this analysis. The hydraulic geometry relation at Trail was used to estimate the mean velocity and mean depth and the adopted sediment properties used a particle size (D_{50}) of 0.7 mm and a specific gravity of 2.9. The sediment transport capacity was computed for each day in 1953 and 1993 using the WSC flow records. The river’s annual sediment transport capacity was then determined by summing the daily values. This analysis showed the potential transport capacity of the Columbia River at Trail was 38,000,000 tonnes/year in 1953 and 18,000,000 tonnes/year in 1993. The actual amount of slag discharged into the Columbia River from the Teck Cominco smelter at Trail varied between 100,000 to 180,000 tonnes/year during this period. Therefore, the river’s potential capacity to transport slag far exceeded the rate that slag was supplied to the river from the smelter discharges. In effect, the transport of slag-sized sediment in the Columbia River at Trail is “supply-limited”, since the river’s capacity to transport the material is much greater than the amount that is being supplied. As a result, the slag has been swept off the river bed surface, exposing the coarse natural cobble and gravel river bed material. This explains why the Columbia River downstream of Trail to the International Boundary has remained a predominantly coarse grained gravel/cobble bed river.



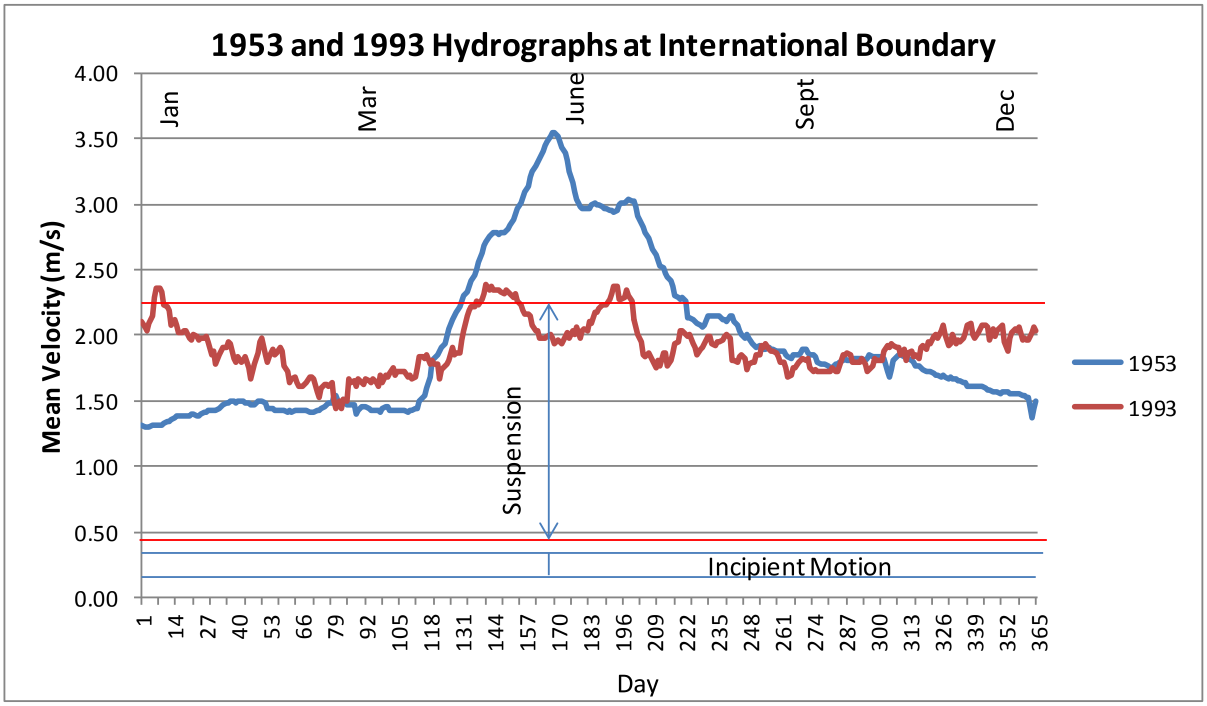


Figure 13: Transport and suspension of slag particles in Columbia River at Trail and International Boundary hydrometric station sites in 1953 and 1993.

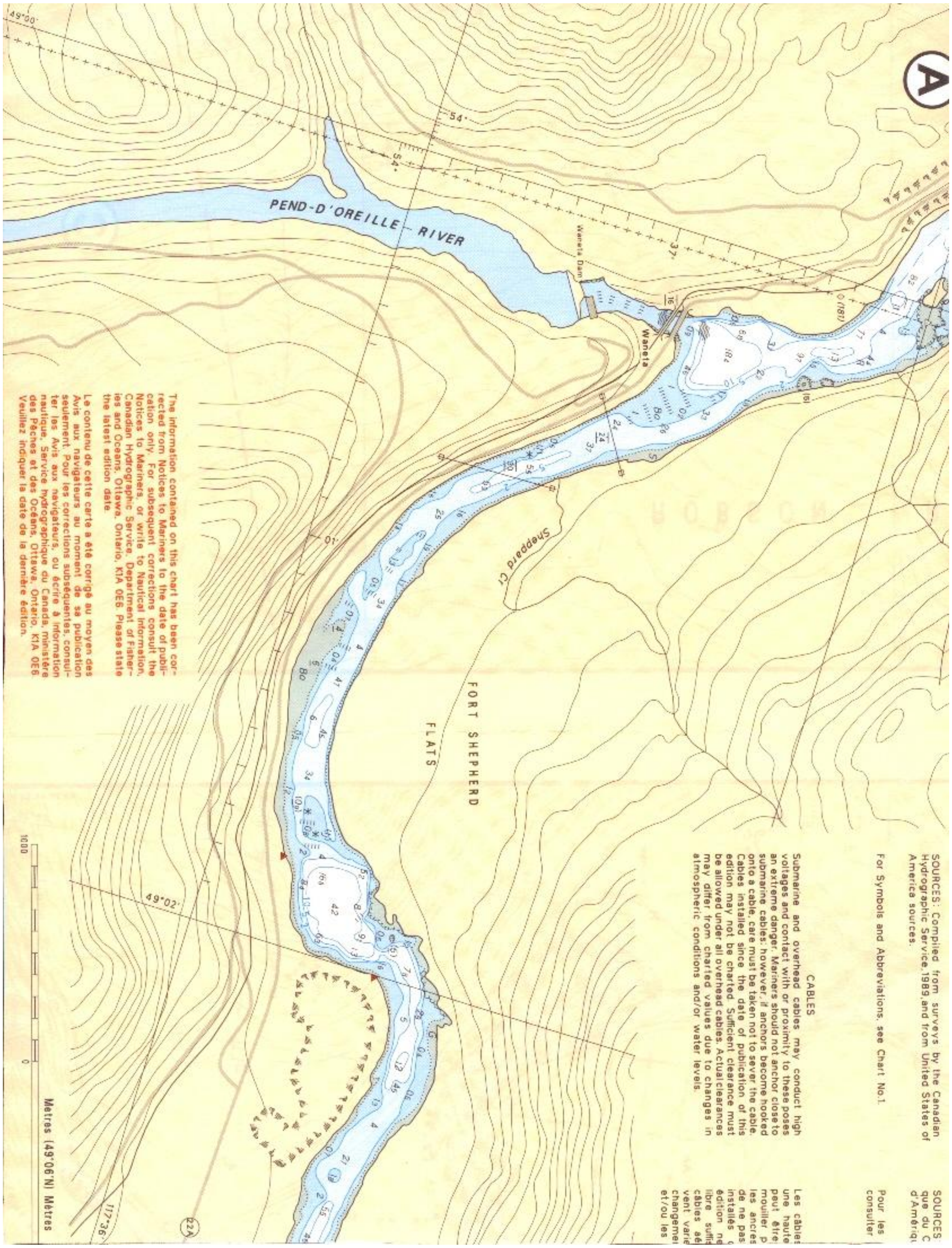
4.5 HYDRAULIC COMPUTATIONS BASED ON HEC-RAS MODEL

4.5.1 MODEL DEVELOPMENT

A one-dimensional hydraulic model (HEC-RAS) was developed of the Columbia River from Birchbank, BC (upstream of Trail) down to Northport, Washington to extend the analysis presented in Section 4.3. The channel topography in the model was based on bathymetric surveys from 1989 by the Canadian Hydrographic Service (CHS). A portion of the river reach near two deep pools (Fort Shepherd pool and Waneta eddy is shown in Figure 14. Details of the hydraulic model development, calibration and verification are described further in Appendix B. This 46 km (28.6 miles) river reach from Birchbank to Northport was described using 122 river cross sections, spaced on average 380 m (1,240 feet) apart. The location of the cross sections is shown in Figure 15. The river discharge was specified at the upstream boundary at Birchbank and the water level was specified at the downstream boundary near Northport. The HEC-RAS model then computed the hydraulic properties (water depth, mean velocity and shear stress) at each of the cross sections for the specified river flow conditions. This provides a more complete representation of the hydraulic conditions along the river than can be determined from the hydrometric measurements at the WSC gauging stations.

Model calibration was carried out to ensure the model can accurately reproduce the hydraulic conditions along the river. This involves an iterative procedure of adjusting channel roughness parameters until the predicted water levels agree with measured levels at key locations (gauging stations). The modeled reach in Canada was based on bathymetric surveys of the river made by the Canadian Hydrographic Service in 1989. The reach in Washington (International Boundary to Northport) was based on bathymetric surveys in 1948, as used in the existing Hydro-Qual model.

The model was run for a range of inflows varying from a low of 2,050 m^3/s (long term daily mean) and a high flow of 10,600 m^3/s (maximum recorded daily discharge). Water surface profiles associated with these six discharges are shown in Figure 16.



The information contained on this chart has been corrected from Notices to Mariners to the date of publication only. For subsequent corrections consult the Notices to Mariners, or write to Nautical Information, Canadian Hydrographic Service, Department of Fisheries and Oceans, Ottawa, Ontario, K1A 0E6. Please state the latest edition date.

Le contenu de cette carte a été corrigé au moyen des Avis aux navigateurs au moment de sa publication seulement. Pour les corrections subséquentes, consulter les Avis aux navigateurs, ou écrire à information nautique, Service hydrographique du Canada, ministère des Pêches et des Océans, Ottawa, Ontario, K1A 0E6. Veuillez indiquer la date de la dernière édition.

SOURCES: Compiled from surveys by the Canadian Hydrographic Service, 1989, and from United States of America sources.

For Symbols and Abbreviations, see Chart No.1.

CABLES

Submarine and overhead cables may conduct high voltages and contact with or proximity to these poses an extreme danger. Mariners should not anchor close to submarine cables; however, if anchors become hooked onto a cable, care must be taken not to sever the cable. Cables installed since the date of publication of this edition may not be charted. Sufficient clearance must be allowed under all overhead cables. Actual clearances may differ from charted values due to changes in atmospheric conditions and/or water levels.

Figure 14: Portion of Canadian Hydrographic Service chart 3055 of Columbia River

MSN, 35240 Columbia River Slag\GIS\35240_MSN_Fig_CrossSectionMap1.mxd

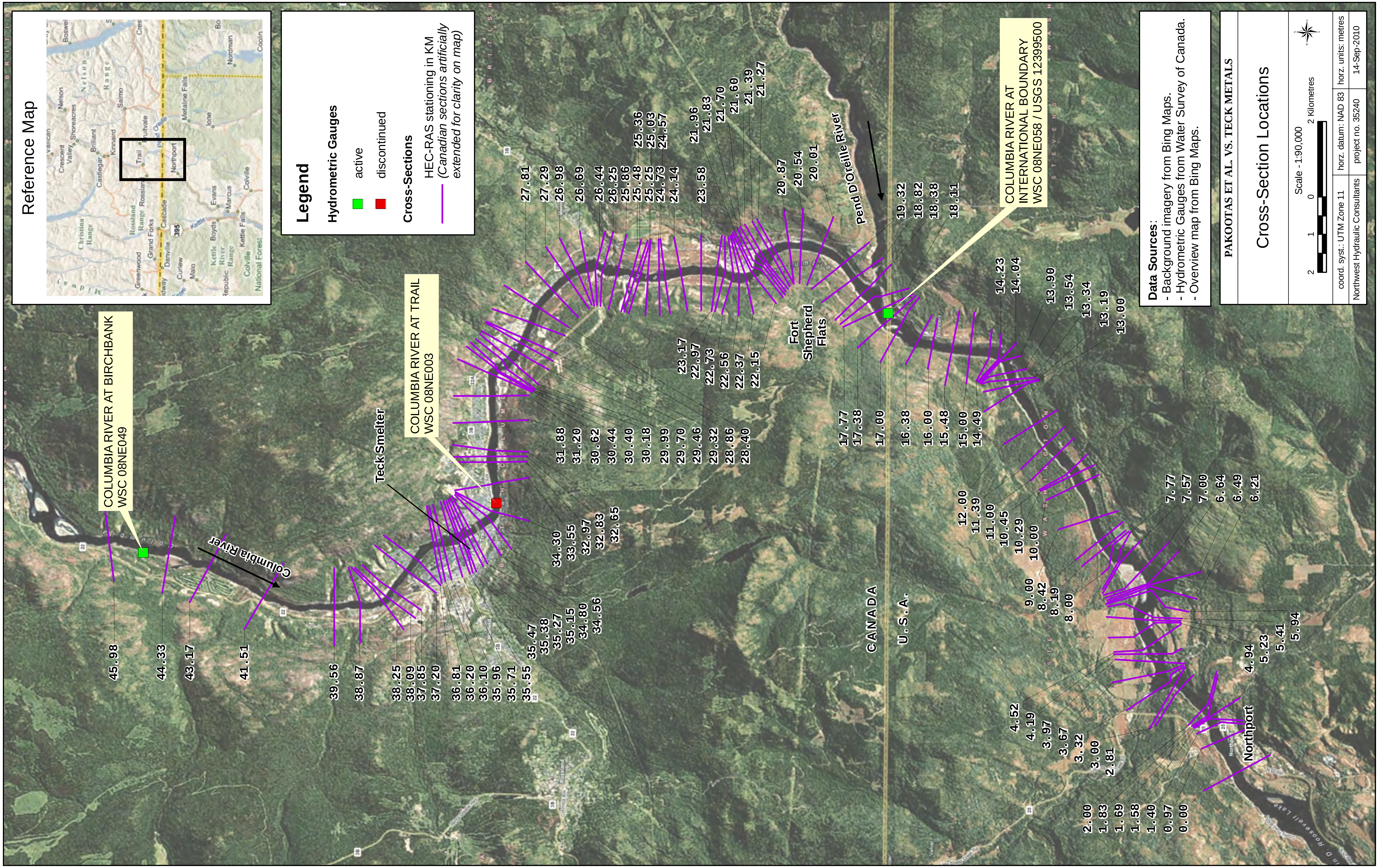


Figure 15

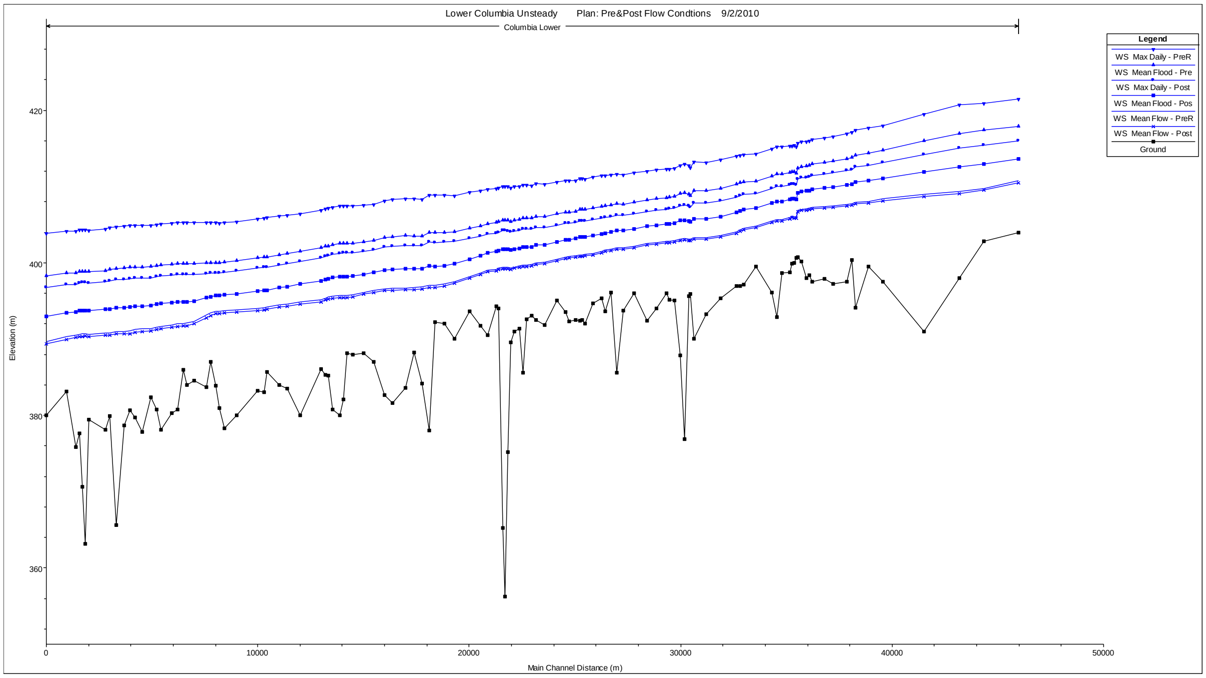


Figure 16: Computed water surface profiles along Columbia River from Northport, Washington to Birchbank, BC. Distances are measured upstream of Northport

4.5.2 COMPUTED VELOCITIES

Figure 17 shows the estimated mean velocity along the Columbia River from Northport upstream to Birchbank for six different discharge conditions. Figure 18 shows the variation in bed shear stress for the same six flow conditions. The graphs in Figure 17 show the velocity varies considerably along the river. However, there is an overall general decrease in velocity in the downstream direction between Trail and Northport associated with a reduction in water surface slope. For example, the top graph in Figure 17 shows that under a mean annual flood (pre-regulation), the mean velocity was 3.0 m/s near the Teck-Cominco site in Trail and 1.5 m/s near Northport. Table 12 compares the average hydraulic properties (mean velocity (v) and bed shear stress (τ)) in the reach from Trail down to the Border and from the Border to Northport, Washington for the six specified flow conditions. The mean velocity and bed shear stress values in the reach from Trail to the border are consistently higher than the values from the border down to Northport. In both cases, the reach-averaged values are well above the threshold for initiating slag transport (see Table 10 and Table 11 for a comparison). The reach averaged values also exceed the limit for maintaining suspension, although the coarse fraction of the slag (greater than 1 mm) is close to the limit. These results show that slag was transported in suspension and as bed load from Trail to Northport. The average transport capacity in the reach from Trail to the International Boundary was higher than in the reach from the International Boundary to Northport.

The large fluctuations in velocity along the river reflect the influence of changes in channel width, as well as the effects of local morphological features such as gravel bars, riffles and pools. The mean velocity increases through narrow constrictions or across shallow “riffles” and decreases in wider expansions or in deep pools. The mean velocity drops to less than 1 m/s in three large pools or scour holes that occur between Trail and the International Boundary:

- KM 30.18: near Bear Creek;
- KM 21.6: just upstream of Fort Shepherd Flats;
- KM 17.38: at the International Boundary.

The local reductions in velocity and shear stress in the pools indicates some of the coarser fraction of the slag will drop out of suspension. However, the velocity and shear stress values are sufficient to maintain bed load transport. Flow regulation after 1972 further reduced the transport of coarse slag via suspended sediment processes through the pools, since the peak flows were reduced substantially. The reduced mean velocities associated with the pools will result in more slag sized sediments on the bed of the pools, compared to other sections of channel, and an accumulation of slag after 1972 when flows were reduced. The actual hydraulic conditions in the pools is complicated by the three dimensional nature of flow in these areas, and actual changes in slag in the pools cannot be modelled using a 1-D model.

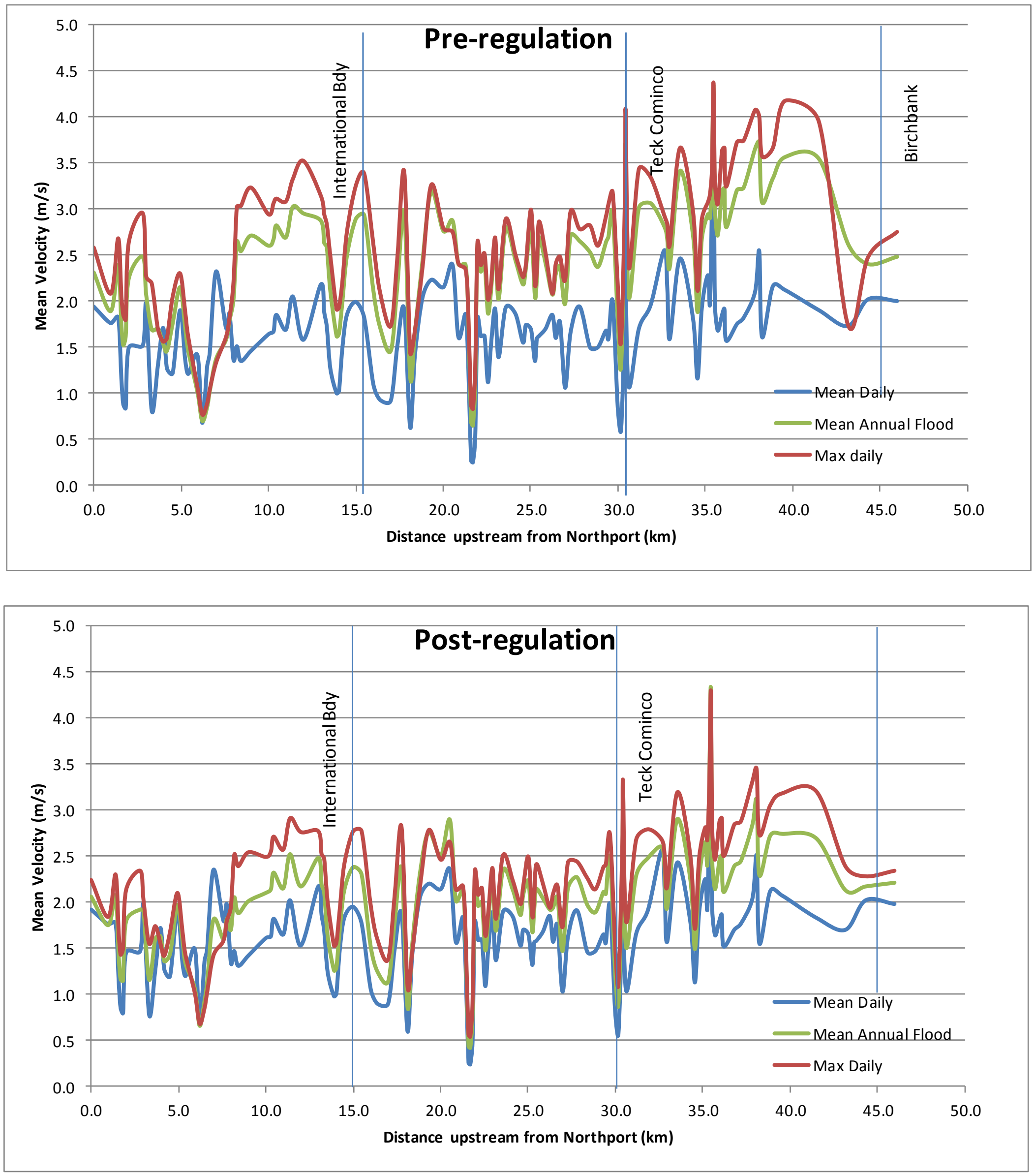


Figure 17: Variation in mean channel velocity from Northport Washington to Birchbank, BC.

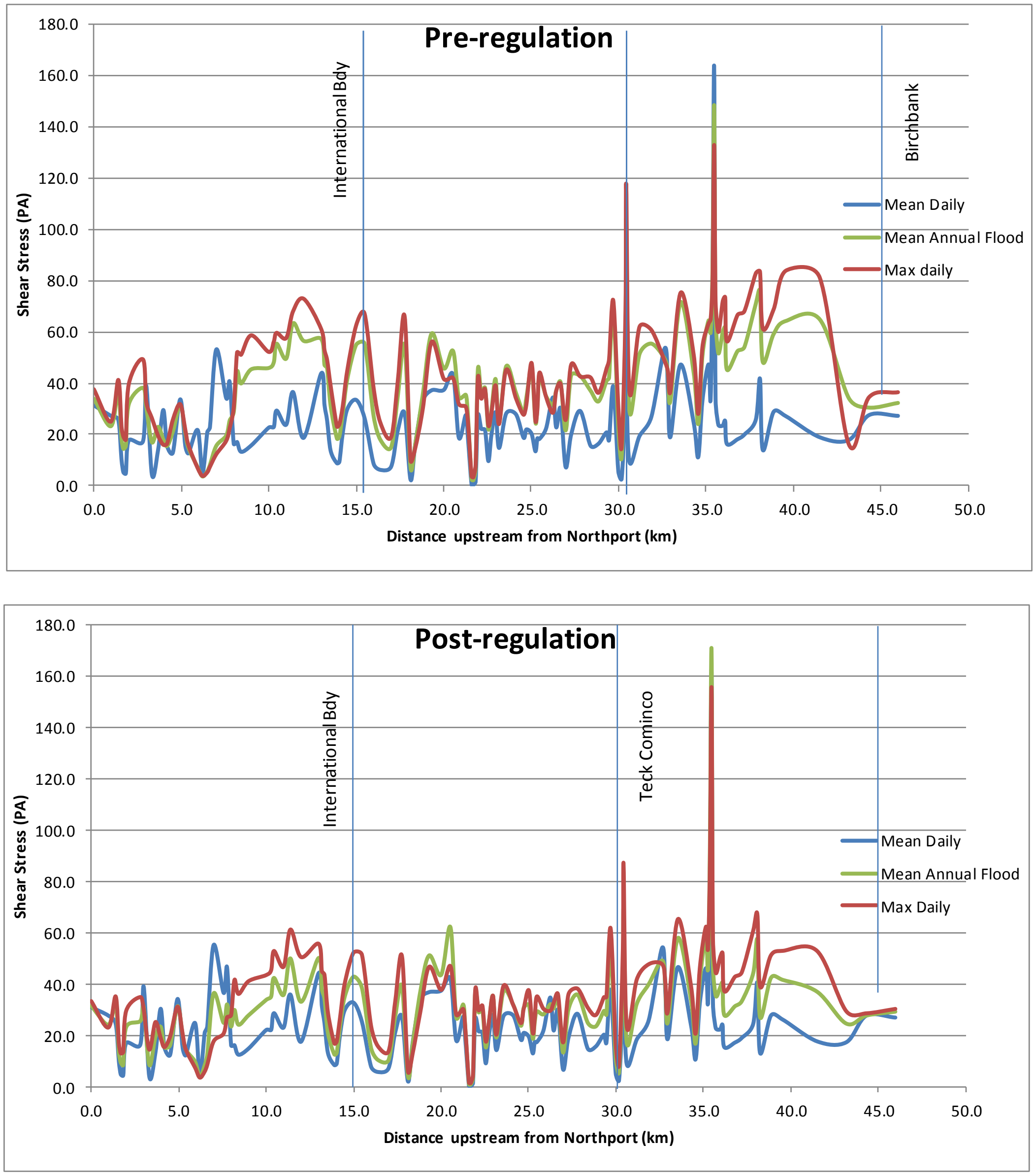


Figure 18: Variation in bed shear stress from Northport, Washington to Birchbank, BC.

Table 12: Comparison of reach-average hydraulic properties from Trail, BC to International Boundary and International Boundary to Northport, Washington

Period	Flow Condition	Trail, BC to International Boundary		International Boundary to Northport, Washington	
		Velocity *v* (m/s)	Bed Shear (τ Pa)	Velocity *v* ((m/s)	Bed Shear (τ Pa)
Pre-Regulation	Mean Daily	1.65	24.2	1.49	21.2
	Mean Annual Flood	2.40	39.3	2.04	30.4
	Maximum Daily	2.56	40.6	2.30	34.8
Post-Regulation	Mean Daily	1.62	23.7	1.48	21.2
	Mean Annual Flood	2.01	31.7	1.72	24.7
	Maximum Daily	2.18	34.2	1.96	29.0

4.6 SEDIMENT TRANSPORT MODELING

4.6.1 ONE DIMENSIONAL MODEL ANALYSIS

Additional insight into the transport processes of the slag was made using the sediment model SRH-1D, developed by the US Bureau of Reclamation (USBR, 2010). SRH-1D is a one-dimensional mobile boundary hydraulic and sediment transport model for rivers. The model uses cross sectional geometry (same as the HEC-RAS model) and simulates the sediment transport at each cross section and deposition or erosion over time over a specified hydrograph. Since the model used the one-dimensional solution for flow simulation, it will not be able to accurately represent complex three dimensional flow situations. Therefore, results from the model need to be assessed carefully.

The sediment transport model represented the Columbia River from Birchbank downstream to the International Boundary and included the Pend d'Oreille River as a tributary input. The cross section geometry in the model was based on the NHC HEC-RAS model. Three different particle sizes of slag were represented:

- 0.25 mm to 0.50 mm (corresponding to a medium sand size);
- 0.50 mm to 1.00 mm (corresponding to a coarse sand size);
- 1.00 mm to 2.00 mm (corresponding to a very coarse sand size).

The specific gravity of the slag sediment was set to be 2.9.

Bed material information of the channel sediments is available for present conditions (using the results of the NHC sediment sampling program summarized in Section 3.5). However, there is no information on the size distribution of the channel bed during the decades of the 1930's to the 1990's when slag was being discharged. Some change to the river bed material may also have occurred over the last few decades in response to the flow regulation from upstream hydro power developments in the 1960's and 1970's. Therefore, the model was primarily used as a tool to assess some hypotheses on the pattern of slag transport along the river.

The first simulation was made to test the hypotheses that most or all of the slag material that was discharged to the river could have remained upstream of the International Boundary. Since the cross sections in the model represent the channel topography that existed in 1989, the simulation was made starting from January 1, 1990 and extended to December 31, 1990. Daily river discharges were input at Birchbank (the upstream boundary) and at the junction of the Pend d'Oreille River. The slag discharge was represented as a constant inflow of 415 tonnes/day, which corresponds to an annual slag quantity of 151,500 tonnes/year. The river bed between Birchbank to a point just upstream of the Teck Cominco smelter was assumed to consist of gravel and cobble-size sediment, representative of the bed material samples collected by NHC in 2010. If all slag discharged from 1930 to 1989 had deposited and remained in the Canadian portion of the river, then the river bed downstream of the Teck Cominco smelter would have consisted mainly of slag. For the purposes of the test simulation, slag was assumed to have deposited as a 1 m thick layer over the natural alluvial channel gravel-cobble sediments.

The model showed that slag on the bed was transported downstream across the International Boundary. Results are summarized in the two plots shown in Figure 19. The top plot shows profiles of the river bed at the start of the year and at the end of the year. The gravel-cobble reach of the river from Birchbank to Trail remained stable. The river bed lowered throughout most of the reach downstream of Trail, since the rate of slag transport far exceeded the rate of supply from the Teck smelter. In other words, the river swept the slag off the bed and transported it downstream. Slag was deposited in two deep pools (Fort Shepherd pool and Waneta pool). Since the one dimensional model could not represent the complex eddies and turbulence associated with the three dimensional nature of these pools it is believed that the rate of deposition was over-predicted.   Never the less, slag was transported downstream through the pools and was transported across the International Boundary. An overall mass balance of the three slag size classes (0.25 mm to 2.00 mm) indicated the rate of transport across the International Boundary was approximately 1.37 million tonnes, which far exceeded the mass discharged into the river during the year from the smelter at Trail (0.15 million tonnes/year). Therefore, most of the slag transported across the International Boundary was derived from erosion of slag material that composed the channel bed downstream of Trail. This shows that it is not reasonable to expect all of the slag discharged into the river to have remained upstream of the International Boundary. If slag had accumulated in a thick continuous deposit on the river bed between Trail and the International Boundary, then the river's bed material transport rate would have been sufficient to transport the material downstream across the International Boundary and rapidly degrade through the slag deposits upstream of the Boundary.

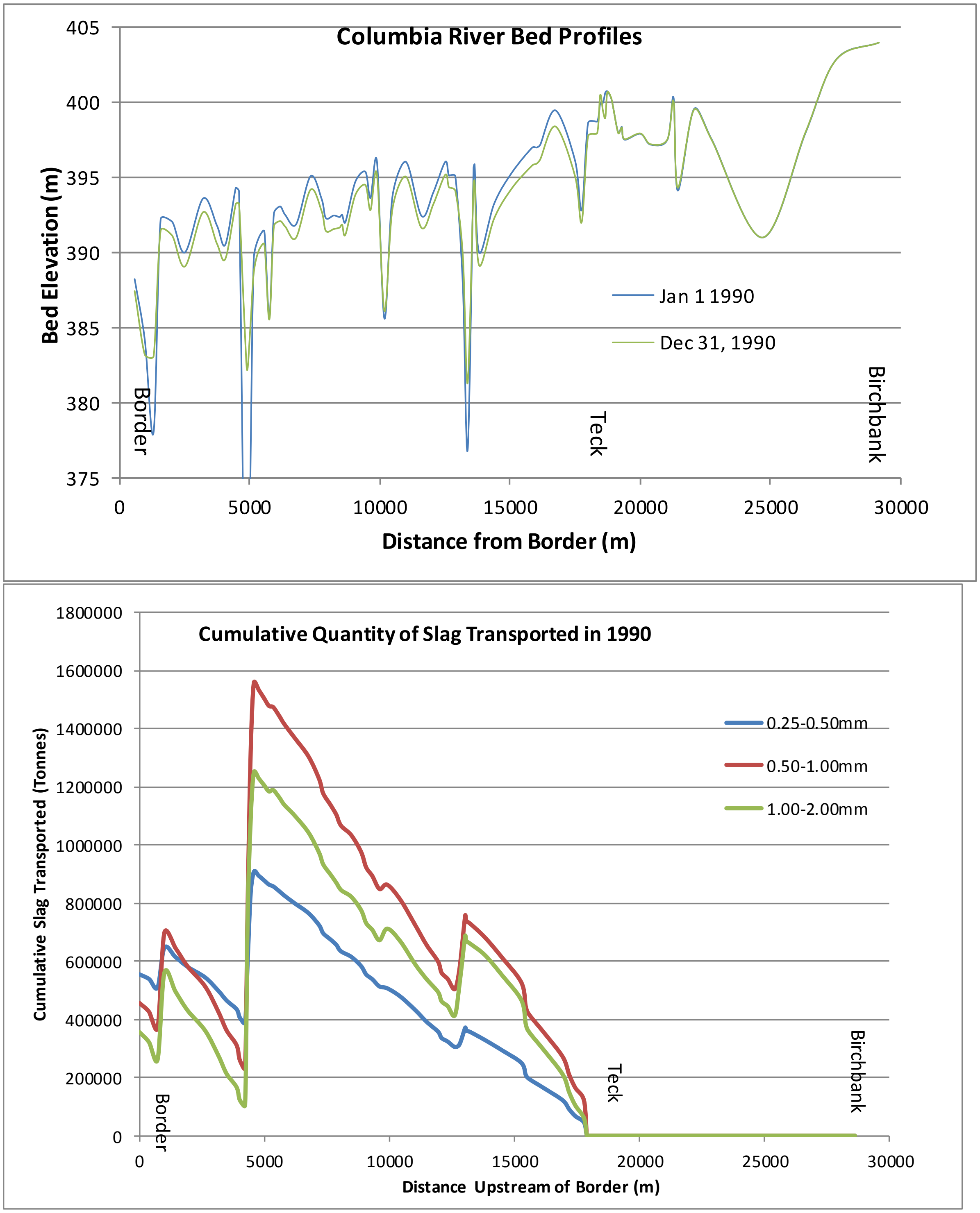
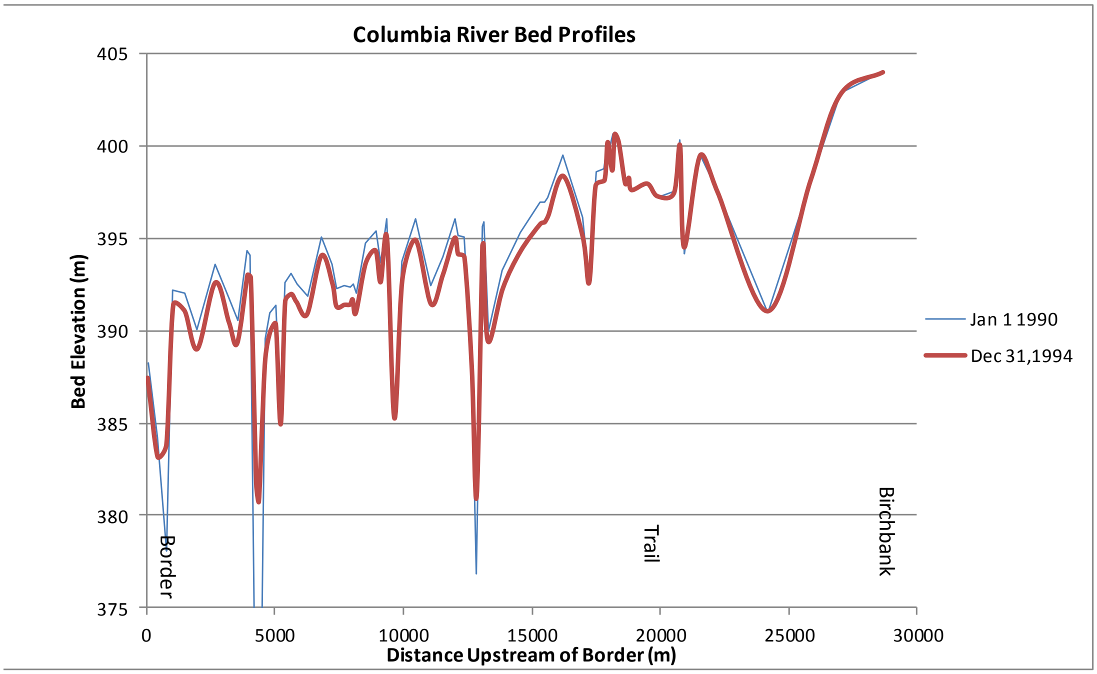


Figure 19: SRH-1D Simulation 1: One year simulation of slag transport for the hypothetical starting situation of a 1 m thick slag deposit on river bed between Trail and the International Boundary

A second simulation was made by continuing the run for a period of five years (1990 to 1994). This again represents a hypothetical initial situation where previous slag discharges had all remained on the Canadian side of the border, depositing a 1 m thick layer of slag over the original gravel and cobble sediments. At the end of five years, a total of 3.15 million tonnes of slag was discharged downstream across the International Boundary. The total slag discharge into the river at Trail during this period was only 0.76 million tonnes. The difference between these two values (2.39 million tonnes) represents the mass of slag that was picked up and eroded from the river bed. After five years much of the slag had been swept off the river bed and the channel had returned back to a gravel bed. However, deposition had continued to occur in the two pools.

The simulation confirms that the river's capacity to transport slag over most of the reach between Trail and the International Boundary far exceeds the rate discharged from the Teck smelter.



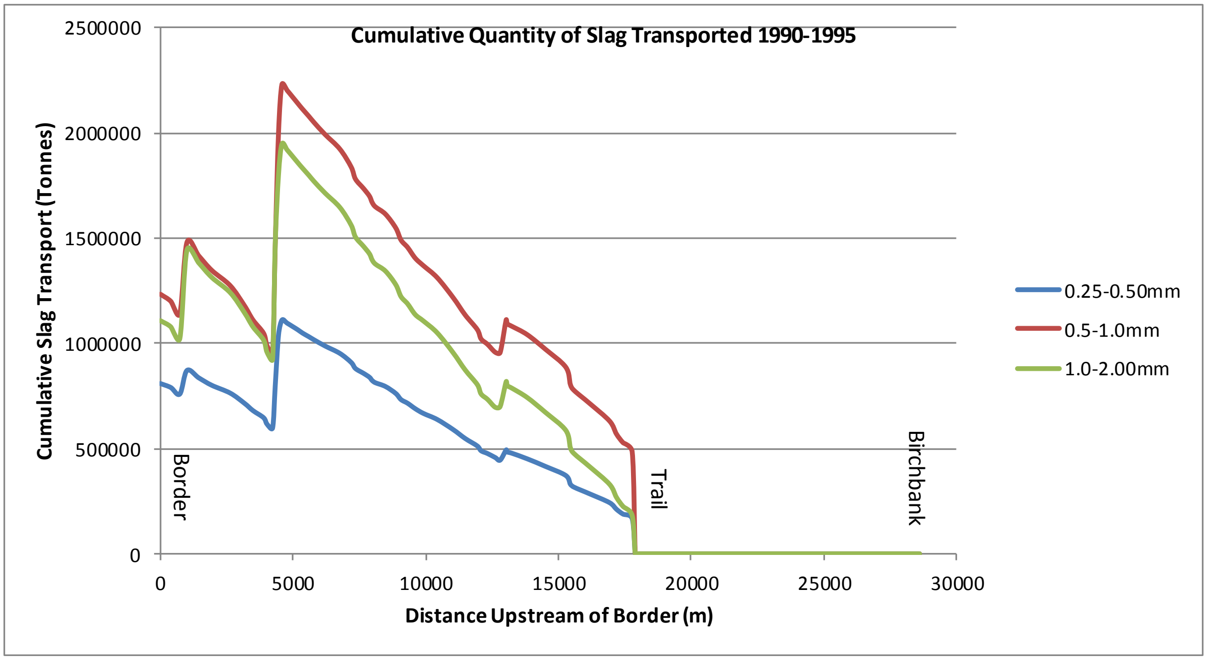


Figure 20: SRH-1D Simulation 2: Five year simulation of slag transport for the hypothetical starting situation of a 1 m thick slag deposit on river bed between Trail and the International Boundary

These results are lower bound estimates of slag transport since the one dimensional model cannot fully represent the complex, highly turbulent conditions in the pools near Ft. Shepherd Flats and Waneta eddy. Secondary currents in these pools will result in shear stresses in the pools that are greater than those predicted using a 1-D model.

4.6.2 THREE DIMENSIONAL MODELING OF POOLS

The deep pools near Fort Shepherd Flats and at the Waneta eddy (confluence with Pend d'Oreille River) were formed by river scour. In the case of the pool near Fort Shepherd Flats, the scour hole was generated by a bedrock spur that extends into the channel and creates an obstruction to the flow. In the case of the Waneta eddy the scour hole was formed by secondary currents and turbulence at the confluence of the Pend d'Oreille River and the Columbia River. Such features are relatively common geomorphic features on large alluvial rivers (TAC, 2001). Portions of these deep pools are subject to flow separation, back eddying and reduced flow velocities where finer sediment may accumulate. Under these particular conditions it is difficult to estimate local sediment transport and deposition with a one dimensional model which uses cross sectional average velocities and shear stresses. In such cases, the magnitude and extent of deposition will be over-predicted since the mean velocity in the cross section will be reduced substantially while the additional shear and turbulence effects generated by the secondary currents will not be represented.

Fissel et al (2002) applied the three-dimensional (3D) model, ASL-COCIRM, to simulate hydraulic conditions in the Waneta Eddy at the Pend d'Oreille River confluence. The extent of their model was approximately 800 m downstream to the international boundary and 1,400 m upstream of the confluence. The results from the model showed the eddy occupied an area extending approximately 300 m each way from the confluence. Figure 21 shows the velocity vectors at 0.5 m below the surface for discharges of 1,812 and 229 m^3/s in the Columbia and Pend d'Oreille Rivers, respectively. For those conditions, the HEC-RAS model predicts average velocities of 1.7 m/s in the Columbia River and 1.2 m/s in the Pend d'Oreille River. However, ASL-COCIRM predicts local velocities of almost twice those average values, indicating the usefulness of a 3D versus a 1D model. The eddies produce a contraction of the effective flow area in the Columbia River, causing velocities along the right side of the channel to reach values of 3 m/s, while in the centre of the eddies velocities are near zero.

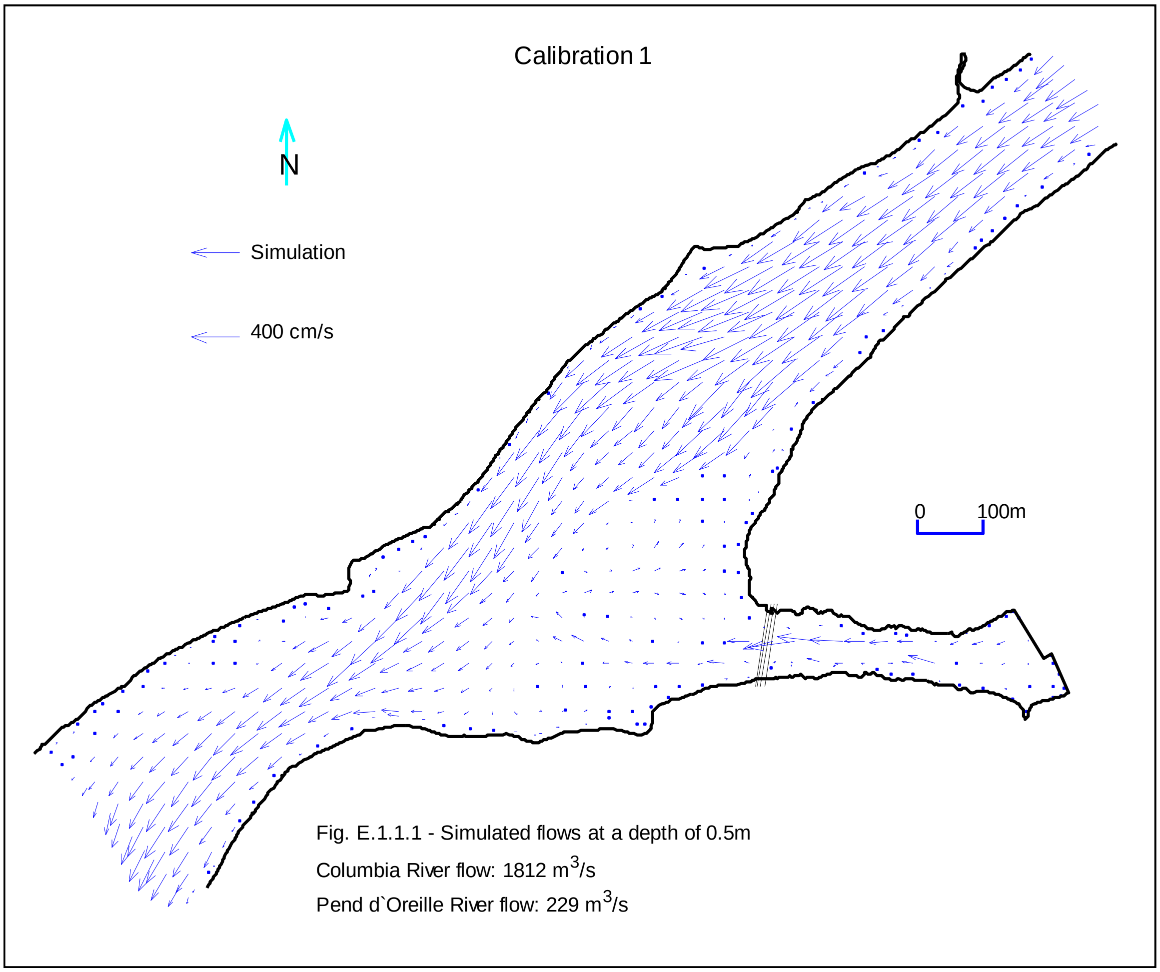


Figure 21: Example of flow field at the Confluence of the Columbia River and Pend d'Oreille River (from Fissel and Jiang, 2002).

NHC made a preliminary simulation of the Fort Shepherd pool using the three dimensional hydrodynamic model PHOENICS, a general purpose computational fluid dynamics model that has been developed for a wide range of fluid-solids modeling (www.cham.co.uk). A simple test simulation was made using 0.25 mm and 1.00 slag particles discharged at the upstream end of the pool during a 2-year flood condition. The preliminary model results, although mainly intended for qualitative assessment and flow visualization, illustrated the complex trajectories of the slag particles as they moved through the pool. These simulations also showed the medium sand-sized slag being flushed out of the pool and transported downstream. A brief animation illustrating the movement of the slag particles is appended to this report.

5 DISTRIBUTION OF SLAG IN COLUMBIA RIVER SEDIMENTS

5.1 DESCRIPTION OF FIELD PROGRAM

Three field investigation campaigns were undertaken to document the distribution and characteristics of slag in the Columbia River upstream of the Canadian/US border. A reconnaissance field program was made in January 2010. The presence of slag was determined by collecting a number of surface grab samples and testing for characteristic analytes. This information was used to plan a more detailed sampling program that was conducted in April, 2010. The detailed program including the collection of material for subsequent target analyte analysis and measurement of surface and sub-surface grain size distributions. A third sampling program was conducted on June 26th, 2010 to collect updated bathymetry data and underwater video in two large pools where slag and other finer grained sediments were thought to accumulate.

Two additional field trips were made to the Columbia River between the International Boundary and Northport, Washington. The first of these was a reconnaissance study similar to that which was completed upstream in January, 2010. A second field visit was conducted in July, 2010 to survey several large pools and to collect bed sediment samples from two pools for subsequent target analyte analysis.

5.2 RECONNAISSANCE SEDIMENT SAMPLING

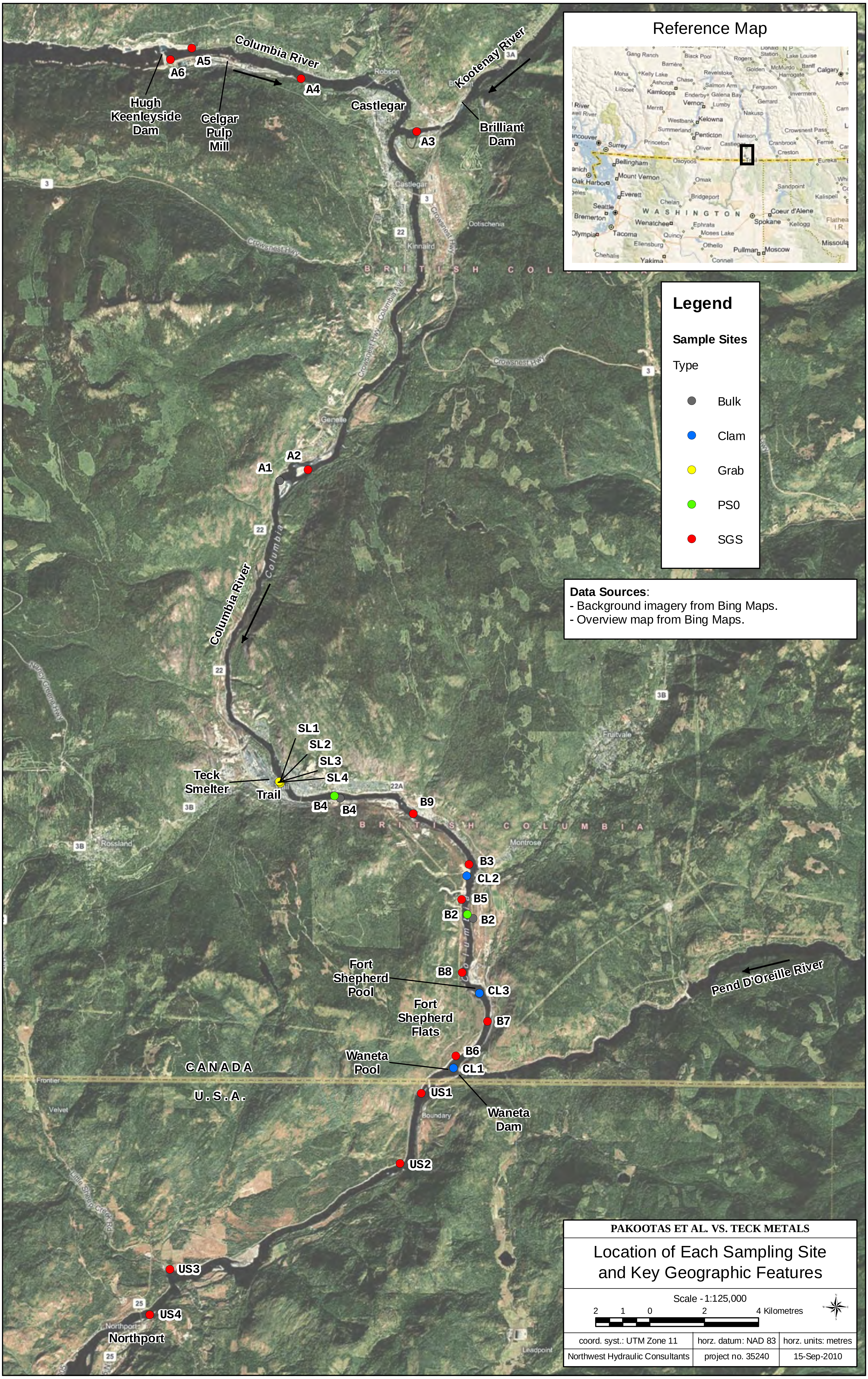
During the reconnaissance field program conducted in January, 2010 five sites ere visited. Four of the sites were between the Teck smelter and the last accessible site above the border (about 3 km upstream). The fifth site was a short distance upstream of the smelter on the opposite bank of the Columbia River.

General descriptive notes and site photos were collected at each location, while additional photos were taken of the surface substrate. The surface was typically found to be armoured with gravel to cobble size material. A small (roughly 0.3 x 0.3 m) section of the armour surface was removed at each site to collect a sample of the finer subsurface material for exploratory analyte analysis. Observations from this field trip were used to plan a more extensive sampling program in April, 2010.

5.3 DETAILED SEDIMENT SAMPLING

5.3.1 FIELD PROGRAM

A detailed field-based sampling program was conducted between April 24 to April 28, 2010 along the Columbia River over a 55 km distance from Hugh Keenleyside Dam to the International Boundary (Figure 22). Discharge at the Birchbank WSC gauge ranged from roughly 1,000 to 1,350 m^3/s.



Legend

Sample Sites

Type	
●	Bulk
●	Clam
●	Grab
●	PS0
●	SGS

Data Sources:
- Background imagery from Bing Maps.
- Overview map from Bing Maps.

PAKOOTAS ET AL. VS. TECK METALS

Location of Each Sampling Site and Key Geographic Features

Scale - 1:125,000

2 1 0 2 4 Kilometres

coord. syst.: UTM Zone 11	horz. datum: NAD 83	horz. units: metres
Northwest Hydraulic Consultants	project no. 35240	15-Sep-2010

MSN, 35240 Columbia River Slag\GIS\35240_MSN_Fig_SampleSites1.mxd

Figure 22

During the April, 2010 field visit four types of sediment samples were collected that included:

- Surface grab samples (SGS),
- Bulk samples (BS),
- Vertical profile samples (PS), and
- Grab samples in the pools using a clam shell type of sampler (CL).

Surface grab samples consist of both small (250 g) surface samples of material finer than gravel-sized sediment (ideally, < 2 mm) taken from the bar surface, and separate, larger (> 2 kg) samples of the same material. The small samples were collected by NHC for subsequent TAL (target analyte list) analysis for the Washington State Department of Ecology. The larger samples were collected for grain size analysis and for potential TAL analysis to characterize the metal content of specific grain size classes. At most locations the surface is well armoured with coarse gravel to cobble-sized material. In such cases, the surface armour layer was removed and samples were collected from the top 15 cm of the subsurface layer (Photo 1). At some locations, the surface was not armoured and so the surface material was sampled directly. A small stainless steel trowel was used to collect sediments which were placed in clear plastic sampling bags and labelled with the site location and laboratory analysis that was to be completed (Photo 2). Sample bags were subsequently placed in a cooler with icepacks to keep samples cool and prevent any biological activity that might modify the availability of metals in the samples. After each sample was collected, the trowel was washed in the river, or with de-ionized water.

Photo 1: Subsurface sediment below armour at site B3.

Photo 2: Bagged samples (250 g) for TAL.

It was initially planned that surface samples would be collected at six sites upstream of the Teck Smelter and at four to ten sites downstream, depending on physical access and water levels at the time of sampling. The rationale for choosing these sampling locations was based on a desire to characterize both the physical and chemical signature of river bed sediments for different reaches (lengths) of Columbia River. The Teck Smelter, Celgar mill and major tributaries all act as reach breaks, since they may introduce sediments or analytes that are distinct from other locations. Figure 22 shows the locations where surface grab samples (SGS) were actually collected. The sites include five upstream and eight downstream (surface grab samples were also collected at three other sites where bulk sampling was completed).

Bulk subsurface samples (BS) were collected at A1, B2 and B4 in accordance with standard bulk sampling techniques (see Section 3.5 for details). A subsample of the finer material from each bulk sample was used for analyte and slag content analysis

At the B2 and B4 sites samples were taken from the wall of a pit at 20 cm intervals to a maximum depth of 1 metre or until groundwater was encountered (see Photo 6 or Photo 7). These profile samples (PS) were placed in the same small plastic bags as were used for the surface grab samples. The intent of these samples is to determine the depth at which slag deposits may be found in the river substrate.

An additional three samples were collected from the bottom of the river bed with an Ekman Dredge (Photo 3). These samples are indicated by CL (clam) in Figure 22. A similar set of four samples were collected downstream of the International Border (samples US1-US4).

In addition to the river bed samples, four grab samples of buried slag deposits adjacent to the Teck smelter were collected (SL1 – SL4; Photo 4).

Photo 3: Ekman Dredge used to collect samples from bottom of river in pools.

Table 13 provides a summary of the measurements made during the field, and the analysis that was conducted on the samples that were brought back to the laboratory. Upon return from the field, the TAL samples were removed from the coolers and refrigerated to prepare for shipping. The larger samples designated for sieving and TAL analysis on specific grain size fractions were air dried until the mass did not change with time. Samples were not over dried (as per convention for sand and gravel) to prevent a loss of mercury from the sediment. Dried samples were sieved on a shaker for 10 minutes into half phi intervals less than 128 mm in accordance with the AASHTO T27 Method. Results from the grain size analysis were presented previously (Section 3.2.5).

Once the A1, SL4, B2 and B4 samples were sieved a subsample of the sediment in the less than 0.063mm, 0.177-0.25mm, 0.71-1mm, 1.41-2mm and 2.83-4 mm grain size classes was transferred to clean 4-oz clear glass jars and labelled with the appropriate size class and site location. Once these samples were prepared they were shipped along with the composite samples collected in the field for subsequent analysis. Chain of custody information was placed in a waterproof bag and taped to the inside lid of a cooler. A second copy of the chain of custody information was attached to the outside of the lid for shipping purposes. Each cooler was sealed with duct tape and a custody seal. The TAL samples were sent via courier to an EPA/WDOE certified laboratory (ALS) in Everett, Washington.

Table 13: Summary of sediment samples collected in April 2010 and the subsequent analysis that was completed

Sample location	Sample type	Date collected	Time Collected	Easting	Northing	TAL analysis conducted on composite sample	TAL analysis conducted on specific grain size fractions	Was sample sieved	Wolman done	Comments
SL1	Grab	24-Apr-10	9:41	448236	5438722	N	N	Y	N	Has some non-slag grains with sample
SL2	Grab	24-Apr-10	9:53	448237	5438697	N	N	Y	N	Relatively fine
SL3	Grab	24-Apr-10	10:02	448211	5438746	N	N	Y	N	
SL4	Grab	24-Apr-10	10:24	448202	5438753	Y	Y	Y	N	Coarser than other three slag samples
A1	Bulk	27-Apr-10	11:58	448211	5449826	Y	Y	Y	Y	
A2	SGS	27-Apr-10	13:00	449247	5450234	N	N	N	Y	
A3	SGS	28-Apr-10	10:24	453257	5462679	N	N	N	Y	Collected on the Kootenay River
A4	SGS	28-Apr-10	13:16	449000	5464631	Y	N	N	N	Has a bit more clay and silt than other sites, clay very close to the surface
A5	SGS	28-Apr-10	12:17	444970	5465734	Y	N	N	N	
A6	SGS	28-Apr-10	13:46	444199	5465331	N	N	N	N	
B2	Bulk	25-Apr-10	14:27	455115	5433872	Y	Y	Y	Y	
B2	PS0	25-Apr-10	14:27	455115	5433872	N	N	Y	N	
B2	PS20	25-Apr-10	14:27	455115	5433872	N	N	Y	N	
B2	PS40	25-Apr-10	14:27	455115	5433872	N	N	Y	N	
B2	PS60	25-Apr-10	14:27	455115	5433872	N	N	Y	N	
B2	PS80	25-Apr-10	14:27	455115	5433872	N	N	Y	N	
B3	SGS	25-Apr-10	16:54	455182	5435713	N	N	Y	Y	
B4	Bulk	24-Apr-10	16:29	450236	5438235	Y	Y	Y	Y	
B4	PS0	24-Apr-10	16:29	450236	5438235	N	N	Y	N	
B4	PS20	24-Apr-10	16:29	450236	5438235	N	N	Y	N	
B4	PS40	24-Apr-10	16:29	450236	5438235	N	N	Y	N	
B5	SGS	24-Apr-10	17:43	454914	5434419	N	N	Y	N	Eddy bar on right bank
B6	SGS	25-Apr-10	9:51	454702	5428664	N	N	Y	N	Right bank bar just upstream of Waneta Eddy, finer tale of bar deposit sampled
B7	SGS	25-Apr-10	10:48	455866	5429932	N	N	Y	N	Drive to bar on left bank downstream of Ft Shepard pool, landslide upslope
B8	SGS	26-Apr-10	16:33	454921	5431736	N	N	Y	Y	Bar upstream of Ft Shepard on right bank
B9	SGS	26-Apr-10	17:04	453128	5437575	N	N	Y	N	Downstream end of bar with sewer outfall and RV dealer
CL1	Clam	25-Apr-10	11:44	454618	5428209	N	N	Y	N	Waneta Eddy sample
CL2	Clam	25-Apr-10	17:43	455088	5435287	N	N	Y	N	Sample of underwater sand bar on RB across from Beaver Creek boat launch
CL3	Clam	26-Apr-10	13:56	455552	5430976	N	N	Y	N	Sample from Ft Shepard pool

5.3.2 SITE CHARACTERISTICS

Characteristics of the six sites visited upstream of the Teck smelter are illustrated in Photo 5. In general these sites had a coarse cobble substrate and the finer sands in the subsurface sediment were sampled. The one exception was site A4 which was mixture of sand, gravel and cobbles on the surface, but had clay within 10 cm of the surface. The sample for this site was collected from the surface material and avoided the underlying clay.

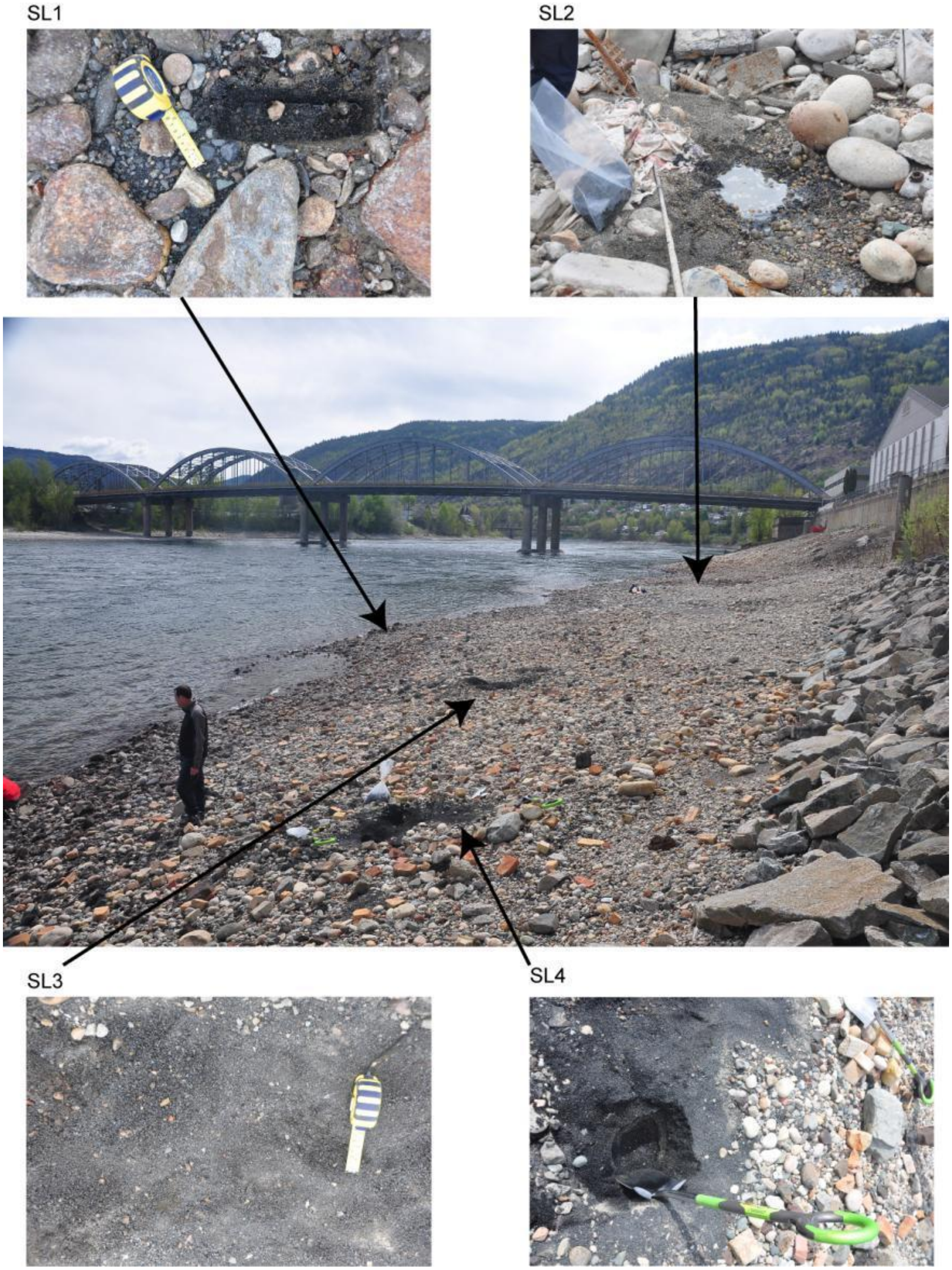


Photo 4: Location of grab samples (SL1-4) at Trail BC.

Photo 5: Sampling sites A1 through A6. See Figure 22 for locations.

B4 is the site that is closest to the Teck smelter, and downstream of the smelter. The site is located on a large, coarse right bank bar that is shown in Photo 6. The imbrication and structure on this bar surface indicate that the bar surface material is not frequently, if ever, mobilized. A 60 cm deep profile of the bar showed that slag material was most prevalent in the top 30 cm of the bed (Photo 6).

At sampling site B2, a bulk sample and 1 meter deep profile of the bar was also completed (Photo 7). In contrast to B4 the bar surface was considerably finer and may be mobile during large floods. The more mobile sediment that characterizes this site likely originates from Beaver Creek (1.5 km upstream) and a large fan that has recently deposited considerable quantities of sediment into the Columbia River along the right bank (750 m upstream). To the east of the sample site a relic coarse bar surface similar to the surface observed at site B4 is visible (see Photo 7). This surface extends under the more recently deposited finer sediment and was observed at the base of the 1 m profile.

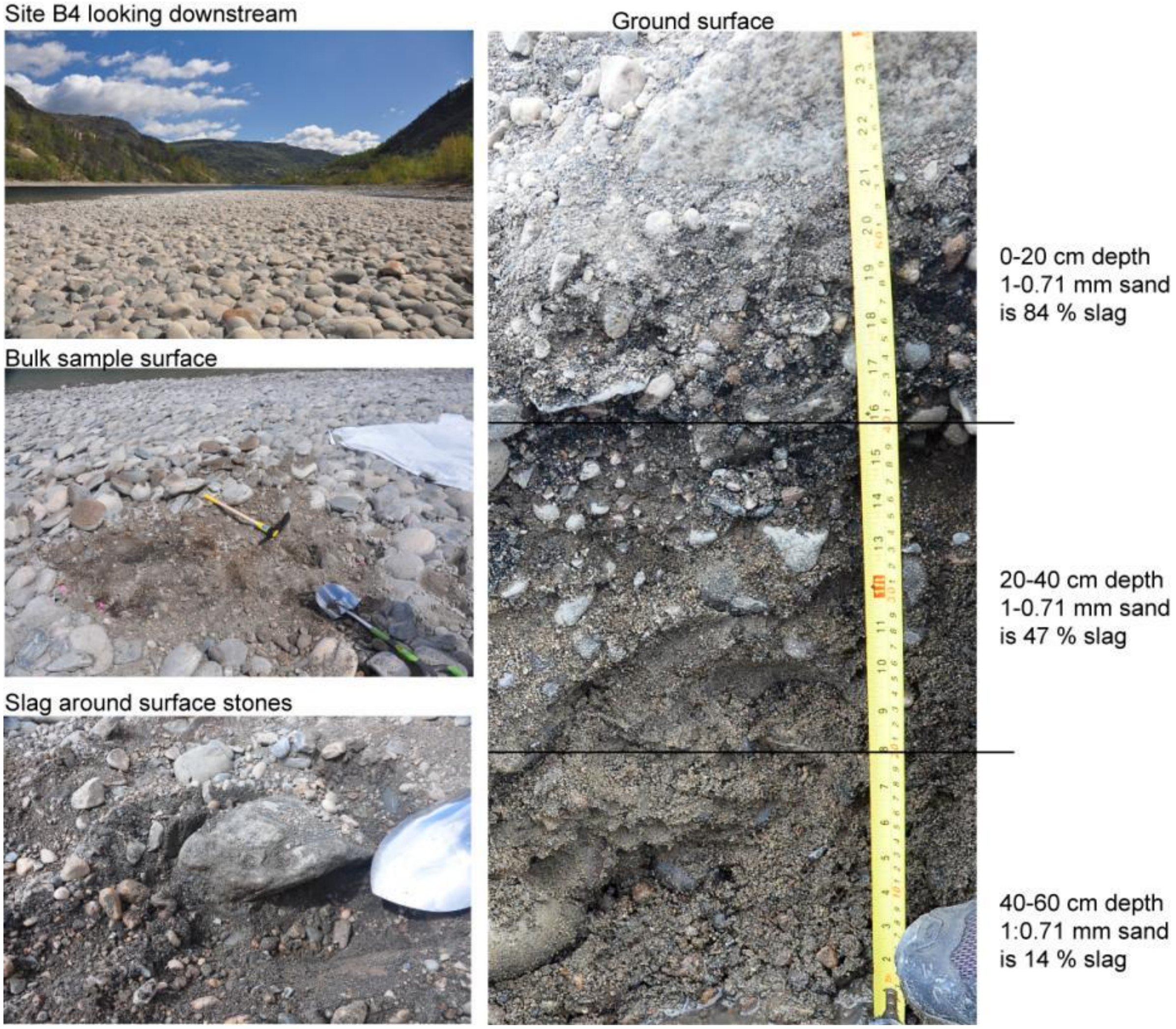
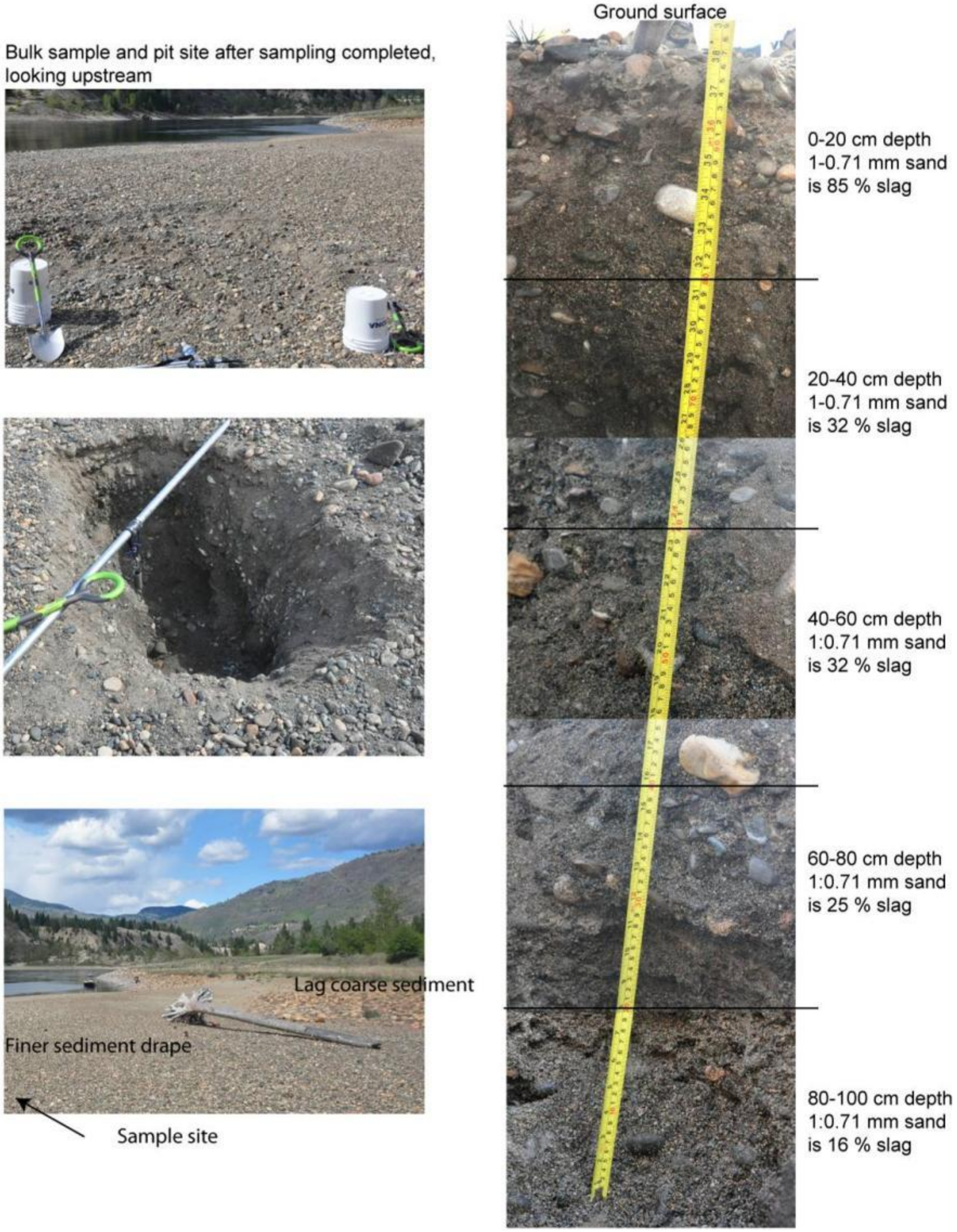


Photo 6: Site B4 where a bulk sample and 60 cm deep profile in the bar was dug.



Bulk sample and pit site after sampling completed, looking upstream

Photo 7: Site B2 where a bulk sample and 100 cm deep profile in the bar was dug.

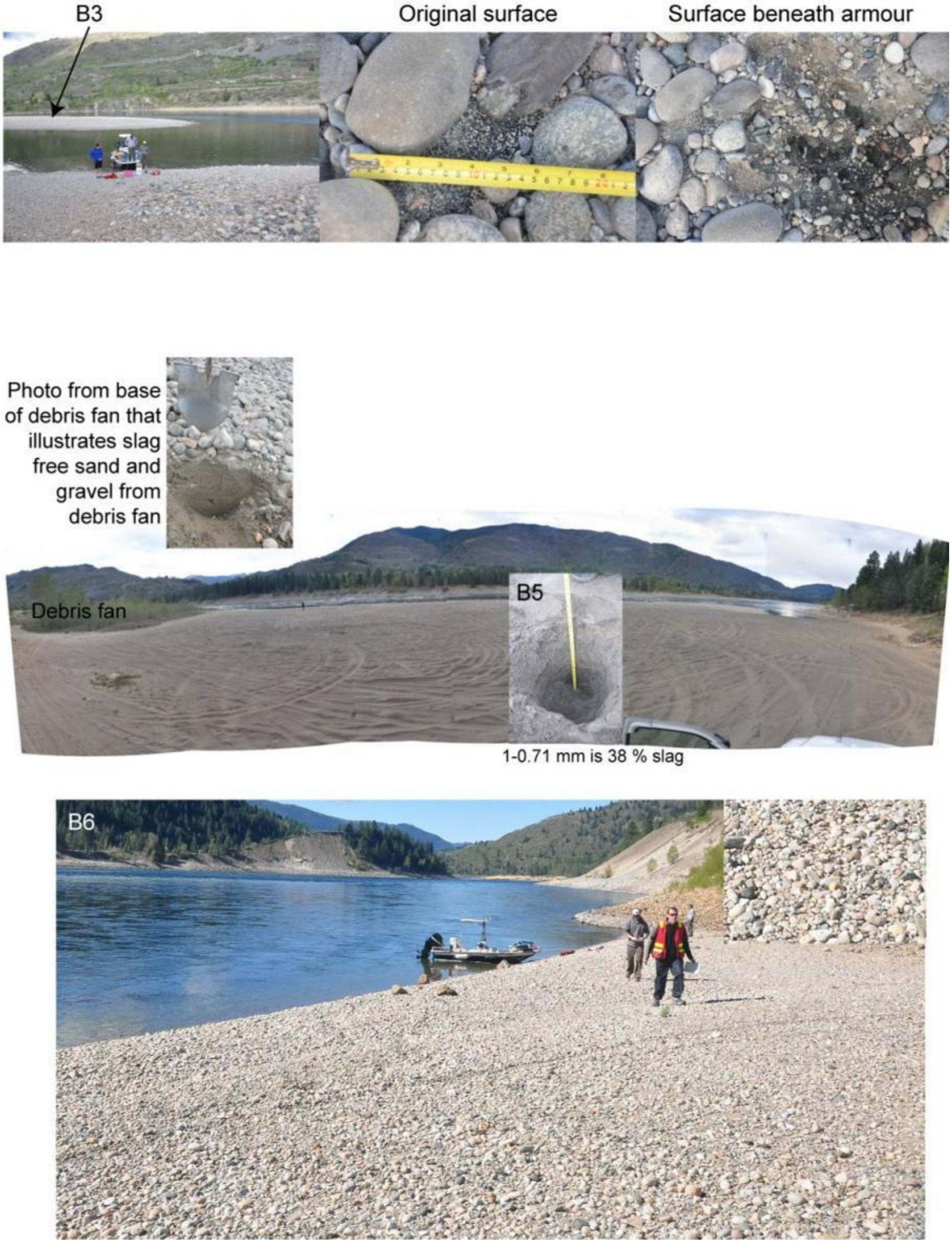


Photo 8: Sample sites B3, B5 and B6.

B7

B8

B9

Photo 9: Sample sites B7, B8 and B9.

Sample sites B3, B5 and B9 are located between the two bulk sample sites and are illustrated in Photo 8 and Photo 9. While B5 is a sand deposit immediately downstream of a debris fan coming out of an unnamed tributary (E455000, N5434800), B3 and B9 are characterized by a coarse cobble/boulder bed. B9 is located just downstream of Bear Creek, a relatively stable steep stream. B3 is located just upstream of Casino Creek and is not associated with any local sediment sources. The bars at B3 and B9 are best characterized as lag deposits from pre-regulation times.

A number of detailed observations were made in the vicinity of two major pools downstream of Trail near Fort Shepherd Flats and near the Pend d'Oreille River confluence just above the Canada-US border. These observations were made to assist in assessing sediment transport and sediment deposition processes along the river. Given the possibility that the pools have been infilling with slag material, an attempt was made to collect material from the pool bottoms. A local boat was hired to transport the field crew and equipment to the site. As an initial test to check for slag on the pool bottom, a magnet was attached to the end of a 400 foot long sinker line, and lowered to the bottom of a roughly 50 foot deep hole. The magnet was retrieved and the presence of slag was confirmed (Photo 10) so an Ekman dredge (clamshell trap) was deployed. At various locations on the pool surface, the boat was used to maintain a constant position, and the trap was lowered until it hit the bottom. A weight was then released to slide down the rope to the trap, triggering the spring-loaded jaws. The weight of the trap and the action of the trap closing enables sand and small gravels to be collected. The closed trap was slowly raised to the surface and opened over a 20 litre pail in the boat (Photo 3). The boat was then moved to a new location and the exercise repeated until a sufficiently large amount of sediment was collected that an accurate grain size distribution could be determined.

Photo 10: Slag collected by magnet from pool bottom in Waneta Eddy.

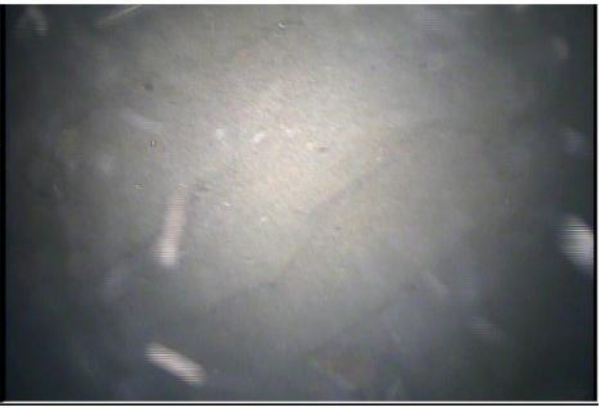
A second field trip was conducted on June 28th, 2010 to provide up to date bathymetry data and a more detailed understanding of the substrate in the bottom of the pools using an underwater video camera. The underwater video camera was tethered to the boat and the GPS derived location of the boat and video images were recorded using a laptop computer. While reviewing the video images the six substrate types shown in Photo 11 were identified. Cobble and sand were the two most common substrate types. Using the spatial information acquired along with the images enable the spatial pattern of substrate in the pools to be identified. Using a combination of the side scan sonar, underwater video camera images and bathymetry data a substrate map was produced for each of the pools.

Gravel

Cobble

Cobble and sand

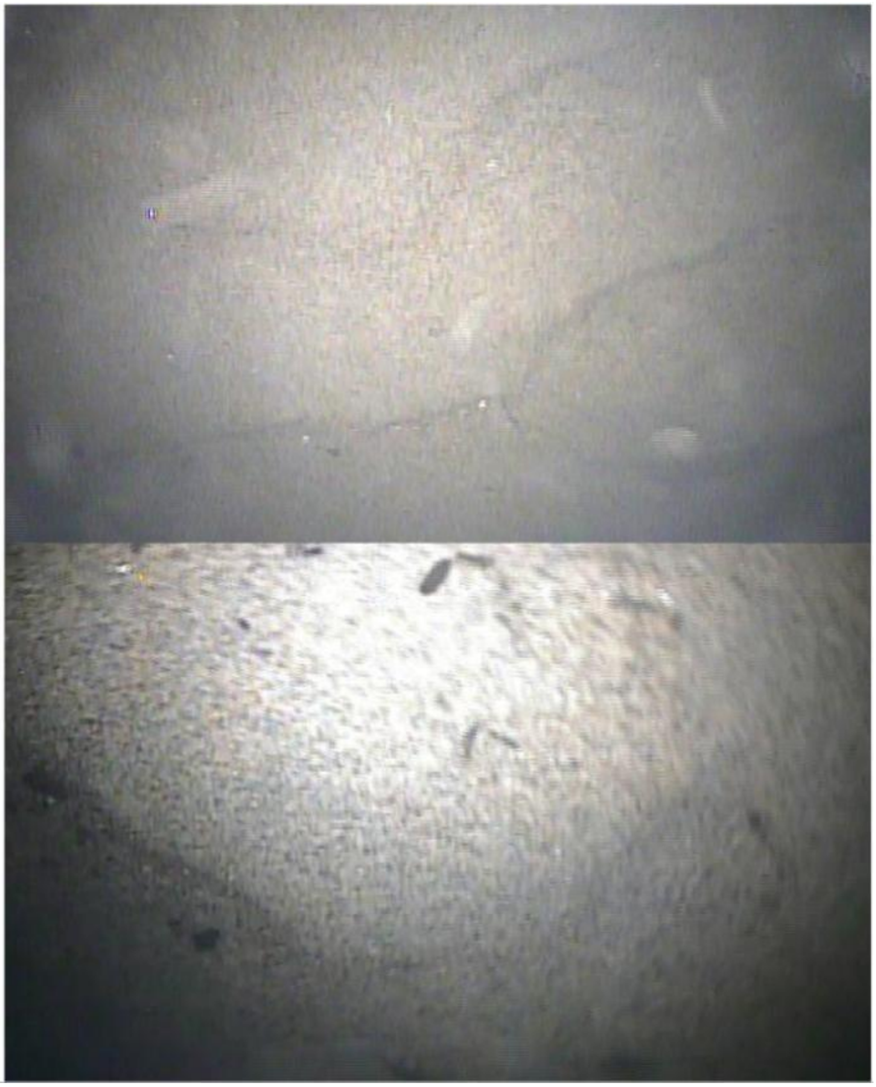
Sand



Bedrock and sand

Bedrock

Photo 11: Photos from underwater video camera showing six types of substrate that were identified in the pools.



Ripples indicate that sand mixed with slag is mobile.

Close up view of ripple. Dark grains are slag particles.

Photo 12: Underwater video image showing slag forming ripples in deep pool near Fort Shepherd Flats

5.3.3 RESULTS FROM DETAILED SAMPLING

Target analyte analysis was completed for the submitted TAL samples using method EPA-6020 except for mercury which is subject to a separate analysis method (EPA-7471). Results of the analysis are summarized in Table 14. For each of the metals that were tested, the average metal concentration was consistently greater downstream of the Teck Smelter. Queneau (2010) reported blast furnace and fumed slag from Teck Cominco's Trail smelter was characterized by elevated levels of lead, zinc, copper and iron. Elevated levels of cobalt and chromium have also been associated with slag sediment (G3 Consulting Ltd., 2001). Figure 23 illustrates how the concentration of metals varies along the Columbia River between Hugh Keenleyside Dam and Northport, WA. Figure 24 illustrates the metal concentrations associated with each grain size class.

Metal concentrations increase markedly downstream of the Teck smelter and remain elevated at all four of the sampling sites in the United States. Based on the results of TAL metals analysis and sorting of particles (Section 3) the presence of slag in all bars and pools has been confirmed from Trail downstream to the International Boundary. The results clearly indicate that slag has been transported downstream of Trail across the International Boundary to Northport.

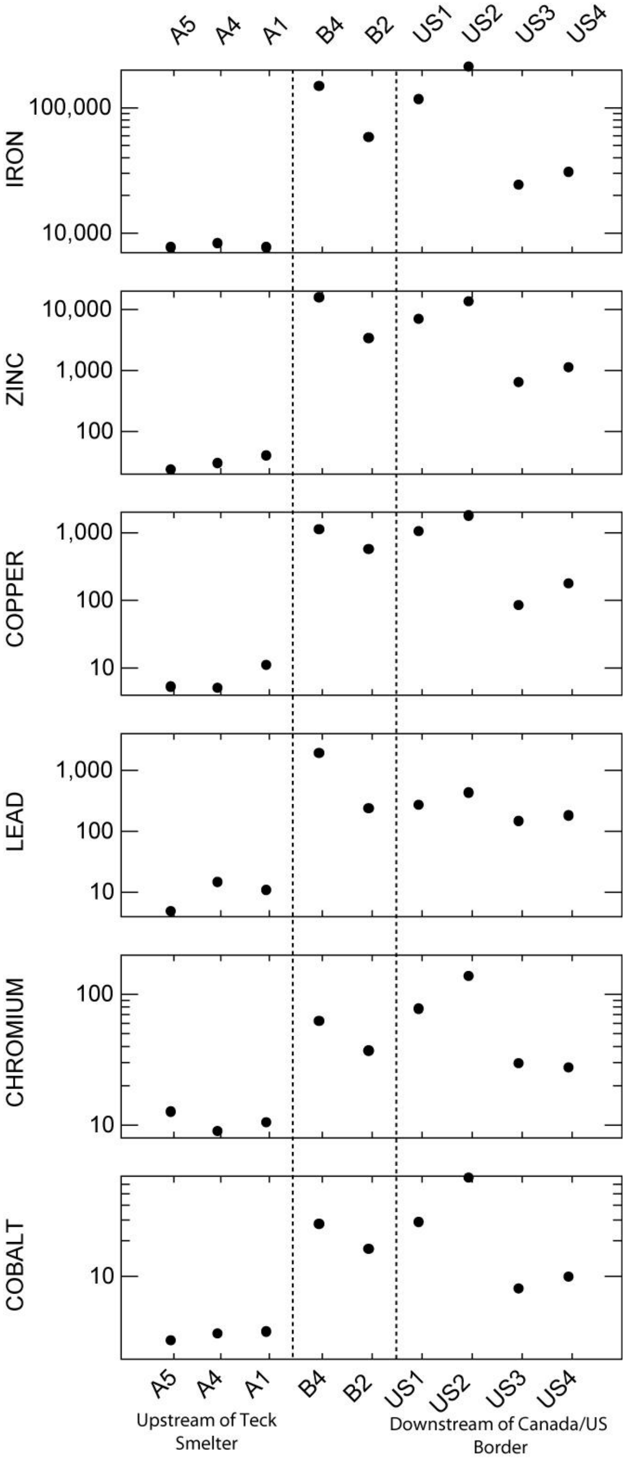


Figure 23: Concentrations of metals associated with slag along the Columbia River. See for location of sampling sites. Data are from less than 2 mm sediment samples. Values in mg/kg

Table 14: TAL analysis results from April 2010 samples (mg/kg)

Study Location ID	size less than	site	Aluminum	Antimony	Arsenic	Barium	Beryllium	Cadmium	Calcium	Chromium	Cobalt	Copper	Iron	Lead	Magnesium	Manganese	Mercury	Nickel	Potassium	Selenium	Silver	Sodium	Thallium	Vanadium	Zinc
A1 (<0.063 mm)	0.063	A1	6600	0.51	3.2	82	0.32	0.57	5600	27	5.6	75	18000	55	3900	310	0.058	18	1200	0.8	0.038	170	0.31	34	160
A1 (0.177-0.25 mm)	0.25	A1	2900	0.085	1	34	0.33	0.2	2200	23	3	8.8	17000	11	1800	130	0.02	8.9	490	0.24	0.038	51	0.31	39	63
A1 (0.71-1 mm)	1	A1	2800	0.047	1	27	0.14	0.2	1800	8.9	2.7	7.3	7300	6.4	2000	140	0.02	8.7	380	0.18	0.038	55	0.31	13	28
A1 (1.41-2 mm)	2	A1	3000	0.047	1.1	29	0.15	0.2	1600	7	2.7	8.7	7800	7.7	2100	170	0.02	7	420	0.18	0.038	43	0.31	14	33
A1 (2.83-4 mm)	4	A1	2300	0.047	1.1	30	0.12	0.2	2000	7.1	2.4	9.7	5800	7.4	1900	130	0.02	6	400	0.18	0.038	44	0.31	9.7	28
A1 (Bagged Sample)	all	A1	3100	0.047	1.2	29	0.13	0.2	2100	9.9	3.2	10	7300	9.6	2600	200	0.02	8.9	450	0.18	0.038	51	0.31	15	36
A4 (Bagged Sample)	all	A4	3100	0.064	1.7	62	0.13	0.2	2400	8.5	3.1	4.6	7900	13	2300	100	0.02	11	930	0.18	0.038	56	0.31	14	27
A5 (Bagged Sample)	all	A5	2800	0.062	1.1	38	0.1	0.2	6600	12	2.7	4.8	7300	4.3	2400	130	0.02	9.2	470	0.18	0.038	68	0.31	12	21
SL4 (<0.063 mm)	0.063	SL4	20000	93	580	500	0.66	140	40000	41	46	4200	140000	25000	7000	3100	8.4	40	4200	8.1	39	2500	4.8	63	30000
SL4 (0.177-0.25 mm)	0.25	SL4	22000	17	170	700	0.66	73	57000	34	41	1500	170000	8800	7600	3000	0.39	16	5700	3.7	11	3600	3.1	55	36000
SL4 (0.71-1 mm)	1	SL4	34000	17	160	950	0.69	73	79000	54	64	1700	230000	7900	12000	3600	0.086	18	8600	3.9	8.2	6600	3.1	91	36000
SL4 (1.41-2 mm)	2	SL4	46000	7.9	110	700	0.77	3	83000	59	79	1500	190000	3700	18000	2100	0.075	22	12000	2.6	5.7	12000	3.1	140	18000
SL4 (2.83-4 mm)	4	SL4	52000	7.2	64	660	0.73	2	89000	58	63	1400	140000	1200	20000	1100	0.041	16	14000	1.8	2.6	15000	3.1	160	2800
SL4 (Bagged Sample)	all	SL4	38000	7.8	86	480	0.73	33	77000	49	58	1300	150000	3600	14000	2000	0.088	16	11000	1.9	4.7	9800	3.1	110	16000
B4 (<0.063 mm)	0.063	B4	8600	13	29	320	0.25	4.2	8100	33	8.5	540	30000	1000	5000	580	1.9	24	1400	1.4	5.2	230	0.61	33	2300
B4 (0.177-0.25 mm)	0.25	B4	8800	37	21	360	0.26	2	19000	37	12	710	64000	630	3700	1200	0.71	13	1500	1	4.5	410	0.31	25	4000
B4 (0.71-1 mm)	**1**	**B4**	**6900**	**4.7**	**7.9**	**260**	**0.66**	**20**	**18000**	**24**	**9.9**	**370**	**61000**	**430**	**2000**	**1100**	**0.31**	**3.2**	**1400**	**1.8**	**0.66**	**530**	**3.1**	**14**	**4900**
B4 (1.41-2 mm)	2	B4	5900	4.7	20	200	0.66	20	15000	15	12	410	50000	1400	1900	940	0.1	3.6	1300	1.8	1.7	600	3.1	13	7200
B4 (2.83-4 mm)	4	B4	7300	10	30	190	0.66	2	17000	12	9	340	42000	1700	3000	760	0.14	7.4	2700	1.9	1.1	1000	3.1	18	10000
B4 (Bagged Sample)	all	B4	17000	8.5	44	550	0.66	36	46000	59	26	1000	140000	1700	5700	2600	0.21	11	3700	2	3.2	1500	3.1	36	14000
B2 (<0.063 mm)	0.063	B2	7900	17	25	370	0.27	2.1	9600	37	12	530	36000	360	4300	630	3.8	19	1200	0.92	12	300	0.52	46	1200
B2 (0.177-0.25 mm)	0.25	B2	7500	23	14	550	0.32	2	21000	49	25	750	72000	270	2900	1500	0.2	11	1300	0.68	3.4	710	0.31	43	4200
B2 (0.71-1 mm)	1	B2	7000	1.8	3.8	99	0.15	0.44	6200	17	6.8	150	28000	75	4400	540	0.14	9.3	810	0.28	0.28	200	0.31	27	1400
B2 (1.41-2 mm)	2	B2	6900	0.71	3.8	59	0.13	0.7	3900	14	5.4	52	13000	49	4700	260	0.037	12	740	0.18	0.089	200	0.31	28	170
B2 (2.83-4 mm)	4	B2	4800	0.78	5.2	54	0.12	1.3	3400	8.9	5.4	55	12000	42	3500	290	0.027	9.2	650	0.18	0.066	100	0.31	21	190
B2 (Bagged Sample)	all	B2	7800	13	12	350	0.66	2	16000	35	16	510	55000	210	3600	1100	0.23	11	1200	1.8	3.3	470	3.1	28	3000
US1	all	US1	12000	45	23	760	0	0	31000	73	27	940	110000	240	4500	1700	0.079	15	1700	0	3.1	680	0	32	6200
US2	all	US2	19000	18	23	1400	0	0	59000	130	64	1600	200000	380	6200	3400	0	17	3000	0	4	1700	0	40	12000
US3	all	US3	8000	2	6.7	240	0.29	2.6	19000	28	7.4	76	23000	130	13000	230	0.2	20	1200	0.57	0.75	180	0	36	570
US4	all	US4	8500	5.1	7.3	280	0.25	3.1	20000	26	9.3	160	29000	160	12000	340	0.42	18	1500	0.74	0.95	190	0	32	1000

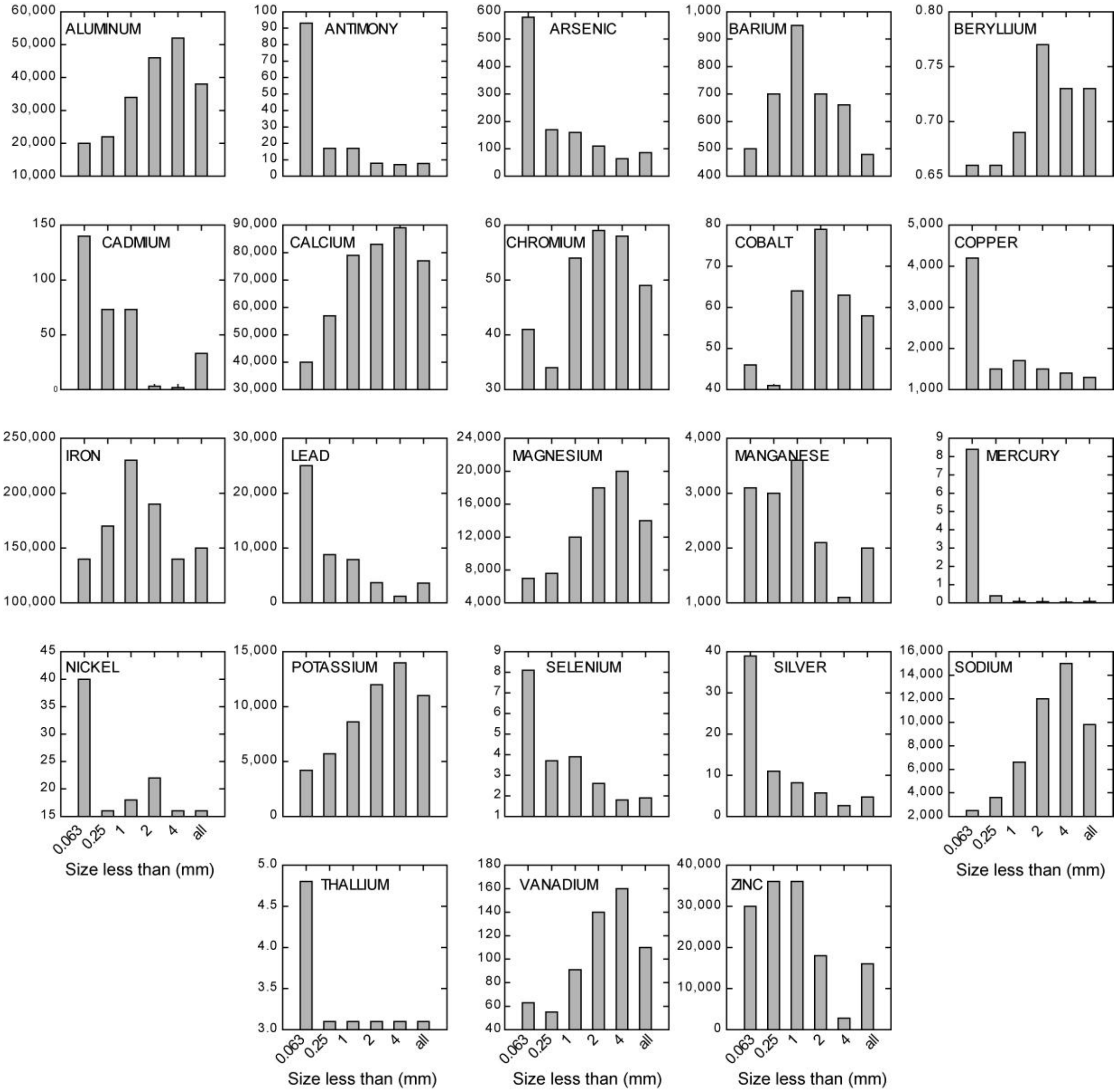


Figure 24: Metal concentrations associated with the SL4 sample for five grain sizes classes and a composite sample. All values in mg/kg.

5.4 ESTIMATED SLAG CONTENT IN RIVER BED SEDIMENTS

5.4.1 METHOD OF APPROACH

The most reliable method of determining the proportion of the bed sediment at each site that was composed of slag material is to take a subsample of the sediment and physically separate all the grains within the subsample into slag and non-slag components. This was completed on a sample of the 0.71-1 mm sediment from each of the samples that were collected. The slag particles were identified by their dark, glassy and angular characteristics that contrasted strongly with the lighter mineral grains originating from the upstream geology (Photo 13).

Photo 13: Photos illustrating slag and non-slag sediment. Grid lines are at 1 cm intervals.

Table 15: Percent of sediment that was physically identified as slag.

Sample Name	% Slag in 1-0.71 mm fraction	% Slag in sample	% Slag in sedimentary unit[1]
SL1	100.0%	100.0%	
SL2	95.2%	95.2%	
SL3	100.0%	100.0%	
SL4	100.0%	100.0%	
A1	0.0%	0.0%	0.0%
B2-BS	5.8%	1.0%	1.0%
B2-PSO	5.4%	1.7%	1.0%$^{\text{B2-BS}}$
B2-PS20	31.6%	10.3%	5.5% $^{\text{B2-BS}}$
B2-PS40	31.6%	7.9%	5.5% $^{\text{B2-BS}}$
B2-PS60	25.0%	5.4%	4.4% $^{\text{B2-BS}}$
B2-PS80	16.2%	3.6%	2.8% $^{\text{B2-BS}}$
B3-SGS	96.6%	52.6%	13.5% $^{\text{B4-BS}}$
B4-BS	84.0%	11.7%	11.7%
B4-PSO	85.7%	24.9%	12.0% $^{\text{B4-BS}}$
B4-PS20	47.4%	9.5%	6.6% $^{\text{B4-BS}}$
B4-PS40	14.3%	2.5%	2.0% $^{\text{B4-BS}}$
B5-SGS	37.5%	1.8%	1.8%
B6-SGS	5.9%	1.3%	1.3%
B7-SGS	54.5%	5.0%	7.7% $^{\text{B4-BS}}$
B8-SGS	5.4%	1.8%	0.8% $^{\text{B4-BS}}$
B9-SGS	75.0%	31.7%	10.5% $^{\text{B4-BS}}$
CL1	87.5%	85.9%	85.9%
CL2	3.4%	0.02%	0.02%
CL3	28.6%	21.8%	21.8%

[1] For those samples where the grain size distribution of the sample did not represent the sedimentary unit, the grain size distribution for the appropriate bulk sample was used instead. In each case that this was done, the bulk sample that was used is indicated adjacent to the percent slag.

5.4.2 Slag by Substrate Type

Within the Columbia River upstream of the Canada/USA border, a number of distinct sedimentary units were identified. These units varied widely in grain size and are described in Table 16. Since slag is only found in large quantity in the very fine gravel and sand size classes the variation in grain size that occurs across different sedimentary units results in large differences in slag content between the different units. For example, the coarse cobble lag sedimentary deposit that characterizes the B4 sample location is composed of relatively little sediment in the sand fraction that could be slag. If all of the sediment between 3.17 mm and

0.19 mm was slag (which correspond to the D_{95} and D_5 of the composite slag sample, respectively) only 24 % of the sediment at this site could be slag as the rest of the sediment is too coarse. In contrast, 90 % of the sand dominated sedimentary units in the bottom of the pools falls between 3.17 and 0.19 mm, suggesting these units are primarily composed of slag sized sediments.

To provide a means of identifying the proportion of the field collected samples that was slag it was assumed that the grain size distribution of the slag sampled downstream of Trail was identical to the composite slag grain size distribution (see Section 4.1). If the grain size distribution remains constant along the channel, then the ratio between the amount of slag in any two grain size fractions is constant. As such the amount of slag sediment in a grain size class of interest ($F_{s\_frac\_i}$) is directly proportional to the amount of slag sediment in the 1-0.71 mm grain size class ($F_{s\_frac\_1\text{-}0,7}$) via a constant of proportionality (C_i).

$F_{s\_frac\_i}/F_{s\_frac\_1\text{-}0,7}=C_i$; (Eq. 7)

Herein, i represents the grain size fraction of interest (e.g. 0.5-0.71mm). For each grain size fraction C_i was determined using the composite slag grain size distribution (see Section 4.1). Once C_i was determined, C_i could be used along with the observed proportion of slag in the 1-0.71 mm grain size class to predict the amount of slag in all the other grain size classes.

To determine the fraction that is slag in each grain size class ($F_{s\_frac\_i}$) we need to relate the proportion of sediment in the grain size class to the total amount of sediment in the fraction:

$F_{s\_frac\_i} = p_{s\_frac\_i} * F_i$ (Eq. 8)

Herein, F_i is the proportion of the total sample that is in grain size fraction i and $p_{s\_frac\_i}$ is the proportion of the sediment in grain size fraction i that is slag. For the 1-0.71 mm grain size class $p_{s\_frac\_1\_0.7}$ and F_i were determined by physically separating the grains and sieving the sample. For the other grain size classes we combine Eq 7 and 8 and solve for $F_{s\_frac\_i}$, which yields:

$F_{s\_frac\_i} = C_i * p_{s\_frac\_1\_0.7} * F_{1\_0.7}$ (Eq. 9)

Eq. 9 was then used to determine the fraction of slag in each grain size class. This approach may be best explained using an example. For a hypothetical sample let us assume the following:

- 30 % of the slag sediment is between 1 and 0.71 mm ($F_{s\_frac\_1\text{-}0,7}$)
- 15 % of the slag sediment is between 0.5 and 0.71 mm ($F_{s\_0.5\text{-}0.7}$)
- 20 % of the 1 to 0.71 mm sediment in Sample Y was observed to be slag
- 10 % of sample Y is between 1 and 0.71 mm ($F_{1\_0.7}$)

Based on these numbers to determine amount of slag in the 0.5 to 0.71 mm fraction in sample Y the approach proceeds as follows:

1. $C_{0.5}$ is first determined:

$C_{0.5}=0.15/0.3 = 0.5$

This implies there is half as much slag in the 0.5-0.71 mm grain size class as there is in the 1-0.71 mm grain size class. In practice thiswas determined using the composite grain size distribution (see Section 4.1).

2. Next the actual amount of slag in the 1-0.71 mm class as a proportion of the total sample is determined

$p_{s\_frac\_1\_0.7}*F_{1\_0.7}$, or $0.2*0.1 = 0.02$.

This implies that for sample Y the 1-0.71 mm slag material makes up 2 % of the total sample.

3. To determine the amount of slag in the 0.5-0.71 mm grain size class we then use the pre-determined $C_{0.5}$ value of 0.5 and the proportion of the total sample in the 1-0.71 mm class that is slag (2%)

$F_{s\_frac\_0.5} = 0.5*0.02 = 0.01$

This implies that for sample Y 0.5-0.71 mm slag makes up 1 % of the total sample.

To determine the total amount of slag in the sample the amount of slag in each grain size fraction is then added together to yield the total proportion of sample that is slag. For a few of the samples the amount of slag predicted for some of the individual grain size fractions exceeded the total amount of sediment in the grain size fraction. In these cases all of the sediment in fraction was considered to be slag. This generally occurred with sandy beach sediments or pool grab samples that contained no coarse sand or fine gravel (E.g. B5 and CL1 through CL3). Summary slag numbers are provided in Table 15.

Samples A1, B2-BS, B4-BS, B5-SGS, B6-SGS, CL1, CL2 and CL3 provide unbiased samples of the grain size distribution of the sedimentary units that they are from. For these samples the amount of slag measured using the above described technique accurately represents the actual amount of slag in the sedimentary unit. With all of the other samples the largest material was excluded when collecting the sediment as the large grain size classes (cobbles and boulders) do not contain slag. As such, for these samples, the measured grain size distributions do not represent the sedimentary unit the samples were collected from. For example, the profile samples from B4 included the finer material found in the pit, but not the large cobbles and boulders that were also present. Since slag is not present in the coarse fraction, slag content would generally be over predicted using the grain size distribution determined from these samples. To avoid this bias, for the samples with biased grain size distributions, the observed amount of slag in the 1 -0.71 mm class ($p_{s\_frac\_1\_0.7}$) was used along with the grain size distribution from the appropriate unbiased bulk sample to predict the amount of slag present (see Table 15). The grain size distribution determined with the B4 bulk sample was used for the majority of sample sites as the B4 site has a distribution similar to the other coarse bar deposits. The grain size distribution determined with the B2 bulk sample was only used for the B2 profile samples. Summary slag content data, by sedimentary unit are provided in Table 16.

Table 16: Distinct identifiable sedimentary units and their slag content

Sedimentary unit	Characteristics	Estimated unit thickness	Proportion of unit estimated to be slag
Coarse armoured Cobble bed (B3, B4, B9)	• Large cobbles/boulders on bed surface • No longer active • Slag would have infiltrated into bed	0.7 m	7.5%
Mobile gravel bed associated with tributary inputs or eddies (e.g. B2)	• Surface is not armoured • Bed can be activated during large floods • May have slag at depth	1.6 m	2.9%
B7		0.5m	5.5%
B8		0.2m	0.9%
Sand bar downstream of gully input (B5)		7.0 m	1.8%
B6		0.7 m	1.3%

5.5 MASS BALANCE OF SLAG REMAINING IN THE CHANNEL OF THE COLUMBIA RIVER

5.5.1 METHOD OF APPROACH

The mass of slag that has deposited in the reach from Trail to the International Boundary consists mainly two main components:

- Material that has sifted through the interstices of the gravel/cobble river bed sediments and is found under the surface armour layer of channel and bar sediments;
- Material that has deposited in portions of deep pools where local reduction in the velocity has allowed the slag to settle out.

5.5.2 SLAG ACCUMULATION IN POOLS

The hydraulic modelling and subsequent field investigations indicated that slag has accumulated in the two major pools downstream of Trail:

- At the deep hole formed by a bedrock outcrop in the river near Fort Shepherd Flats;
- Near Waneta eddy where the river widens at the confluence of the Columbia River and Pend d'Oreille River.

Bathymetric surveys of the two pools were made in 1948 and 1989 by the Canadian Hydrographic Service. NHC re-surveyed the pools in June 2010 to assess the recent bed level changes that have occurred in these sites. The 1948, 1989 and 2010 geodetic elevations were converted to a triangulated irregular network (TIN) model using tools in Arc/Info GIS. A separate TIN was created for both the Ft. Shepherd and Waneta area pools using a bounding polygon to restrict the interpolation to the common extent of data. A TIN represents a surface created by joining adjacent points into a series of triangles. Contours are incorporated into the model as breaklines that influence the interpolation between points. Contours can also be used instead of points as the primary source of elevations for the model. As TIN models cannot be directly subtracted from each other in GIS, each had to be converted to a regular grid. A 5-m spacing was chosen as this is smaller than the distance between adjacent points or contours for the 1948 and 1989 surveys, and minimizes the averaging inherent in converting the denser 2010 data to a grid. The difference in elevation between the surfaces represents the bed level changes (erosion or deposition) that has occurred over time. Figure 25 shows a plot of deposition and erosion at the two sites between 1948 and 1989. Figure 26 shows plot of deposition and erosion at the two site between 1989 and 2010.

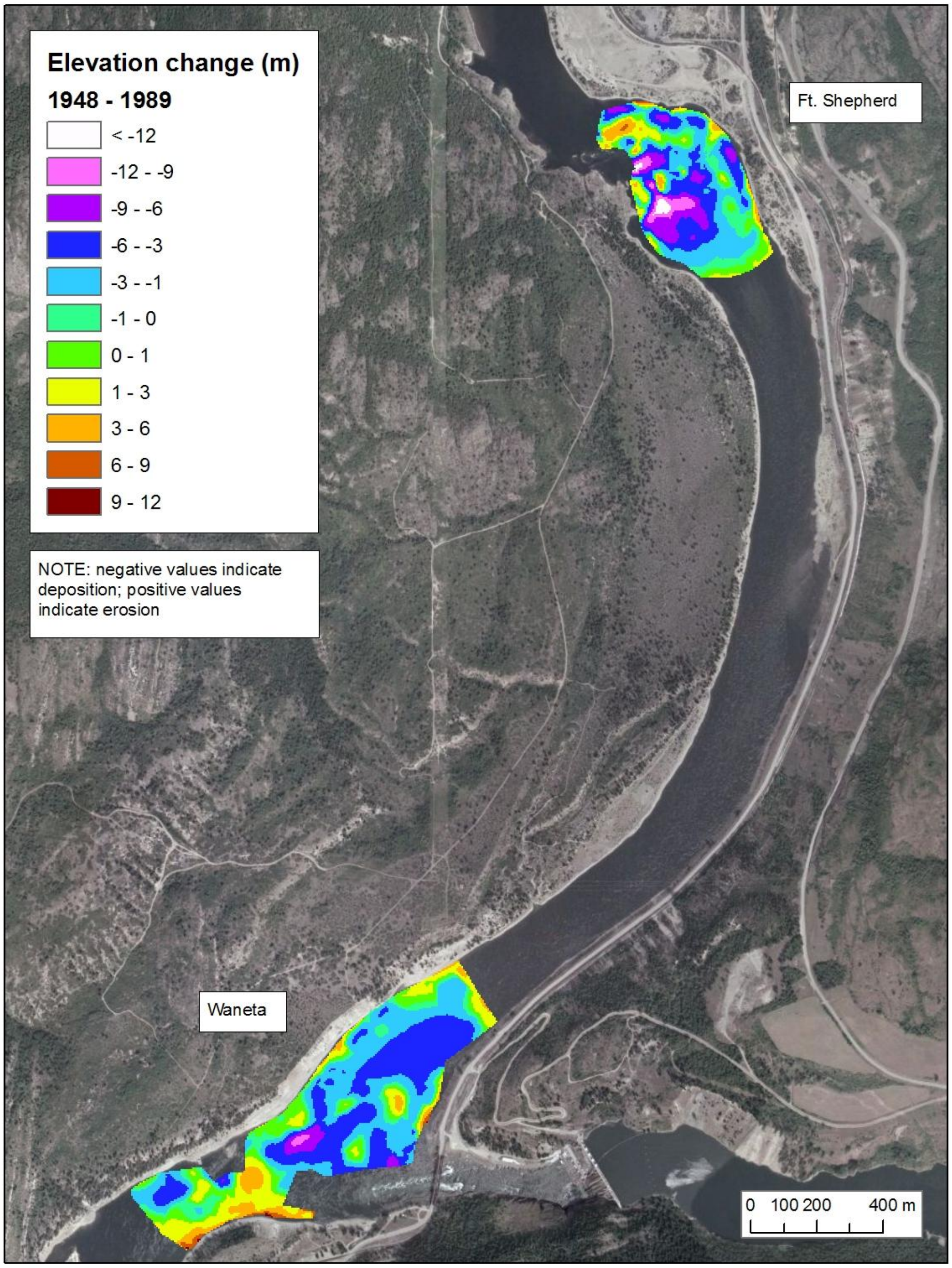


Figure 25: Scour and Fill at Ft. Shepherd Pool and Waneta Pool, 1948 to 1989

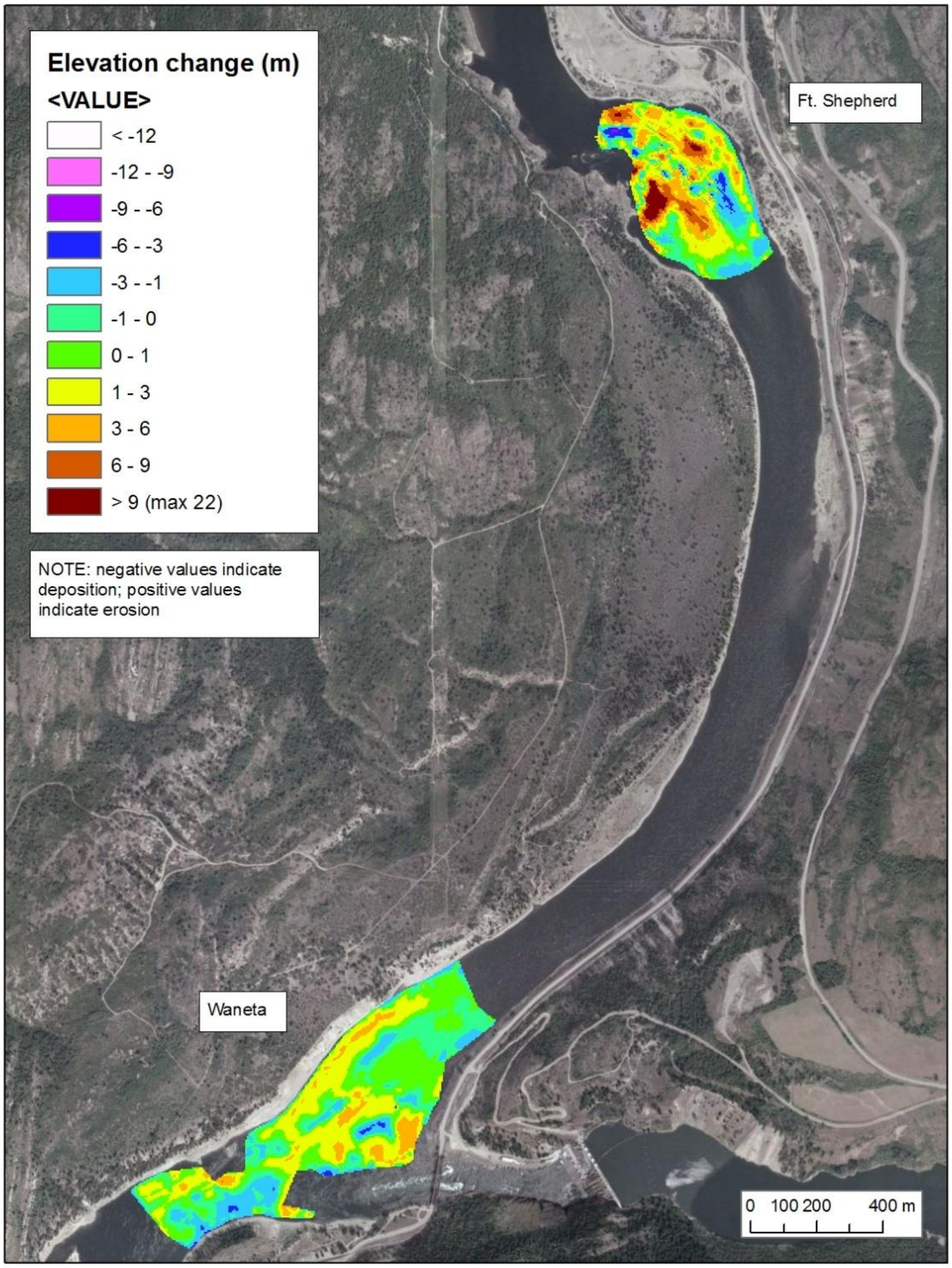


Figure 26: Scour and Fill at Ft. Shepherd Pool and Waneta Pool, 1989 to 2010

Between 1948 and 1989, there was a net deposition of 437,000 m^3 of sediment in Fort Shepherd pool (Table 17) and a net deposition of 450,000 m^3 of sediment in Waneta Pool. This material was deposited during a period of both natural and regulated flows. Based on the direct sampling of the pool bottom in April 2010, slag, sand and gravel material was observed on the bottom of both pools.

The 1948 and 1989 CHS bathymetric surveys span a period of 41 years between 1948 and 1989. Since we are interested in developing a mass balance for the period since slag discharges to the river commenced in 1930, the surveyed deposition volumes were adjusted to account for possible deposition during the period between 1930 and 1948. The total volumes deposited in the pools over the 59 year period between 1930 and 1989 ($V_{1930\text{-}1989}$) were estimated as follows:

$$V_{1930\text{-}1989} = V_{1948\text{-}1989} \times 59 / 41$$

The adjusted net deposition volumes for the period 1930 to 1989 were as follows:

- Fort Shepherd Pool: 629,400 m^3
- Waneta Pool: 646,900 m^3

It is possible that less material was deposited in the pools before 1973 when peak flows were much larger and the pools may have scoured annually, but this cannot be determined. The approach taken provides a conservative estimate that is apt to overestimate the amount of slag stored upstream of the Canadian/US border.

Comparison of the 1989 and 2010 surveys shows material is now being scoured from these sites. At Fort Shepherd pool, there has been a net loss of 333,620 m^3 of material since 1989. There is a similar pattern at Waneta, though the volume loss (177,000 m^3) is smaller. As material is removed from Fort Shepherd pool, it may be re-depositing downstream in Waneta pool, which would explain the lower scour rate. The net scour that is evident from the 2010 surveys reflects the effect of eliminating slag discharges to the river in 1995. Since the upstream supply of slag to the pools has ended, localized deposits in pools that are still mobilized during high flow periods are gradually being depleted as they continue to be transported downstream. In addition the lower slag content in the Fort Sheppard pool compared to the Waneta eddy pool suggests that as the wave of slag sediment moves downstream it is being replaced by fine sediment supplied by tributaries along the river.

Accounting for the scour between the 1989 and 2010 surveys, the net accumulation of material (sand and slag) from 1930 to 2010 amounts to 295,780 m^3 at Fort Shepherd pool and 469,900 m^3 at the Waneta pool.

Only a portion of the deposited material in the pools represents slag. Based on the field observations and underwater sampling, it was found that a portion of the sediments on the bottom of two pools consist of gravel and cobble material , rather than sand or slag sediments. However, in order to provide an upper bound estimate of the amount of slag that could have deposited in the pools, it was assumed that all of the deposited volumes represented sand-sized sediments. Based on the sampling program in June 2010, it was estimated that 22% of the deposited material in the Fort Shepherd pool consisted of slag and 86% of the deposited material in Waneta pool consisted of slag. Based on these values the net volume of slag deposited between 1930 and 2010 in the two pools between is as follows:

- Fort Shepherd Pool: 65,070 m^3
- Waneta Pool: 404,100 m^3

Table 17: Net volume changes over time at Fort Shepherd and Waneta pools

Fort Shepherd Pool	Scour (m^3)	Fill (m^3)	Net Change (m^3)
1948 – 1989	63, 250	500,630	+ 437,380
Estimated 1930 – 1989			+ 629,400
1989 – 2010	402,520	68,900	- 333,620
1948 -2010			+103,760
Estimated 1930 – 2010			**+ 295,780**
Waneta pool	Scour (m^3)	Fill (m^3)	Net (m^3)
1948 – 1989	182,070	631,620	+ 449,550
1930-1948			646,900
1989 – 2010	276,530	99,530	- 177,000
1948-2010			+272,550
Estimated 1930 – 2010	--	--	**+ 469,900**

5.5.3 SLAG MASS IN ARMOURED CHANNEL AND BAR SEDIMENTS

The slag that is found in the major bars is estimated as the product of the deposit volume and the slag fraction in each bar. The slag fraction for each bar is presented in Table 16. The bed of the wetted channel is considered to have the same unit thickness and slag fraction as the coarse armoured bars (B3, B4 and B9). The wetted channel and bars were digitized from Bing Maps, which allows ortho-rectified imagery to be added directly to the GIS through a web-based mapping service. The date of the imagery is not known, but as bars are no longer mobilized, imagery that may be several years old still accurately depicts current channel morphology. Water levels were lower in Google Earth imagery (dated October 11, 2006) revealing greater bar area. The edge of bars were digitized in Google Earth, exported as KML files, converted to shapefiles (ArcMap format) and imported to the existing map. The outline of Ft. Shepherd and Waneta pools was also imported and the entire river between Teck smelter and the border was divided into contiguous polygons.

The deposit volume for each bar unit is the product of unit area and unit thickness. Unit area is calculated directly in the GIS using topology tools. Unit thickness is estimated based on analysis of the profile samples, where it is observed that the slag fraction of sediment samples declines with depth from the surface. Since slag particles are generally much finer than most of the material in the bars (e.g. see Figure 8) they are able to infiltrate the bed through the interconnected void space created by larger particles. By fitting a trend line through the data, it is possible to estimate the maximum depth to which slag might be found (i.e. where the percentage of slag declines to zero). This yields a depositional thickness of 0.7 metres for the coarse bars (and by extension, for the wetted channel) and up to 1.6 m for the finer bar 'B2'.

The maximum depth that slag (and sand) can infiltrate static (immobile) channel bed and bars is a function of the supply of this material and the grain size distribution of the bed and bars. Experimental studies have shown this depth to typically be 2 to 3 X the D_{90} of the sediment (where the D_{90} is the size of material that 90% is smaller than). For the 3 sites sampled, the D_{90} ranges from 35 mm to 300 mm, so it is reasonable to expect infiltration as deep as 0.9 metres. For the coarse bars, the estimated infiltration falls within the range of expected values. The deeper infiltration at B2 is due to the mobile nature of these finer sediments. Similarly, a sandy bar (B5) with a thickness of nearly 7 metres could have slag particles throughout this entire depth as the entire deposit could be reworked by the river. Slag depth at bars where no profile samples were collected was estimated from the linear equation for the trend line, adjusting the intercept according to the fraction of slag found at the surface.

5.5.4 MASS BALANCE RESULTS

Table 18 below presents the summary results of the slag volume deposited within the channel.

Table 18: Sediment and slag deposition volumes for different sedimentary units.

Bar / Unit	Unit thickness	Unit area	Volume	Slag fraction	Slag Volume
B3, B4, B9, bed (wetted channel)	0.7 m	3,632,442 m^2	2,542,709 m^3	7.5 %	190,700 m^3
B2	1.6 m	14,855 m^2	23,768 m^3	2.9 %	690 m^3
B5	6.95 m	15,254 m^2	106,015 m^3	1.8 %	1910 m^3
B6	0.7 m	15,400 m^2	10,780 m^3	1.3 %	140 m^3
B7	0.5 m	42,046 m^2	21,023 m^3	5.5 %	1160 m^3
B8	0.2 m	38,783 m^2	7757 m^3	0.9 %	70 m^3
Ft. Shepherd	1.7 m[1]	178,452 m^2	295,000 m^3	22 %	65,070 m^3
Waneta	1.5 m[1]	318,524 m^2	469,900 m^3	86 %	404,100 m^3
1. Estimated by dividing net volume change by pool area				**TOTAL**	**663,840 m^3**

It is estimated that approximately 663,840 cubic metres of slag remains in the channel between Trail and the International Boundary. The majority of this volume is found at the bottom of Waneta pool.

The bulk density of the deposited slag in the river bed is estimated to be 1.8 tonnes/m^3 (based on a specific gravity of 2.9 and a porosity of 0.4). This means there is approximately 1,195,000 tonnes of slag remaining in the river bed between Trail and the International Boundary.

For comparison, between 1930 and 1995, approximately 12 million tonnes of slag were discharged to the river at Trail by Teck-Cominco. The mass of slag remaining within the Canada is approximately 10 % of the total amount discharged. The great majority of the slag (at least 90%) has been transported by the Columbia River downstream of the International Boundary into Washington State. Furthermore, it is expected that a portion of the slag remaining in Canada will continue to be transported downstream in the future.

6 ASSESSMENT OF RESULTS

6.1 REVIEW OF STUDY FINDINGS

Several independent methods have been used to assess the transport and movement of granular slag discharged into the Columbia River at Trail, including:

- Reviewing previous results of suspended sediment sampling along the Columbia River and comparing its sediment supply to its sediment transport capacity;
- Computing the initiation of motion, initiation of suspension and transport capacity of slag using analytical sediment transport equations and long-term hydrometric measurements made by Water Survey of Canada at Trail and the International Boundary (with USGS);
- Computing the initiation of motion and initiation of suspension of slag using sediment transport equations and a one-dimensional hydraulic model (HEC-RAS) from Birchbank down to Northport, Washington;
- Computing slag transport, erosion and deposition using a one-dimensional sediment model (SRH-1d) from Trail down to the International Boundary;
- Sediment sampling and assessing the distribution of slag and metals commonly associated with slag along the river from Birchbank down to Northport, Washington;
- Developing a mass balance of slag distributed in the channel of the Columbia River from Trail down to the International Boundary using results of sediment sampling and comparison of bathymetric surveys from 1948, 1989 and 2010.

The results from all of these methods are consistent and demonstrate that slag discharged from the Teck Cominco smelter was transported downstream as bed load and in suspension across the International Boundary.

A small fraction of the slag that was discharged has remained in Canada. This slag has deposited locally in slack water areas (behind obstructions or in back eddies), or has sifted into the pore space of the gravel and cobble sediments that form most of the river bed or has infilled some of the large pools such as at the Waneta eddy near the confluence of the Columbia River and Pend d'Oreille River. We estimate only 10% of the total slag discharged to the river between 1930 and 1995 remains upstream of the International Boundary. The remaining 90% has been transported downstream to Northport.

6.2 COMPARISON WITH OTHER INVESTIGATIONS

The assessment that slag has been transported downstream from Trail past the International Boundary is consistent with other previous investigations. Aquatic Resource Ltd. (2001) compared suspended sediment samples on the Columbia River downstream of Birchbank to near the International Boundary in 1995 (when slag was still being discharged to the river) and in

1999 (after slag discharges ended). The sampling was carried out at several locations both upstream and downstream of Teck Cominco's slag discharge site in Trail:

- Birchbank (upstream of Teck Cominco slag discharge point);
- Downstream of Stoney Creek (upstream of Teck Cominco slag discharge point);
- New Bridge in Trail (just downstream of the Teck Cominco slag discharge point);
- Old Bridge in Trail (1 km downstream of the Teck Cominco slag discharge point);
- Downstream island near Waneta (downstream of the Teck Cominco slag discharge point).

The analysis indicated the sand fraction (2.00 mm to 0.063 mm) accounted for approximately 50% of the total suspended load at Birchbank, with the silt (0.063 mm to 0.004 mm) and clay fraction (finer than 0.004 mm) accounting for the rest. The sand fraction increased to between 60% and 70% of the total suspended load in 1995 at the two bridge sampling sites (downstream from the slag discharge point). The size fraction coarser than 0.25 mm (representative of slag material discharged to the river) accounted for between 20% to 35% of the suspended load at these sites in 1995.

The following text is extracted from the Aquatic Resources (2001) report:

Q: Have the suspended and bottom sediment particle size distributions at Columbia River sites changed between 1995 and1999?

A: The suspended sediment particle size distributions were generally similar in the two years of study at the Birchbank and d/s Stoney Creek sites (upstream of Cominco). Downstream of Cominco, suspended sediment samples were generally finer in 1999 than in 1995 due to a lack of slag discharges.

In 2009 URS Corporation prepared a draft work plan for excavating slag that had deposited at Black Sand Beach (BSB) near Northport, in Stevens County, Washington. The following texts describes the characteristics of the slag and its association with the material discharged at Trail (URS, 2001):

Granulated slag from historic smelter discharges from Teck Cominco's Trail, British Columbia operations have accumulated on BSB.

Based on survey data collected in 2009, the estimated quantity of granulated slag material at the BSB is approximately 4,600 to 5,000 cubic yards, with an estimated 4,200 cubic yards at the downstream beach and 400 cubic yards at the upstream beach, with the remainder on the middle beach or located on top of the rock outcroppings.

7 CONCLUSIONS

Historic hydrometric measurements by federal agencies (WSC and USGS) at Trail and the International Boundary show the Columbia River is a fast-flowing, powerful river that can easily mobilize and transport slag particles into suspension throughout the year. The transport capacity of the river in this reach far exceeds the rate of supply of slag from the Teck Cominco smelter at Trail.

Sediment transport modeling using observed hydrometric data, hydraulic data from a one dimensional hydraulic model (HEC-RAS) and a one dimensional sediment model (SRH-1D) all show that the Columbia River transported slag downstream from Trail across the International Boundary to Northport throughout the period 1930 to 1995.

Metallurgical slag has been identified on all channel bars sampled downstream of the Teck Cominco smelter in Trail to the International Boundary. The slag is most commonly found beneath the armoured surface layer down to a depth of 1 metre below the surface. Slag particles are found locally along the shoreline in slackwater areas (in the lee of obstructions or indentations in the shoreline) and in some of the deep pools.

The volume of slag that has remained in the Columbia River in Canada (either deposited in the deep pools or found in the interstices of the gravel bar material) is a small fraction of the total slag discharged to the river between 1930 and 1995. Based on the field sampling, bathymetric survey comparisons and mass balance calculations we estimate approximately 90% of the slag discharged to the river was transported downstream across the border into the United States.

Only about 10% of the total mass of slag discharged into the River has remained within Canada. Direct observations using video imaging equipment shows the slag material in the pools is mobile and is continuing to be transported downstream.

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