Pakootas et. al. v. Teck Cominco Metals Ltd.

Opinion on the Transport and Fate of Metallurgical Slag Discharged into the Columbia River

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

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May 13, 2011

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EXECUTIVE SUMMARY

On September 2010 I submitted a report to the Confederated Tribes of the Colville Reservation and the State of Washington on the transport and fate of metallurgical slag material that was discharged into the Columbia River by the Teck Cominco (Teck) smelter at Trail, British Columbia. The study extended from Trail, B.C. downstream to near the town of Northport Washington.

My response to comments from Teck's experts on the McLean (2010) report are contained in Appendix A. The comments by Teck's experts did not challenge my conclusion that most (90%) of the metallurgical slag discharged into the Columbia River at Trail was transported downstream across the International Boundary into Washington State. Therefore, the findings and opinions expressed in McLean (2010) are unchanged.

In January 2011 I reviewed Teck's expert reports that attempted to estimate the quantity of sediments (and contaminated metals) that were deposited in the Columbia River upstream of Grand Coulee Dam from various sources including natural sediment generated in the Upper Columbia River (UCR) watershed, slag discharged from the Teck smelter at Trail and the LeRoi smelter near Northport, from mill tailings discharges and mine waste as well as from landslides along Lake Roosevelt. A detailed review was carried out on the methodology, assumptions, available data and calculations that were used by Teck's experts including Dr. T. Dunne, Dr. J. Bradley, Mr. A. Brown, Dr. A. Riese, Dr. T. McNulty, Mr. W. Grip and Dr. M. Johns.

Historical information (using maps and photos dating back to the 1890's), as well as field investigations, river surveys and detailed numerical modeling analysis was conducted to assess the reasonableness of Tecks predictions of river hydraulics and sedimentation.

I conclude that the available information is inadequate and incomplete to make meaningful estimates of sediment quantities retained in the UCR site from the various alleged sources. Reliable predictions of sedimentation and sediment transport rates cannot be made without systematic long-term field measurements. This conclusion is further supported by the US Army Corps' manual on sediment yield and sedimentation analysis:

The large variety of sediment yield methods can be placed into two broad categories-methods based on direct measurement and mathematical methods. Only those based on direct measurements are considered a rigorous approach; mathematical methods are trend indicators at best. (USACE, 1989 pg. 3-3).

Direct measurements include (1) suspended sediment discharge sampling (with follow-up lab analysis to determine the grain size distribution of the load),(2) bed load discharge measurements, (3) repeat bathymetric surveys of the Columbia River and Lake Roosevelt to estimate deposition or erosion quantities and (4) sediment sampling of the bed material to determine size of the sediments making up the river bed and reservoir deposits. These measurements need to be sustained over several years or even decades to provide reliable estimates of longterm sediment loads. These data are also vital for calibrating and verifying any predictions based on sediment transport equations or sediment models. Such data are not available in the UCR watershed and Teck did not collect it.

The only relatively continuous long-term sediment load measurements on the Upper Columbia River were collected by Water Survey of Canada (WSC) between 1965 and 1981. However, the grain size distribution of the load was never measured, making it impossible to separate the coarser sand fraction from the finer silt and clay fractions. This greatly reduces their usefulness for making any predictions about sediment deposition in Lake Roosevelt, since the grain size controls whether the sediment will deposit or be flushed through the reservoir. Also, Bradley erroneously assumed the WSC sediment sampling was carried out upstream of Trail and represented the "natural" sediment load without any contribution from Teck's slag discharges. We confirmed with WSC that the measurements were collected at Trail downstream of Teck's smelter and therefore, included both natural sediment and slag discharged by Teck. This exaggerated the contribution from "natural" sediment and under-represented the contribution from Teck slag by approximately 30%. Bradley's estimates of tributary sediment inflows and size distributions are not based on direct sediment transport measurements from actual tributary streams in the UCR basin.

Brown attempted to estimate the quantity of sediment discharged into the Columbia River from mill tailings and erosion of mine waste. He used the Universal Soil Loss Equation (USLE), to attempt to estimate the sediment load by mine waste further assuming all 487 mine waste sites had identical precipitation, slope and grain size characteristics. The USLE is not appropriate for estimating sediment loads generated from mine waste without conducting site specific calibration or providing independent verification tests against measured sediment transport rates. Even if one assumes that erosion actually reaches surface waters capable of transporting these materials, these reported sediment loads should be considered only as "order of magnitude" estimates and could easily overestimate the actual sediment loads by a factor of ten or more. The estimates are expected to over-predict because soil erosion or soil loss is not the same as sediment yield, since eroded soil may be re-deposited a few inches away from where it was dislodged. Eroded soil is re-deposited in sediment storage zones throughout the stream network including swales, at the base of eroding slopes, floodplains, channel bars and islands.

Brown estimated the amount of mill tailings and mine waste reaching the Columbia River after passing through Boundary Dam, Seven Mile Dam and Waneta Dam on the Pend Oreille River. Brown used Churchill's equation, a simple empirical method that does not account for the size of the sediment being transported. The trapping efficiency of potential mine waste and tailings in the reservoirs depends on several factors including the size of the sediment (sand and gravel will be trapped much more easily than clay and silt), the velocities and depths in the reservoir and the dam operations and arrangement of intakes and discharge structures. None of these factors was assessed. For example, no sediment sampling or grain size analysis was available, no cross sections of the reservoirs were used, no hydraulic modeling was carried out to estimate velocities and no consideration was given to the specific dam designs. The analysis does not meet the normal standard of practice in a sedimentation analysis.

Bradley estimated the quantity of sediment from each alleged source that was retained in the UCR upstream of Grand Coulee Dam using a one dimensional sediment model (HEC-RAS). This model requires inputs of water and sediment discharge over a series of years or decades as well as the initial channel topography at the start of the simulation and then predicts the sediment transport rate along the river channel and the quantity of deposition or scour that will occur during each time step. The river bed topography is then updated and modified to reflect the deposition or scour that has occurred. The sediment model predictions were never validated against actual field measurements of sediment transport rate or observed bed level changes and no evidence was provided to demonstrate whether any of the predictions were realistic.

In March 2011, I initiated a program of field measurements at selected reaches of the Columbia River, including water levels, bathymetric surveys and velocity measurements and also conducted additional detailed modeling using more sophisticated two-dimensional and three-dimensional models to assess the reasonableness of Bradley's HEC-RAS sediment model. This assessment showed the HEC-RAS model could not represent many of the physical processes that govern sediment deposition along the Columbia River. For example, the HEC-RAS model could not accurately simulate the effect of eddies or bedrock obstructions that cause sediment deposition along the channel sides and in sheltered areas. The one dimensional model also produced very unrealistic hydraulic conditions at two locations, generating "water falls" in the river that do not exist. I discovered these modeling errors by carrying out initial tests using only Bradley's hydraulic model in the HEC-RAS program. This analysis indicated the model produced an abrupt 20 foot drop in the water surface, just north of the International Boundary at the junction with the Pend Oreille River. A second drop of approximately 13 feet occurred near the Little Dalles around River Mile 728. Comparison of actual water surface profiles with the hydraulic predictions as well as recent field reconnaissance by boat confirmed that the model predictions were incorrect. A review of Bradley's output from the natural sediment model showed the initial inaccuracies in the hydraulic computations triggered unrealistic sedimentation rates to occur, with the river bed rising by approximately 100 feet near River Mile 728, forming an unusual spike in the profile, with a high waterfall dropping over the deposit. Bradley's output show that most of the deposition occurred in the 1920's, before Grand Coulee Dam was constructed. Comparison of predicted bed levels in 2010 with actual surveys and field observations shows the model predictions were not realistic in this location. This shows that initial errors in the river topography or hydraulics can propagate through the model and generate completely erroneous model predictions over a period of years. Furthermore, it illustrates the unreliability of making predictions without verifying or validating the results against field observations. This invalidates Teck's attempt to make a quantitative comparison of sediment deposition from its different alleged sources.

Bradley's model cannot be used to quantify the distribution of sediment deposits in the Upper Columbia River or the relative contributions of deposits from various sources (slag, alleged mill tailings and mine waste and natural sediment) since it was not validated against measurements of sediment transport or historical sediment deposition patterns. Furthermore, the model predictions do not agree with field observations and produce unrealistic conditions (waterfalls that do not exist and massive piles of sediment that do not occur).

Given the lack of direct field measurements and absence of validated results, the relative contribution of sediment from the various sources is presently unknown, and indeed is probably unknowable at the present time.

CREDITS AND ACKNOWLEDGEMENTS

The following NHC personnel participated in the study:

- Dr. David McLean, Ph.D., P.Eng., hydraulics and sedimentation
- Dr. Darren Ham, Ph.D., fluvial geomorphology and GIS analysis
- Mr. Peter Brooks, P.E., river hydraulics and sedimentation
- Ms. Vanessa O’Connor, P.Eng., hydraulic modeling
- Dr. Jose Vasquez, Ph.D., numerical modeling
- Dr. Malcolm Leytham, Ph.D.,P.E., hydrology
- Ms. Madalyn Ohrt, GIS
- Ms. Christine McKim, drafting

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1 INTRODUCTION

1.1 BACKGROUND

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 (Teck) smelter at Trail, British Columbia during the period 1930 to 1995. Dr. David McLean P.Eng. of NHC submitted his opinion in a report dated 17 September 2010 (NHC, 2010). On 14 January 2011 Teck Cominco Metals provided a number of expert reports that included comments on the findings in the NHC 2010 report. Subsequently NHC was requested by the Confederated Tribes of the Colville Reservation and the State of Washington to respond to those comments and to review and critique sections of Teck's rebuttal reports concerning hydrology, hydraulics, erosion, sediment transport and sedimentation. The opinions contained in this report represent NHC's response to that request.

1.2 OUTLINE OF REPORT

This report contains nine chapters and six appendices. Chapter 2, *Overview of Upper Columbia River* provides a description of the most important physical characteristics of the river and provides a context for much of the technical discussion that follows. Chapter 3 through Chapter 7 critique the opinions and findings in the Teck expert reports that relate to hydrology, hydraulics, erosion, sediment transport and sediment deposition in the Upper Columbia River. Chapter 8, *Conclusions*, summarizes my findings on these issues. Chapter 9 lists the references that were used in this assessment.

Appendix A summarizes my responses to comments and opinions expressed by Dunne and Bradley on McLean (2010).

A substantial amount of investigations (both in the field and numerical analysis) were carried out to support my assessment of the opinions expressed by Teck's experts. These supporting investigations are described in Appendix B through Appendix F.

Appendix B documents the Upper Columbia River prior to Grand Coulee Dam using early maps, surveys, terrestrial photos and air photos. I used this information to assess the physical characteristics of the river, particularly its capacity to transport sediment prior to regulation and impoundment.

Appendix C summarizes bathymetric surveys and velocity measurements that were conducted on the Columbia River between Northport and Marcus Flats in March 2011. These data were used for several different purposes-(1) to assess vertical bed level changes that have occurred since the last river surveys from the 1940's, (2) to document present day hydraulic characteristics and processes, (3) to calibrate NHC's independent numerical models (4) to assess the reasonableness of predictions made by Teck's hydraulic and sediment modeling efforts.

Appendix D illustrates and explains the different types of numerical models that are available to assess river hydraulics and sedimentation processes. This appendix uses one dimensional, two dimensional and three dimension numerical models at several representative reaches of the Upper Columbia River to illustrate the different assumptions and the limitations with these methods.

Appendix E describes results from NHC's two dimensional numerical modeling at two test reaches of the Upper Columbia River between Northport and China Bend. NHC's models were used to illustrate physical processes such as flow separation and back eddies that affect sediment transport and deposition in a complicated river. Results of NHC's field observations and numerical modeling are then compared to predictions from simple one dimensional models to illustrate the limitations of these methods and how this can lead to erroneous results.

Appendix F describes NHC's review of the input hydrological data that was used in Bradley's long-term simulations of sedimentation in the UCR. The accuracy and reliability of Bradley's model depends on the representativeness of the input data that were used. Since actual discharge data were not available for several decades during these simulations, Bradley had to make a number of assumptions to "fill in" these missing records. These assumptions introduce additional uncertainties in the model predictions and bias his comparisons of relative contributions of sediment from different sources.

1.3 TECK REBUTTAL REPORTS

I reviewed the following reports and related attachments from Teck during the course of my investigations:

- Thomas Dunne, Ph.D.: Opinion on Sediment Sources and Sedimentation in Lake Roosevelt, Washington, January 9, 2011.
- Dr. J. Bradley, Sediment Transport Analysis of the Columbia River Between Grand Coulee Dam and Birchbank, Canada (with Appendix). West Consultants Inc., January 14,2011.
- Expert Report of Adrian Brown, P.E. Pakootas et al v. Teck Cominco Metals Ltd., January 14,2011.
- Expert Report of Arthur C. ("Sandy") Riese, Ph.D., R.G. CHG. Pakootas, et al. v. Teck Cominco Metals, Ltd. January 14, 2011.
- Expert Report of Terence P. McNulty, DSc, P.E., Pakootas v. Teck Cominco Metals Ltd. Eastern District of Washington, January 14, 2011.
- Statement of Opinion, Wayne M. Grip, President Aero-Data Corporation, Concerning Production of Aerial Photographs for Mill Sites, November, 2010.
- Expert Report of Mark W. Johns, Ph.D., P.G., L.G. In: Joseph A. Pakootas, et al. v. Teck Cominco Metals Ltd. Exponent, Bellevue,WA., January 14,2010(sic).

The opinions expressed in the present report focus specifically on issues related to hydrology, hydraulics, sediment transport, erosion and deposition of sediment and other contaminants.

1.4 RESPONSE TO TECK COMMENTS ON MCLEAN (2010)

The responses to Tecks comments on McLean (2010) are summarized in Appendix A of this report. The Teck comments did not challenge the key finding, that most (90%) of the metallurgical slag discharged into the Columbia River at Trail between 1930 and 1995 was transported downstream across the International Boundary into Washington State. Therefore, the findings and opinions expressed in McLean (2010) are unchanged.

2 OVERVIEW OF THE UPPER COLUMBIA RIVER

This chapter highlights the most important physical characteristics of the river and provides a context for much of the technical discussion that follows.

2.1 SETTING

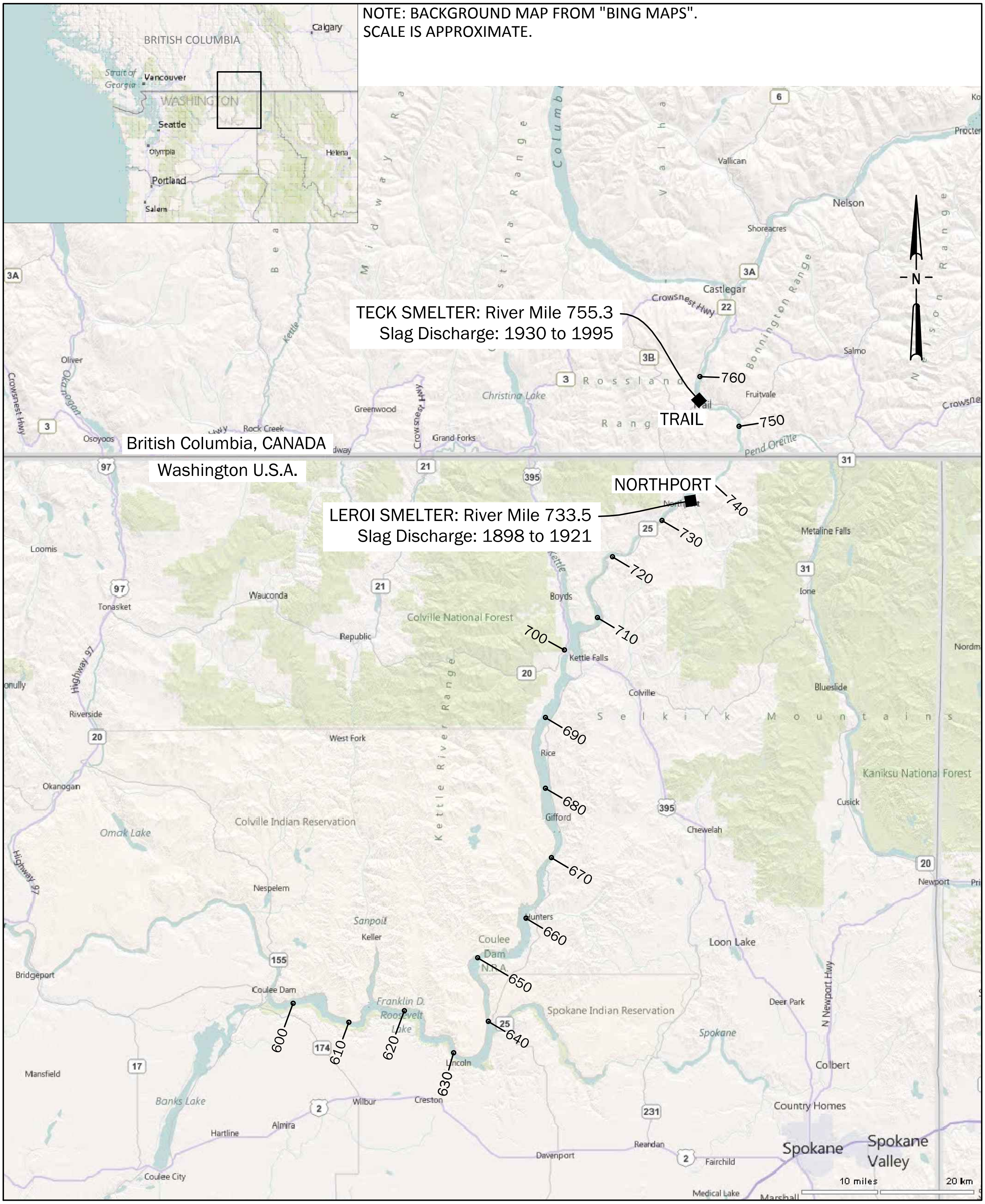
Figure 1 shows the Columbia River in the study area, along with reference River Miles (RM) and the location of Teck's smelter in Trail and the former LeRoi smelter near Northport, Washington. Teck Cominco's smelter at Trail discharged approximately 10 million tons of metallurgical slag into the Columbia River between 1929 and 1995. The slag was predominantly sand-sized. Bradley pg 21 stated that the LeRoi smelter near Northport Washington discharged approximately 2 million tons of slag to the Columbia River between 1898 to 1909 and an additional 0.4 million tons between 1916 and 1921.

The Columbia River originates in the Canadian Rockies and has a drainage area of 34,030 mi^2 by the time it reaches the town of Trail. The river is joined by the Pend Oreille River just upstream of the International Boundary, increasing the drainage area to 59,700 mi^2. The other significant tributaries entering upstream of Grand Coulee Dam include the Colville River, Spokane River and Sanpoil River (Table 1 indicates their location in River Miles). The drainage area at Grand Coulee Dam is 74,700 mi^2. Although the drainage area increases substantially south of the border, most of the runoff volume is generated north of the border. For example, comparison of annual flows at the International Boundary and at Grand Coulee Dam show an increase in flow volume of only about 10%.

Table 1: Reference Distances

Location	River Mile	Distance From Trail (miles)
Trail, B.C.	755	0
International Boundary	745	10
Northport, Washington	735	20
Marcas Flats	705	50
Colville River Confluence	699	56
Spokane River Confluence	638	117
Sanpoil River Confluence	616	139
Grand Coulee Dam	597	158

Figure 2 shows the various dams on the Columbia River and its tributaries that are discussed in this report. Figure 3 shows the location of a number of mills in the UCR watershed. Brown (2011) purported that these mills discharged mine tailings into tributaries leading to the Columbia River. Figure 4 shows the location of selected hydrometric gaging stations where discharge data has been collected by federal agencies (US Geological Survey (USGS) in the United States and Water Survey of Canada (WSC) in British Columbia).

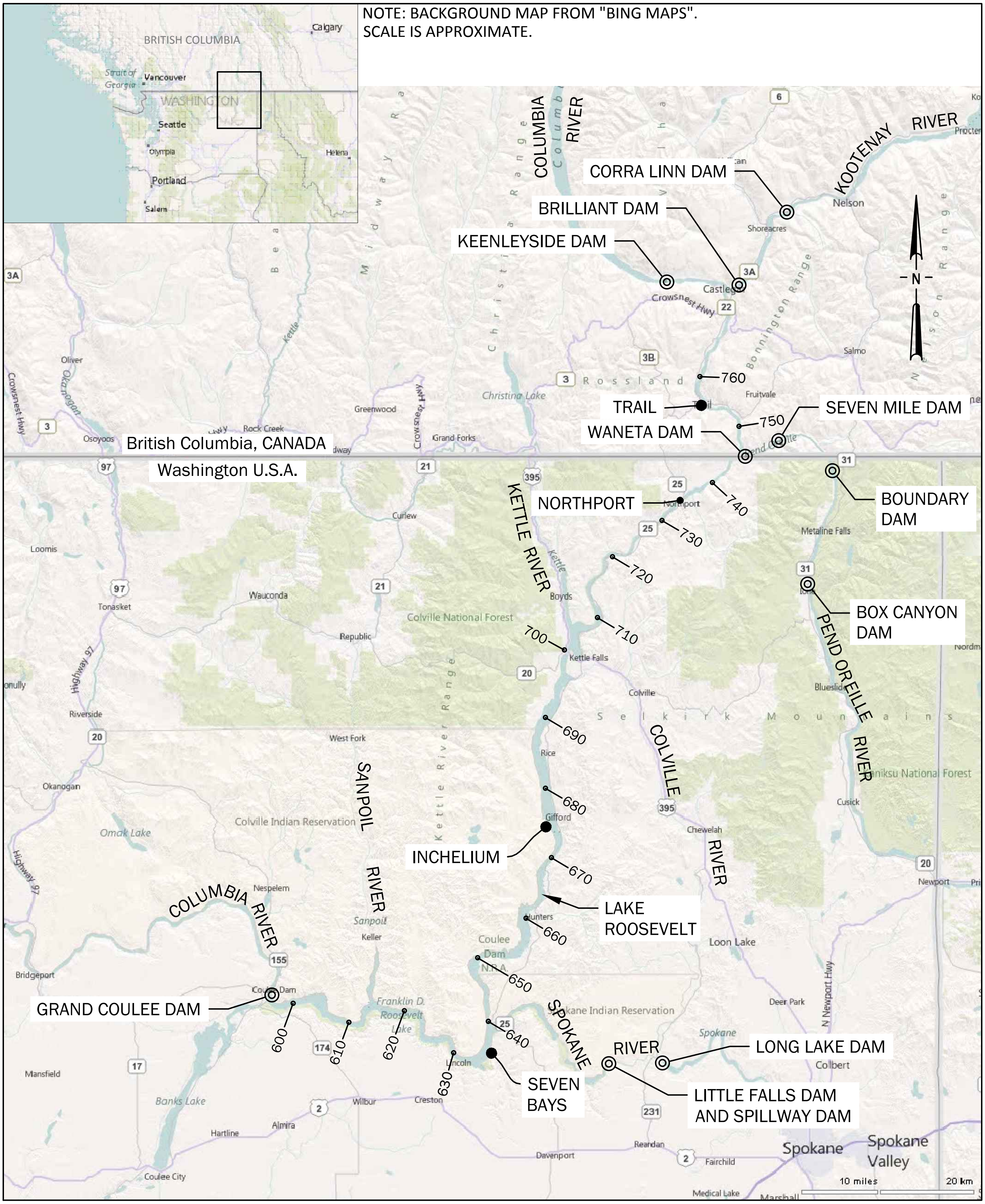


NOTE: BACKGROUND MAP FROM "BING MAPS".
SCALE IS APPROXIMATE.

TECK SMELTER: River Mile 755.3
Slag Discharge: 1930 to 1995

LEROI SMELTER: River Mile 733.5
Slag Discharge: 1898 to 1921

Figure 1: Study Area Showing Trail and Le Roi Smelters



NOTE: BACKGROUND MAP FROM "BING MAPS".
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Figure 2: Study Area Showing Dams in the Upper Columbia Watershed

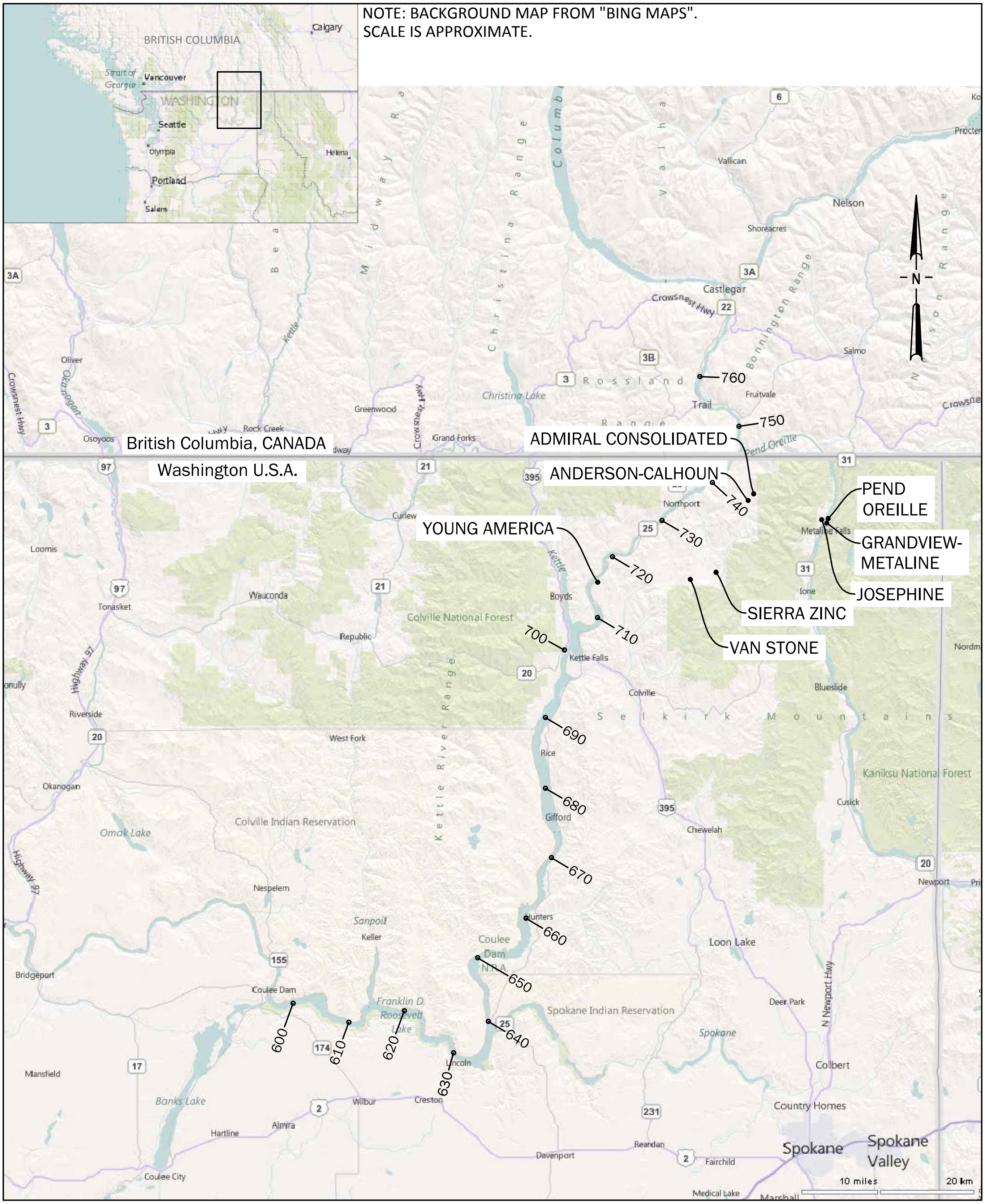


Figure 3: Study Area Showing Mine Locations

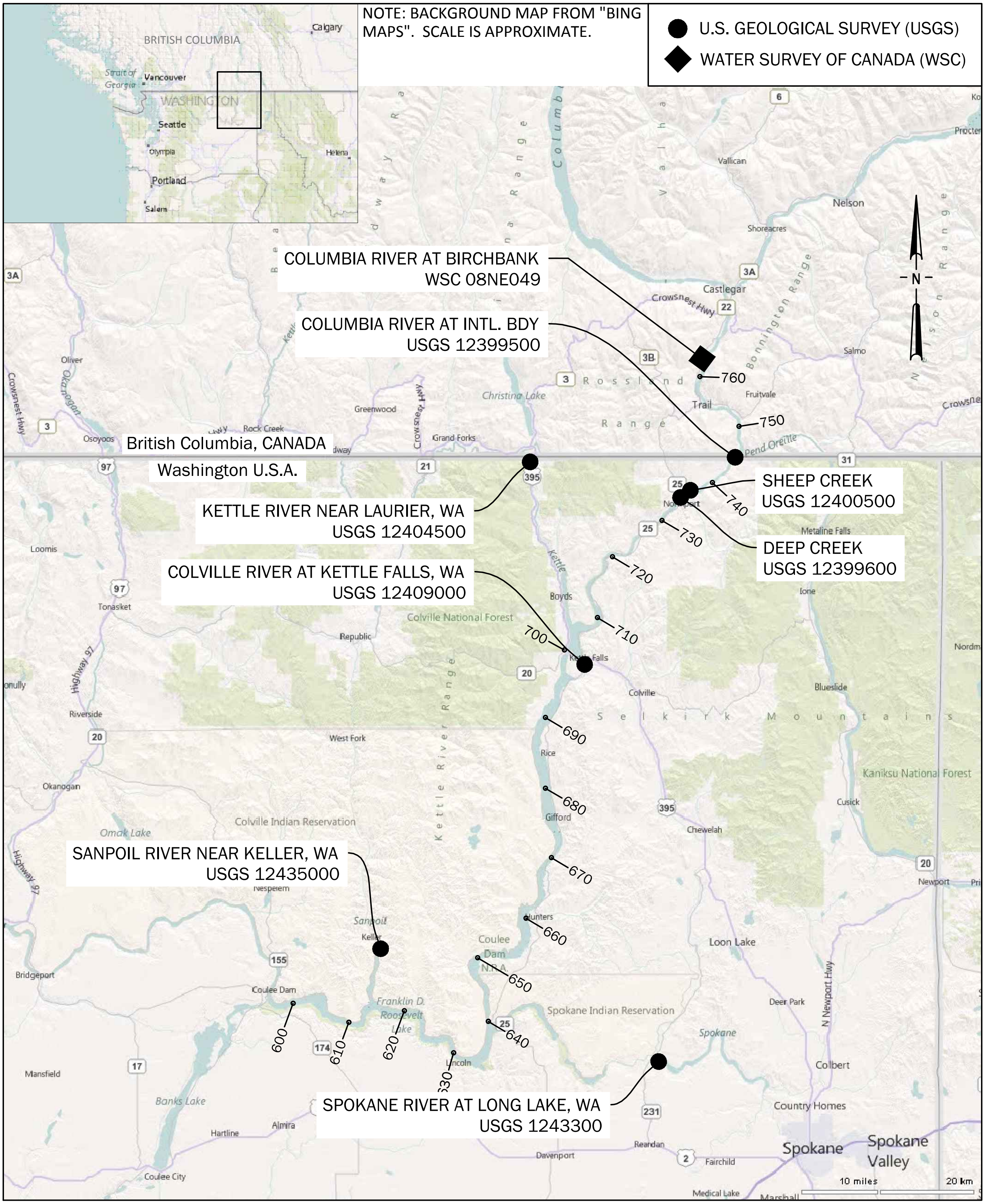


Figure 4: Location Map Showing Selected Stream Flow Gages

The hydrological and hydraulic conditions on the Upper Columbia River (upstream of Grand Coulee Dam) can be divided into three time periods:

- Before 1940, prior to construction of Grand Coulee Dam when the river was free-flowing and unregulated;
- 1941-1970 (approximately), after Grand Coulee Dam was constructed but prior to significant flow regulation from other upstream dams in Canada;
- 1971-present, after upstream flow regulation significantly altered the flow regime by reducing the freshet peak flows in May-June and increasing the winter low flows.

Figure 5 provides an overall time line for several of the important events that have impacted the UCR. The Le Roi smelter near Northport operated intermittently between 1898 and 1908, prior to Grand Coulee Dam and prior to any upstream flow regulation in Canada. The Teck smelter discharged slag into the Columbia River between 1930 and 1995, spanning free-flowing and impounded /regulated conditions.

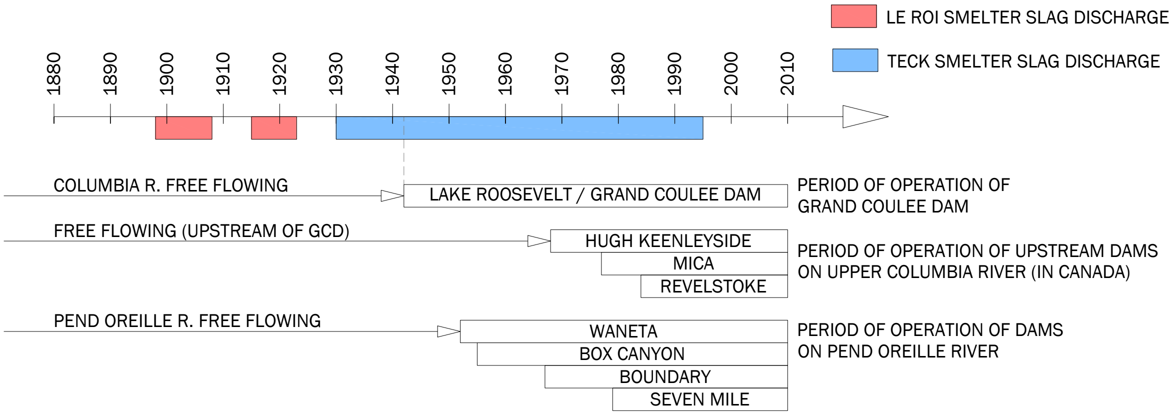
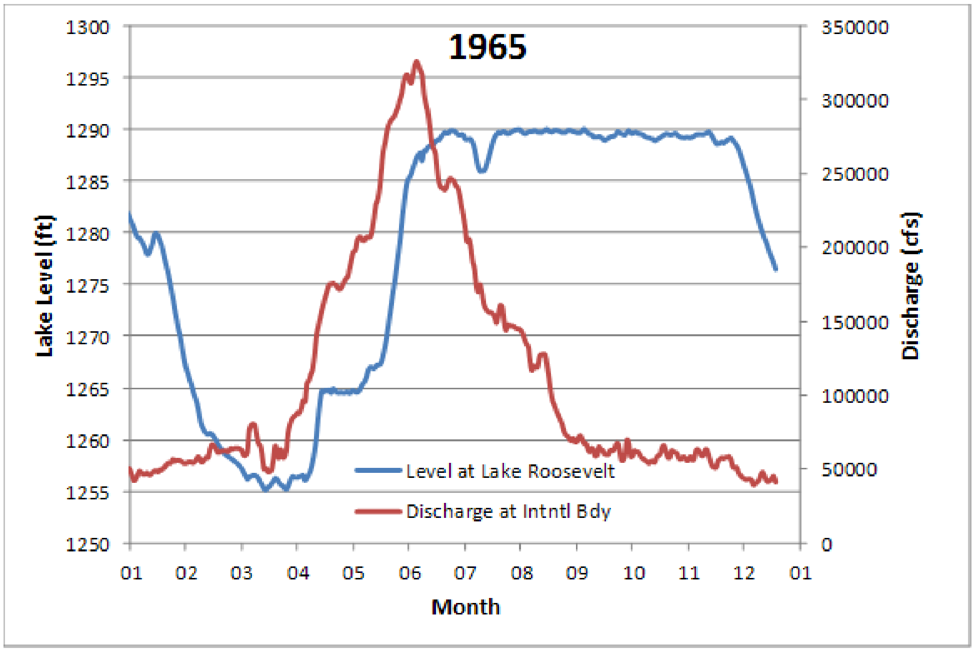


Figure 5: Time Line For the Upper Columbia River

Figure 6 shows the seasonal pattern of runoff and water levels in Franklin D. Roosevelt reservoir as determined from the published USGS records.



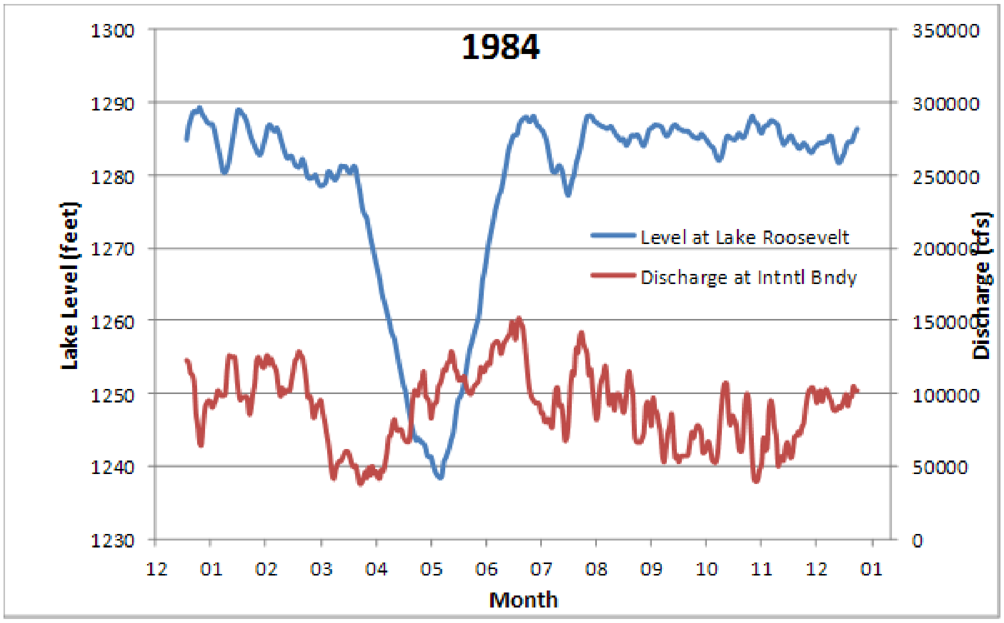


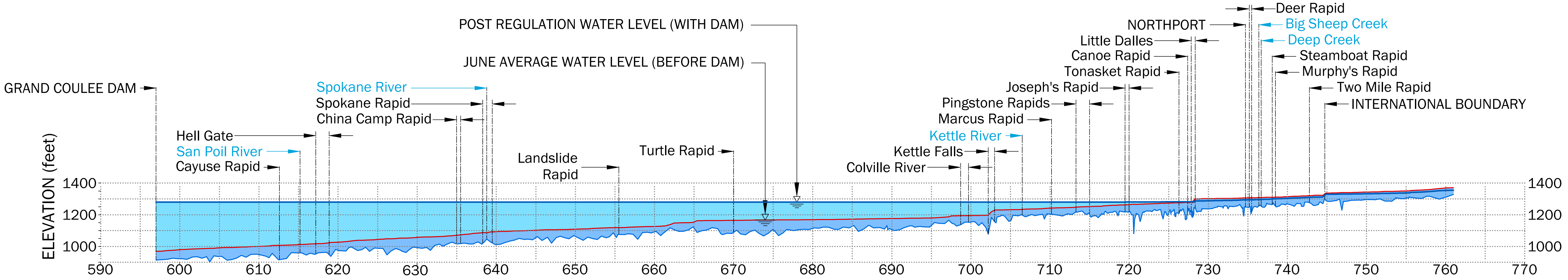
Figure 6: Monthly flow hydrograph and reservoir level, showing the difference between pre-regulation (1965) conditions and post-regulation (1984) conditions.

Appendix B documents the characteristics of the free-flowing Columbia River using archival sources, historic maps and terrestrial photos from the 1890's as well as from air photos of the river in 1931. We also consulted early descriptions of the river from Symons (1882) which described the particular challenges to navigability in this reach, Ball (1939), who filmed the river just prior to dam construction and Layman (2006) who compiled accounts from early map-makers and photographs from the 1890's to 1920's. Photos 1 to 6 (at the end of this main volume show the river in 1892 at several locations between Grand Coulee and the International Boundary.

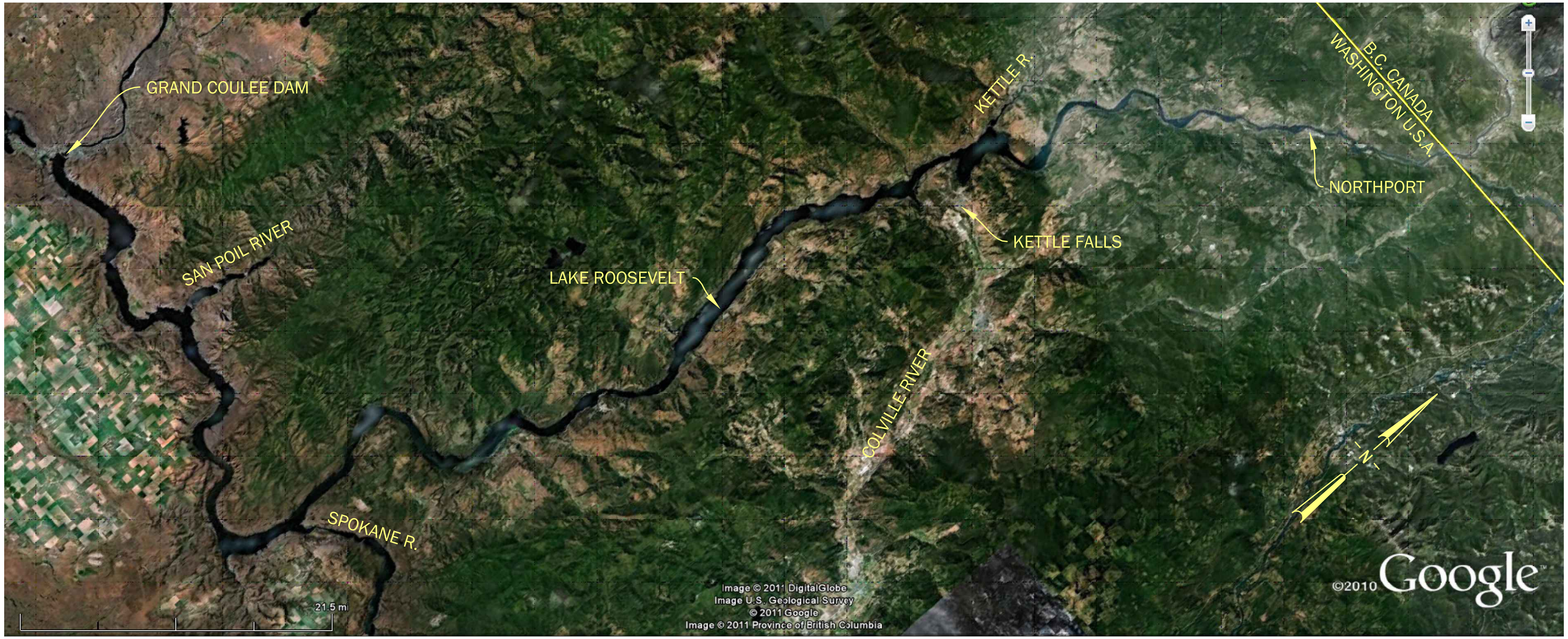
Figure 7 shows a longitudinal profile of the Columbia River from Grand Coulee Dam to the International Boundary using the topography in Bradley's HEC-RAS model (reported to be based on surveys from 1940's). The river bed dropped 356 feet from the International Boundary to Grand Coulee, which corresponds to an average slope of 0.00046 or 2.4 feet/mile. This slope is virtually identical to the free flowing section of the river in Canada between Trail and the International Boundary (McLean, 2010).

Table 2: Rapids on Upper Columbia River Before Grand Coulee Dam

Rapid	River Mile (Approximate)
Pen-Waw Bar	608
Cayuse Rapid	612
Hell Gate	619
China Camp Rapid	636
Spokane Rapid	639
Elbow Rapid	655
Landslide Rapid	666
Turtle Rapid	670
Gifford Rapid	675
Grand Rapid	696
Kettle Falls	705
Marcus Rapid	710
Pingstone Rapid	714
Nine Mile Rapid	715
Joseph's Rapid	720
Tonasket Rapid	726
Canoe Rapid	727
Little Dalles	728
Bishops Bar	733
Deer Rapid	735
Steamboat Rapid	738
Deadman's Eddy	738
Murphy's Rapid	739
Two Mile Rapid	743



COLUMBIA RIVER PROFILE
VERTICAL EXAGGERATION 105.6x



PLAN (NTS)

Figure 7: Profile of Upper Columbia River from Grand Coulee Dam to International Boundary

The historic air photos, ground photos and river surveys illustrate the tremendous power of the Columbia River prior to damming and upstream flow regulation. The river was frequently confined and flowing through bedrock and had a gravel and cobble bed, with frequent rapids and chutes. Table 2 lists 24 prominent rapids in a distance of 135 miles. Surveys in 1898 include the notation near Elbow Bend (River Mile 660) that the average current speed was 7.1 miles/hour or 10.3 feet/sec. In such rivers, sand, silt and clay sized sediment moves in suspension and behaves as “wash load”, meaning that these fine sediments are flushed through the channel in suspension without depositing in the main channel. The wash load sediments may settle out in back eddies, behind obstructions in slackwater areas along the banks or on the floodplain during major floods. In the case of wash load, the river’s transport capacity is much greater than the amount of sediment being supplied from upstream. This is significant because it means that if any mill tailings (which are mainly silt size) discharged into the Columbia River prior to Grand Coulee Dam would have behaved as wash load. Similarly, all of the LeRoi slag (which discharged into the river between 1898 and 1908) would have behaved as wash load.

2.2 GRAND COULEE DAM

Grand Coulee Dam is the largest dam constructed on the Columbia River and one of the largest dams in the world. The dam has an overall height of 550 feet and stores approximately 9.4 million acre-feet of water (Bureau of Reclamation Fact Sheet). According to Williams (1941): *“the altitude of the river at the Canadian border determined the height of Grand Coulee Dam, which raises the water 355 feet to 1,292 feet above sea level”*. Williams explained further (pg 754):

> *Since Grand Coulee Dam backs up the water to the Canadian boundary, one might think the flood damage in the upper valley would be increased. But our engineers, removing obstructions in the Little Dalles, have actually lowered the flood level.*

Figure 8 shows the changes that have occurred near the Little Dalles due to this blasting. Our recent survey comparisons of bed levels shows this excavation explains the bed lowering that has occurred upstream of the Little Dalles. The effect of the excavation is discussed further in Chapter 5, since it was not accounted for in the modeling that was carried out by Teck’s consultants.

The total storage volume of reservoir (V) is reported to be 9.4 million acre-feet. The average annual flow (Q) on the Columbia River is approximately 98,840 cfs. The average residence time (T_r) of the reservoir is defined as $T_r = V/Q$, which corresponds to approximately 47 days. This represents the average time a particle of water would spend travelling through the reservoir before being discharged through Grand Coulee Dam. The distance from Northport near the head of the reservoir to Grand Coulee Dam is about 138 miles. Therefore, the average speed of the water is 138 miles/47 days = 2.94 miles/day or 0.18 feet/sec.

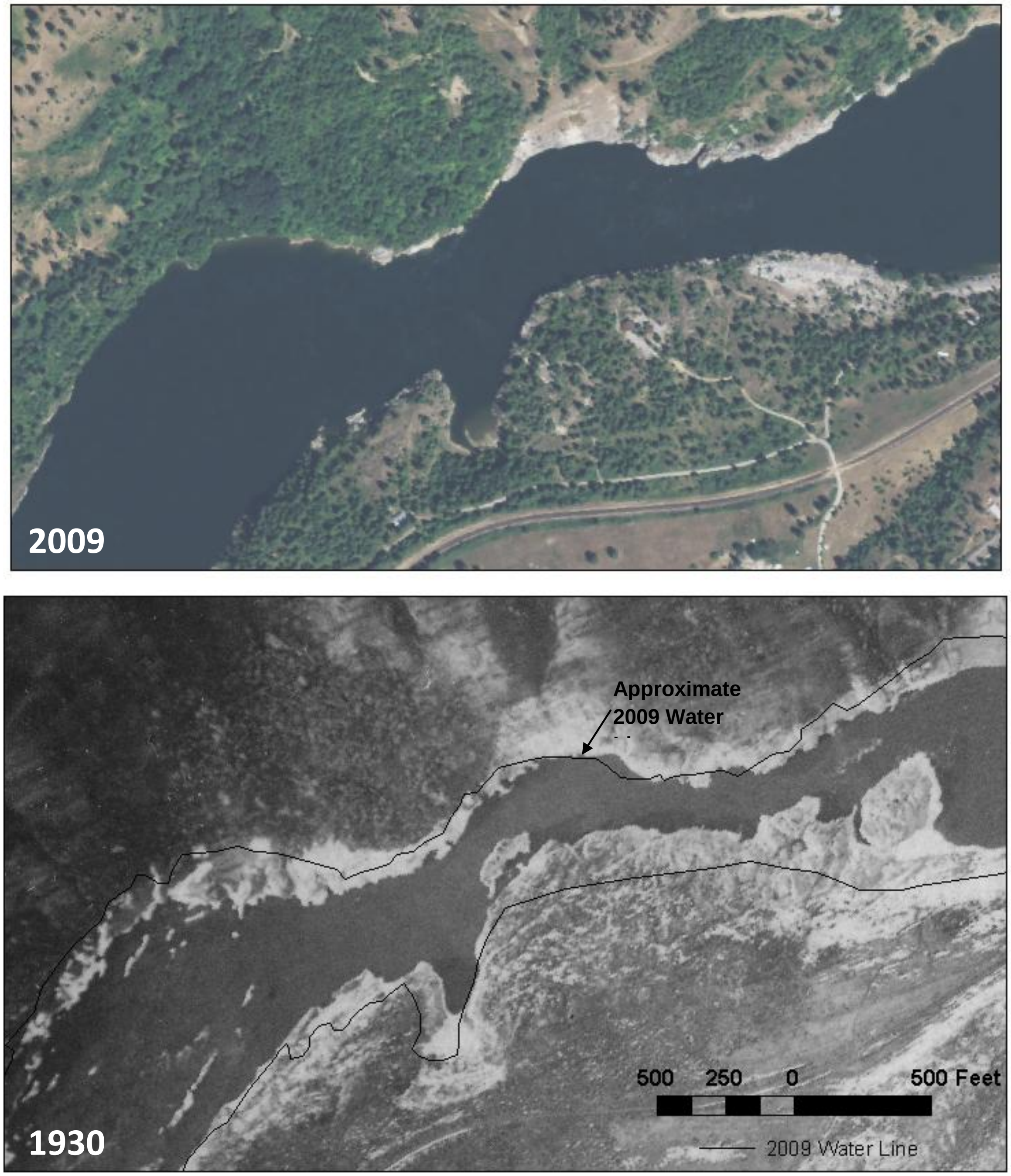


Figure 8. Aerial photos of the Little Dalles before and after channel modifications

2.3 SEDIMENTATION PROCESSES

2.3.1 SEDIMENT LOADS

The sediment load of the Upper Columbia River is low in comparison to many of the large river in North America due to the large number of major lakes and reservoirs in the watershed. Approximately 23 miles upstream of Trail, the Columbia River flows out of the Arrow Lakes. The Columbia River is joined by the Kootenay River 6 miles downstream, which drains out of Kootenay Lake. These two lakes effectively trapped virtually all incoming sediment from the two rivers. Subsequently, hydro dams were constructed on both the Arrow Lakes and Kootenay Lake, which has further increased their trap efficiency.

Water Survey of Canada (WSC) measured the suspended sediment concentration at Trail from 1965 to 1981 (but used discharge records further upstream at Birchbank and labeled the data as “at Birichbank” in their publications (see McLean, 2010). Some statistics from these measurements are given in **Table 3.**

Table 3: Summary of historical suspended sediment data - 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

The total suspended load varied from a high of 1,130,000 tonnes in 1967 (a high flow year) to a low of 209,000 tonnes in 1977 (a low runoff year) and averaged 491,000 tonnes. Since WSC measured the sediment loads from the bridge in the town of Trail, these measurements include the contribution from Teck's slag discharges. By comparison, the slag discharges to the Columbia River at Trail averaged approximately 170,000 t/year during the period 1966 to 1981 or about 35% of the river's annual suspended sediment load. Using a mean annual discharge of 70,600 cfs for the Columbia River at Trail and an average annual slag discharge of 170,000 t/year, the average concentration of slag would be 2.6 mg/l. By comparison, the average daily concentration was estimated to be 7.8 mg/l.

Water Survey of Canada did not measure the size distribution of the suspended sediment load, since the concentration values were very low. However, results from some miscellaneous sampling were made in 1995 (before slag discharges to the river ended) and 1999 (after slag discharges ended). The suspended sediment consisted of approximately 50% sand (2.00 mm to 0.063 mm) and 50% in the silt-clay range.

Miscellaneous suspended sediment measurements were reported by the USGS at Northport. The data were collected between 1976 and 1981, with typically 5 to 12 samples collected each year. Given the few number of samples collected per year, the USGS did not attempt to estimate the annual load. Figure 9 shows suspended sediment rating curve plots at Northport along with the upstream WSC data from Trail. The data shows the suspended sediment concentration at both sites does not correlate well with discharge. Instead, the suspended sediment behaves as "wash load", with the transport rate and concentration depending on the rate of supply, rather than on discharge or velocity. In this respect the Columbia River is "supply-limited", meaning it could carry much more sediment than is available as a result of watershed sediment production and anthropogenic inputs.

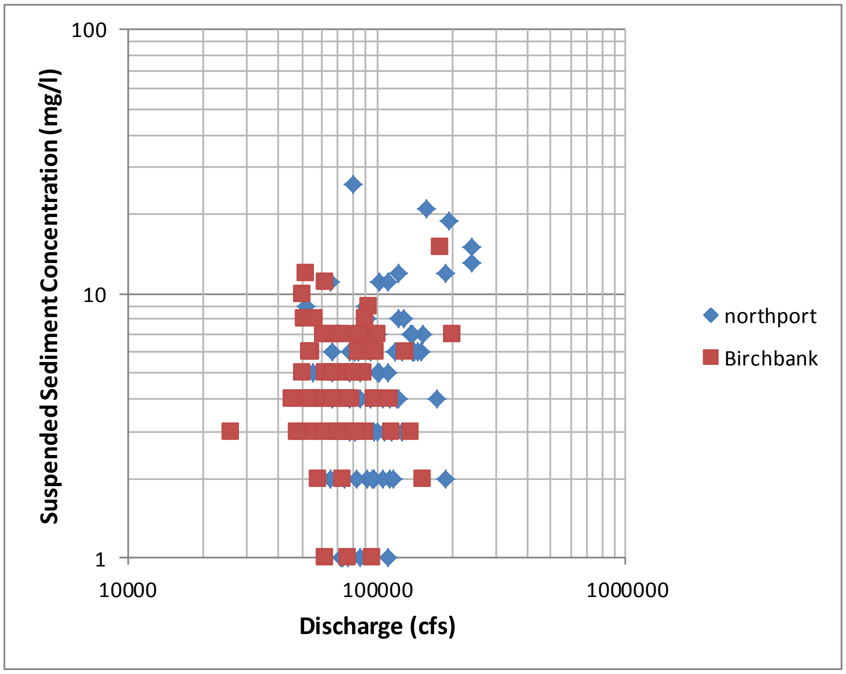


Figure 9: Suspended sediment rating curves at Northport and Birchbank (Trail)

The concentrations at Northport tend to cluster somewhat higher than at Trail for the same discharge. However, this may reflect several factors such as sampling methods as well as local sediment inflows.

2.3.2 SEDIMENT DEPOSITION IN LAKE ROOSEVELT

The Columbia River consists mainly of boulders, gravel and coarse sand in between Trail and the International Boundary (McLean, 2010). There is limited information on the grain size distribution of the river bed material downstream of the border and in the reservoir. Results from previous studies by CH2MHILL (2006) and Johnson et al (1990) are shown in **Figure 10** and **Figure 11** respectively. The samples by CH2MHILL were sub-divided into two fractions – **Figure 10** shows gravel, sand and fines < 75 µm. The distribution for the fraction smaller than 75 µm (silt, clay and colloids) were also analyzed.

These plots show the fines (silt and clay fraction) generally account for less than 10% of the sediments in the channel from River Mile 735 to around River Mile 700. Downstream of River Mile 700 the silt and clay fraction increases to between 70% and 100%. The fines consisted mainly (80%) of silt near River Mile 695, but the silt fraction decreased with further distance downstream. The clay fraction increased from about 20% at River Mile 695 to 40% at River Mile 600 near Grand Coulee Dam. These results show that the incoming sediment is selectively deposited in the downstream direction, with the sand and silt deposited near the upstream end (River Mile 690 to 735) and the finer silt and clay deposited nearer the dam.

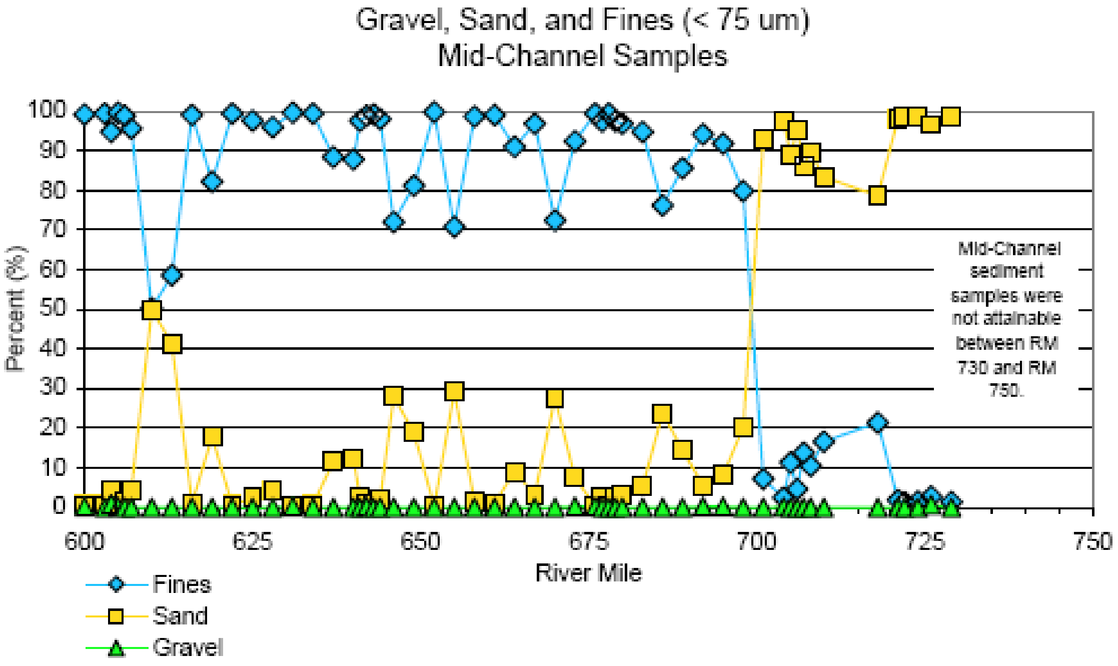
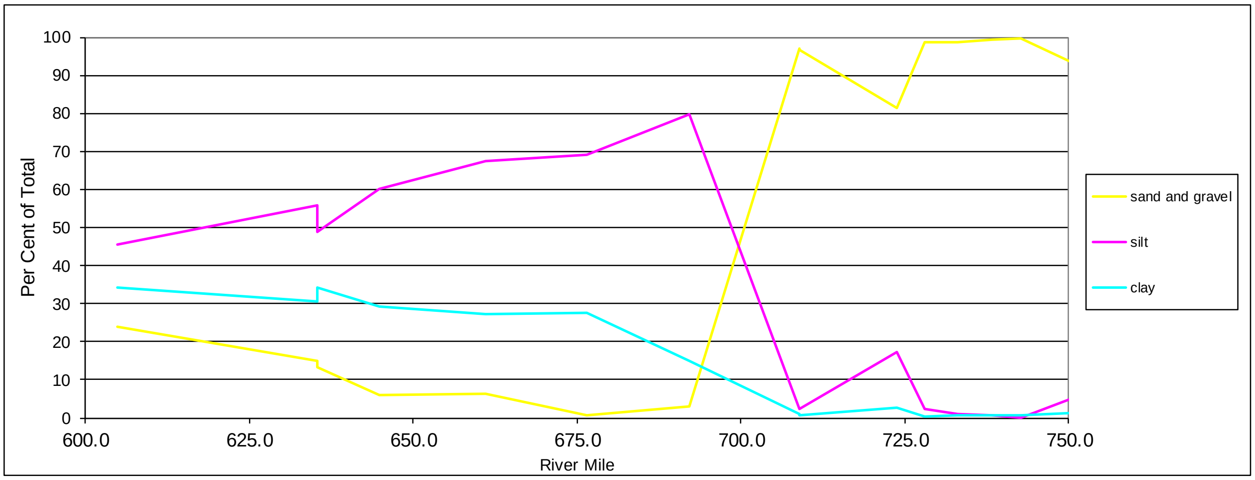


Figure 10: Distribution of sediment sizes along reservoir (CH2MHILL, 2006, Figure 5-8)

A similar overall pattern was documented by Johnson (1990), as shown in **Figure 11**.



From: Johnson et al (1990)

Figure 11: Distribution of sediment sizes along reservoir

Sand-sized slag particles are widely distributed in the river bed and along the banks of the upper and transitional reaches of Lake Roosevelt, particularly between the International Boundary and Northport. For example, Cox (2005) wrote: "*Slag particles make up from 70 to 90 percent by weight of the sand-sized particles of a black sand beach at RM 743 near the International Boundary. Particles of metallurgical slag have been found farther downstream in sediments of the Columbia River and Lake Roosevelt although easily identifiable slag grains diminish in number and size downstream of Northport".* Cox identified slag particles in cores situated in the middle section of the reservoir at River Mile 705, 692 and 668. NHC observed fine slag particles in the reservoir near River Mile 715 and 707 during site inspections in March 2011. Other recent studies by the US Geological Survey (Weakland et al, 2011) identified sand-size "black colored particles" in channel deposits near Marcus Flats (River Mile 705) and China Bend (River Mile 725).

3 REVIEW OF REPORT BY PROF. DUNNE

3.1 SUMMARY OF DUNNE'S OPINIONS

This report provided a general methodology for constructing a sediment budget of all major sources of sediment and associated metals entering the Upper Columbia River downstream of Trail, British Columbia before and after the impoundment of Lake Roosevelt behind the Grand Coulee Dam. A sediment budget is an accounting of the input, transport, storage, and export of sediment for a river basin, channel reach, lake, or other sedimentation system. Such a budget is necessary to account for the origin, amounts, and metal concentrations of sediments on the bed of Lake Roosevelt in its middle and lower reaches. In order to analyze the origin of sediments and associated metals on the bed of Lake Roosevelt it is necessary to conduct a comprehensive, quantitative accounting of all major sediment and metal sources within the watershed of the Upper Columbia River basin.

According to Prof. Dunne, the sediment budget approach to resolving the sources and disposition of contaminated and uncontaminated sediment in Lake Roosevelt would require estimation of the following quantities:

1. The annual supply and grain-size distribution of slag entering the Columbia at the Teck smelter site (I_{Teck}).
2. Average annual supply, grain size, and metal concentration of suspended sediment from the Columbia River upstream of Trail and from each major tributary before and after its impoundment (I_{US}).
3. Average annual supply rate, grain size, and metal concentration of sediment from all unimpounded tributary basins throughout the post-1930 period (I_{TRIB}).
4. Average annual supply rate, grain size and metal content of sediment from all major mine disposal sites that can be located in the tributary basins, and estimation of how much of the sediment entering the tributaries reached Lake Roosevelt before and after impoundment (I_{MINE}).
5. A minimum estimate of the sediment supply and grain sizes of sediment that has entered the lake from landsliding along its margin ($I_{Landslide}$).
6. The annual rates of sediment transport and deposition of sediment and metals from each of these sources along the Columbia River and Lake Roosevelt since 1930, and the mixing of sediments from the various sources. This calculation of sediment distribution would be accomplished with a well-tested computer model of flow, hydraulics, and sediment transport, such as HEC-RAS or SRH-1d, which Mclean (2010) employed (O and $\Delta S/\Delta t$).

Prof. Dunne did not conduct specific studies or analysis to implement this sediment budget assessment. However, a number of subsequent studies by others provided various components to each term in the sediment budget.

3.2 CRITIQUE OF PROF. DUNNE'S REPORT

I expressed Prof. Dunne's outline of the Upper Columbia River/Lake Roosevelt sediment budget in algebraic form as follows:

$\frac{\Delta S}{\Delta t}=I_{Teck}+I_{LeRoi}+I_{US}+I_{TRIB}+I_{MINE}+I_{LS}-O$ where (Equation 1)

ΔS is the quantity of sediments (or metals) retained in the reservoir in one year (Δt)

I_{Teck} is the annual discharge of slag from Teck's smelter at Trail

I_{LeRoi} is the annual discharge of slag from the LeRoi smelter near Northport

I_{US} is the annual discharge of natural sediment on the Columbia River upstream of Trail

I_{Trib} is the annual discharge of natural sediment from tributaries draining into the Upper Columbia River

I_{MINE} is the annual discharge of mill tailings and mine waste discharged into the Upper Columbia River

$I_{Landslide}$ is the annual sediment input to Lake Roosevelt from landslides

O is the annual quantity of sediment discharged downstream from the site.

These terms are included above in Prof. Dunne's list of components.

The accuracy of the sediment budget and its overall usefulness as a predictive tool depends on the uncertainties in each term of the budget. If the uncertainties are very large, the conclusions that can be drawn from the sediment budget may be meaningless. Therefore, although the methodology provided by Prof. Dunne may be sound, the practical results of the analysis depend on the assumptions and detailed calculations made by others responsible for each term in the equation.

Producing a quantitative sediment budget on a large river or watershed is a difficult task that requires a large amount of data collected systematically over periods of years to decades. I have developed and supervised several sediment budgets on the Lower Fraser River in southwest British Columbia (McLean and Church, 1999; McLean, Church and Tassone, 1999; McLean and Tassone, 1991; NHC, 2002; Ham, 2005; NHC, 2008). The lower Fraser River is similar in scale to the Upper Columbia River and experience with sediment budgets on the Fraser River is very relevant to the Columbia River. Developing sediment budgets requires a careful accounting of the errors and uncertainties in each term of the equation. This requires extensive field measurements to verify any assumptions in the analysis and to confirm the reasonableness of any predictions using sediment transport equations or sediment models. For example, the sediment budget on the lower Fraser River used systematic bed load and depth-integrated suspended load sampling by Water Survey of Canada that spanned a period of over 20 years. Repeat bathymetric surveys of the river channel were conducted several times over a period of 50 years and were used to provide independent estimates of sediment transport rates. Based on this experience we have found that where predictions from any sediment transport equations or models disagree with field evidence (which is frequently the case), the direct field evidence should take precedence.

Prof. Dunne did not provide any opinion on whether the available data on the Upper Columbia River was adequate for producing a quantitative sediment budget or whether additional data should be collected to supplement the existing data. The data required to produce a budget of just the sediment component (without considering the associated metal content) are very comprehensive and include:

- Hydrological data on the mainstem Columbia River and all major tributaries for the duration of the sediment budget analysis;
- Hydraulic, topographic and morphological data characterizing the stream channel network draining into Lake Roosevelt and the reservoir itself, preferably for a range of dates spanning the time interval of the sediment budget analysis;
- Bed material characteristics in the mainstem Columbia River, major tributaries and in Lake Roosevelt. Samples from the reservoir reach of the Columbia River prior to Grand Coulee Dam are also needed;
- Sediment yield and sediment transport data on the mainstem Columbia River and all major tributaries, preferably for a range of dates spanning the duration of the sediment budget.

3.3 SUMMARY OF FINDINGS

The accuracy of the sediment budget and its overall usefulness as a predictive tool depends on the uncertainties in the data and the assumptions made in the detailed analysis for each term in the budget. Based on my review of the available data and the actual analysis carried out by other Teck experts, I believe that the available information and data are inadequate to develop a reliable, quantitative sediment budget of the Upper Columbia River and Lake Roosevelt.

4 REVIEW OF REPORT BY A. BROWN, P.E.

4.1 SUMMARY OF BROWN'S OPINIONS

Brown estimated mine waste and tailings discharged from mines and mills located on State lands and estimated the quantities retained in Lake Roosevelt using mine information supplied by Bull (2011) and airphoto interpretation carried out by Grip (2011). The computed sediment loads from the mine waste rock and mill tailings were adopted as inputs to the sediment modeling results by Bradley (2011) and the subsequent estimates of metal loadings to Lake Roosevelt made by Johns (2011).

4.1.1 BROWN'S OPINION ON MILL TAILINGS

Brown offered an opinion on the mass of mill tailings retained in Lake Roosevelt from eight mines and mills from Ferry, Stevens, and Pend Oreille Counties. The main steps in Brown's analysis were as follows:

1. The mass of tailings generated each year was compiled using results from Bull (2011).

2. The mass of tailings discharged from each facility into streams draining the site was estimated.

3. The transport of discharged tailings from the mill site to Lake Roosevelt was then estimated. Three mills (Grandview-Metaling, Josephine and Pend Oreille) accounted for over 90% of the estimated mass. Tailings from these mills were discharged into the Pend Oreille River, which has been regulated by a series of hydroelectric dams since 1952. The amount of sediment trapped behind the dams was estimated using a trap efficiency equation developed by Churchill (1948). For times before the dams were constructed it was assumed 100% of the mill tailings was transported through the stream network to Lake Roosevelt. Similarly, for other mill sites located on streams that did not have dams, it was assumed 100% of the sediment was discharged to Lake Roosevelt.

4. The amount of mill tailings deposited in Lake Roosevelt was estimated using the Churchill (1948) equation. Estimates of sediment trapped in the reservoir were also made by Bradley (2011).

5. The mass of metals in tailings sediment trapped in Lake Roosevelt was computed by multiplying the mass of tailings deposited in the reservoir by the metal concentration in the tailings.

Brown estimated 9,299,314 tons of tailings was deposited as sediment in Lake Roosevelt (Table 1 main report pg. 4).

4.1.2 BROWN'S OPINIONS ON MINE WASTE ROCK

Brown offered opinions on the erosion and transport of mine waste rock from 487 different mines in the Upper Columbia River watershed that cumulatively produced 38,867,040 tons of ore and 65, 782,428 tons of waste rock. He estimated the amount of erosion from the waste using the Universal Soil Loss equation. The quantity of sediment produced each year was then routed through the stream network, rivers and reservoirs to Lake Roosevelt using the same methodology as in the tailings analysis. The mass of material derived from erosion of mine waste rock deposited in Lake Roosevelt was estimated to be 454,000 tons (Table 2 main report pg. 11).

4.2 CRITIQUE OF BROWN'S OPINIONS

4.2.1 OVERVIEW

Brown used oversimplified methods and assumptions without carrying out any independent checks or verification of his predictions of sediment discharges into the Columbia River. The reliability of the sediment discharges should be considered as "order of magnitude" estimates at best and most probably over-estimate the actual sediment inflows. Three main deficiencies in the analysis were identified, including:

- The use of the Universal Soil Loss equation (USLE) to estimate sediment loads from erosion of mine waste rock;
- The assumptions and methodology used to route sediment loads produced at the mine/mill sites through the tributary stream network down to the Columbia River;
- The method for estimating the trapping of sediment from the various dams on the Pend Oreille River (Waneta Dam, Seven Mile Dam, Boundary Dam and Box Canyon Dam) as well as in Lake Roosevelt.

4.2.2 RELIANCE ON OTHER EXPERTS

Brown relied on other experts such as Grip who provided opinions on the occurrence of mine waste adjacent to mines and mill sites and as well on the likelihood of transfer by water through the local drainage network to the Columbia River. It was incorrect to assume that all waste discharged to land would be transported to the Columbia River. The amount of sediment that could be transported will depend on the amount of runoff and details of the stream network. Furthermore, there are intermediary storage zones on the bed, in channel bars, and on the floodplain which trap a fraction of the waste sediment before reaching the Columbia River. Also, vegetation can develop on sedimentary deposits, stabilizing the deposits and preventing further erosion. This issue is discussed further in Section 4.2.4.

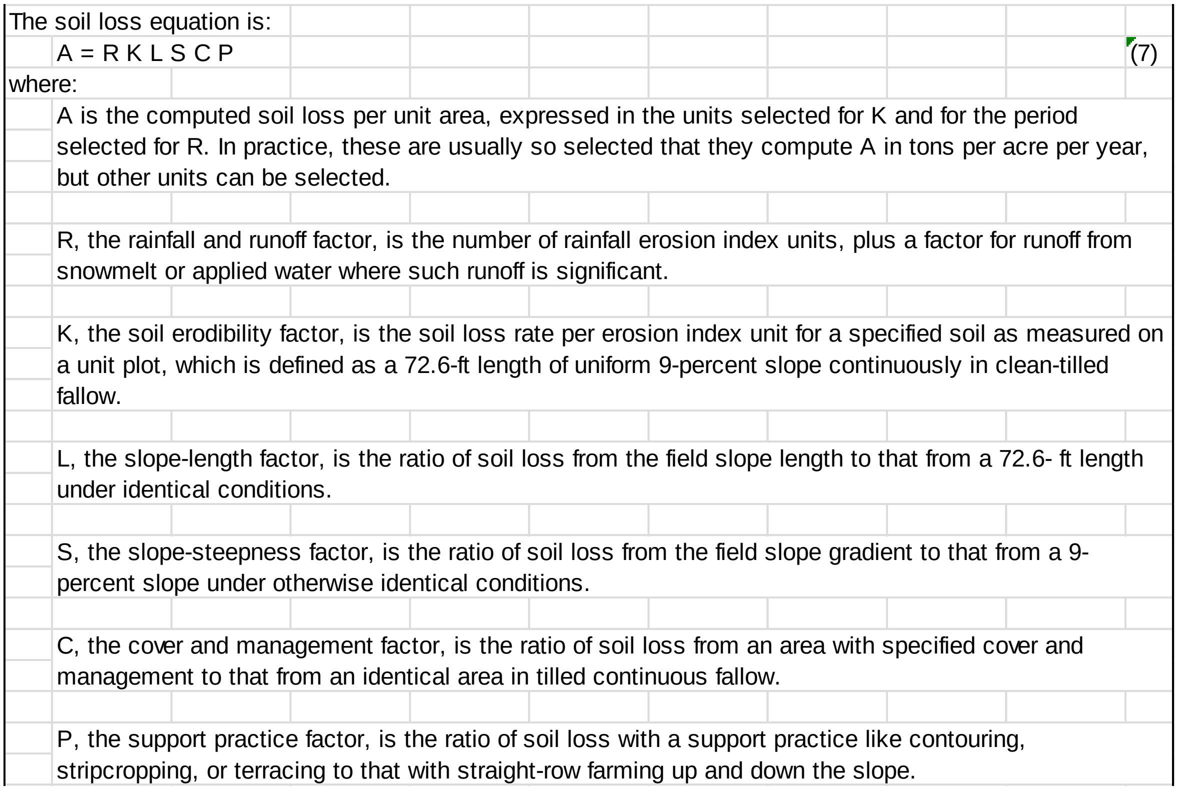
4.2.3 LIMITATIONS OF THE UNIVERSAL SOIL LOSS EQUATION

Oversimplified Representation of Mine Sites in the Region

Estimates of mine waste erosion were made using the simple Universal Soil Loss equation . The relation (extracted from Brown's spreadsheet) is reproduced on the following page. This equation was developed for assessing soil loss on agricultural fields and to assess the effects of various cropping patterns on soil loss. The sediment erosion rate determined by the USLE depends on six parameters. However, the equation was simplified and reduced to a single variable. Brown converted the USLE equation to express the sediment load (S in tons/year) generated by the erosion of the waste rock at each of the 487 mine sites. His equation was expressed in terms of only one parameter - the quantity of waste rock (W) generated by the mine (expressed as tons/year):

$$S = 0.032814\ W^{0.763571} \qquad \text{(Equation 2)}$$

Therefore, the soil, topography, rainfall, vegetation, slope, land cover and local site conditions at all 487 mines was assumed to be identical. No site specific surveys, soil particle size measurements, runoff measurements or sediment measurements were presented to justify such a critical assumption.



The soil loss equation is:

$$A = R\ K\ L\ S\ C\ P \qquad (7)$$

where:

A is the computed soil loss per unit area, expressed in the units selected for K and for the period selected for R. In practice, these are usually so selected that they compute A in tons per acre per year, but other units can be selected.

R, the rainfall and runoff factor, is the number of rainfall erosion index units, plus a factor for runoff from snowmelt or applied water where such runoff is significant.

K, the soil erodibility factor, is the soil loss rate per erosion index unit for a specified soil as measured on a unit plot, which is defined as a 72.6-ft length of uniform 9-percent slope continuously in clean-tilled fallow.

L, the slope-length factor, is the ratio of soil loss from the field slope length to that from a 72.6- ft length under identical conditions.

S, the slope-steepness factor, is the ratio of soil loss from the field slope gradient to that from a 9-percent slope under otherwise identical conditions.

C, the cover and management factor, is the ratio of soil loss from an area with specified cover and management to that from an identical area in tilled continuous fallow.

P, the support practice factor, is the ratio of soil loss with a support practice like contouring, stripcropping, or terracing to that with straight-row farming up and down the slope.

Eroded Mine Waste Assumed to Continue to Contribute to Sediment Discharges

Brown computed the annual mass of sediment discharged at each mine from the cumulative annual waste quantities produced over the life of the mine. He summed the annual sediment loads to estimate the total sediment quantity generated over the mine's operation. This approach overestimates the total sediment load produced over the time period since it does not account for any reduction in the mass of the waste pile due to the removal of material by previous erosion. In other words, sediment that had been eroded away from the waste pile was still assumed to be contributing to new erosion from the site. My review of the spreadsheet results indicated this erroneous assumption can lead to overestimating the sediment load by up to 34%.

Inappropriate Use of Universal Soil Loss Equation

The Universal Soil Loss equation (USLE) was originally developed for estimating the effects of various agricultural practices and cropping patterns on soil loss or erosion on farm land in the central and eastern United States. The estimated soil loss from the USLE is the average value for a typical year, and the actual loss for any given year may be several times more or less than the average rate. The equation estimates the amount of soil eroded from a slope (critical for farmers concerned about loss of topsoil), but this quantity is not the same as the sediment yield or the actual sediment load transported in stream channels or rivers. Soil erosion or soil loss is not the same as sediment yield. Eroded soil may be re-deposited a few inches from where it was dislodged (USACE, 1989 pg. 3-1). This difference is important since much of the sediment that is eroded from a particular slope will be re-deposited in swales or at the base of slopes or on floodplains or other intermediate sediment storage zones in the landscape. The ratio between the actual sediment load transported in a channel and the total material eroded is termed the sediment delivery ratio. Depending on the site specific characteristics of the drainage network and the sediment sources, the sediment delivery ratio can vary between 0 and 1.

Using the Universal Soil Loss equation to estimate sediment loads generated from mine rock waste is not appropriate, nor is it likely to produce reliable predictions of actual sediment loads into the surrounding river system.

A reliable method to estimate the amount of sediment that was transported from the sites in streams and rivers is by direct sediment measurement using accepted standards as developed by agencies such as the US Geological Survey (Guy, 1970, Chap. C1; Porterfield, 1972 Chap. C3; Edwards and Glysson, 1999 Chap C2). The US Army Corps of Engineers (USACE) manual on sedimentation analysis also emphasised the importance of using direct field measurements of sediment yield and sediment transport rather than predictions from computational methods. In discussing methods of estimating sediment yield the following advice was provided:

> *The large variety of sediment yield methods can be placed into two broad categories-methods based on direct measurement and mathematical methods. Only those based on direct measurements are considered a rigorous approach; mathematical methods are trend indicators at best. (USACE, 1989 pg. 3-3).*

Improved Techniques For Estimating Sediment Discharges Were Not Used

Recently there has been considerable effort to develop better methods for estimating sediment yield and sediment loads generated by land erosion. One development has been to replace the Universal Soil Loss Equation with a Revised Universal Soil Loss equation (RUSLE) that accounts for sediment delivery in order to directly compute sediment yield rather than soil loss. Another development has been to use GIS-mapping tools to characterize the sediment source areas and the entire watershed topography and stream network through which the sediment is routed. Examples of erosion and sediment yield models include KINEROS and SWAT (Flanagan et al, 2002, Flynn and van Liew, 2009, EPRI, 2001, Summer, 2002). These numerical methods still require extensive field data (both runoff and sediment loads) for model calibration and verification. For example, Flynn and van Liew (2009 pg. 68-75) describe the effort to develop a calibrated SWAT model for predicting sediment loads and sediment yield from the Lamar River, a tributary of the Yellowstone River in Yellowstone National Park. The work involved two years of calibration measurements and four years of measurements for model validation. This is an indication of the level of effort required to develop reasonably accurate estimates of sediment loads produced in a relatively simple stream network. The methodology, data and analysis that were used to estimate the sediment inputs from mine waste rock and mill tailings are not comparable to the current state of the art practice by hydrologists and sediment transport specialists.

4.2.4 ESTIMATING SEDIMENT LOADS SUPPLIED TO COLUMBIA RIVER

Sediment loads generated by the 487 mine waste rock sites and mill tailings were assumed to be transported through the stream network to the Columbia River. Only the trapping effect of dams on the Pend Oreille River was accounted for using a simple trap efficiency relation. For all other cases, all of the sediment generated at the mine/mill sites was assumed to reach the Columbia River.

Inadequate Assessment of Sediment Routing From Mine to Columbia River

Sediment generated at a site in the Upper Columbia River watershed is transported through a network of stream channels and is subject to interruption and deposition due to storage in channel bars, slackwater areas along channel margins, pools and floodplains, infiltration and trapping in the bed of coarser bed sediments. All of these processes attenuate and alter the sediment loads and need to be assessed on a site by site basis.

No hydraulic or sediment transport analysis or direct field measurements were used to characterize the sediment routing from the mine waste sites to the Columbia River. For example, no measurements of particle grain size were presented at any of the tailings or mine waste sites, yet the sediment particle size is a critical parameter for quantifying any erosion or sediment transport process. Furthermore, no detailed assessment was made along any of the streams between the mine sites and Lake Roosevelt. Accepted hydraulic engineering practice would require collecting a range of basic data such as stream profiles and representative stream channel cross sections, as well as observations on channel morphology and bed material characteristics (grain size from gravel bars and banks) and sediment transport data (suspended sediment load and size distribution of the sediment load and bed load). Furthermore, in order to make realistic predictions about the transport and fate of sediment entering the stream network, an accepted hydraulic engineering analysis would include characterizing the stream hydrology, estimating hydraulic characteristics using a 1D hydraulic model (such as HEC-RAS), estimating sediment transport characteristics for each grain size fraction of the sediment inputs using a standard model such as SRH-1D or HEC-RAS. Also, specific geomorphic investigations are required to identify any local sediment deposition zones such as back eddies, channel margins and slack water areas along the channels. These standard techniques were all used in McLean (2010) to define the transport and fate of slag from Trail to the International Boundary. In my opinion, the same standard should be applied to the analysis of tailings and mine waste transport down tributaries to Lake Roosevelt.

Limitations of Brown's Method - Example of Midnite Mine

Brown's analysis purported to show that Midnite Mine in Stevens County accounted for 41% of the total quantity of mine waste rock discharged into the Columbia River. Therefore, Brown's estimate of total waste rock discharge relies to a large part on his assumptions of transport from Midnite Mine to Lake Roosevelt.

Brown assumed that all the mining waste (and associated metals) eroded from the mine site was transported down the channel network to Lake Roosevelt. We have reviewed the basis for these pathway / transport assumptions. This simplistic analysis does not consider whether the eroded material is even directly coupled to a channel segment, the size of the material, or intermediate deposition on the channel bed, bars, floodplain or backwater zones. The following assessment examines the potential for waste rock eroded from Midnite Mine to have come to be located in Lake Roosevelt. Midnite Mine is an inactive open-pit uranium mine located in the Blue Creek watershed, a small tributary basin that directly drains to Spokane Arm of Lake Roosevelt (**Figure 12**).

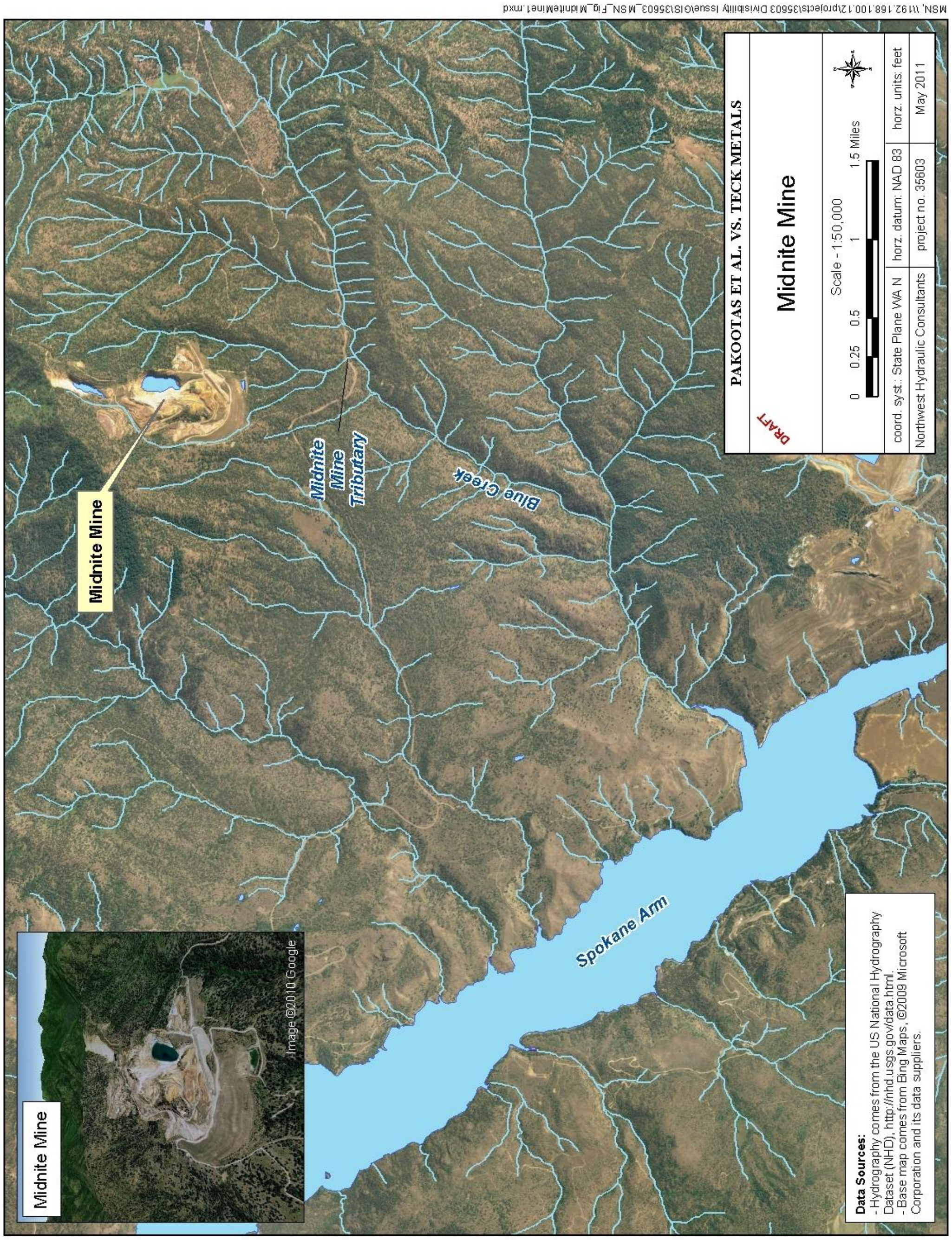


Figure 12: Location of Midnite Mine

According to EPA (2010) records, waste rock dug from six pits was dumped in piles and used to backfill pits, build haul roads and contour the surface and open pits, while backfilled pits and waste rock piles remain on site. It is also noted that two pits contain water collected from several seeps, including surface water runoff, but some seeps and groundwater emerge in three small intermittent tributaries to Blue Creek that collectively form Midnite Mine drainage. Brown does not make any inferences about the grain size distribution of the material transported from the mine site to Lake Roosevelt. However, given his assumption that all material is transported through every channel network to Lake Roosevelt implies that he assumes the material is very fine and travels in suspension. There is information on the nature of stored waste material based on results of geotechnical investigations by URS Corporation (2002) for the US EPA that Brown does not consider in forming his opinions. The URS study found that waste rock piles consisted mostly of coarse sand and gravel material, including cobbles and boulders. The fine fraction (silt and clay) at individual sampling sites ranged between 1% and 49%.

Midnite Mine drainage has been continuously gaged by the USGS since 1984 (USGS 12433556). The watershed drains an area of 1.3 square miles with an estimated slope of roughly 8% between the gage and the base of the south spoils 3900 feet upstream. Channels with this gradient typically exhibit a step pool morphology (Church, 1992). Step pool channels are generally stable and transport mainly finer materials during more frequent discharges, and larger material only during exceptional flows (Montgomery and Buffington, 1997). Mean daily discharge ranges from 0.1 to 1 cubic feet per second and peak flows exceed 3 cubic feet per second only 0.06% of the record (Church et al., 2008). The three intermittent tributaries, therefore, would normally convey roughly 0.033 to 0.33 cubic feet per second of flow each, and rarely, more than 1 cubic foot per second. These minor flows would have little capacity to convey the coarser sediment found in the waste piles. Geochemical sediment samples collected from Midnite Mine tributary in 1975 (reported in Church et al., 2008) describe the deposits as sand and silt which confirms the supposition that these small intermittent channels do not mobilize and transport the coarser sand and gravel material that makes up much of the mine waste.

The available USGS gage data includes measurements of stream velocity, water depth and channel width (Figure 13) for the Midnite Mine tributary gage), which is basic essential hydraulic information but Brown did not use any of this information in his analysis. The measurements can be used to calculate initiation of motion for particles and should be used to form an opinion on whether the flow in the stream is sufficient to transport the range of sediment sizes that exist. Since Brown (2011) did not consider the sediment or flow information that is available, his opinion that all the mine waste that is eroded is transported to the Upper Columbia River is not substantiated.

Midnite Mine tributary discharges into Blue Creek about 5.65 miles upstream of Spokane Arm and drains an area of 6 square miles. Blue Creek has also been gaged since 1984 by the USGS (gage 12433542). At the gage, the mean annual flood is nearly 12 cubic feet per second. The channel remains steep (2.6%) though considerably less than Midnite Mine tributary. Channel morphology cannot be discerned from available imagery, but likely conforms to a step-pool morphology with occasional rapids and riffles given the known gradient (Montgomery and Buffington, 1997). Minor accumulations of bars may be present, and the channel is also described as having a floodplain and delta (Church et al., 2008). The existence of a floodplain, and particularly a delta, provide definitive evidence that much of the finer material transported from the mine waste piles is trapped and does not reach Lake Roosevelt at all as Brown opines.

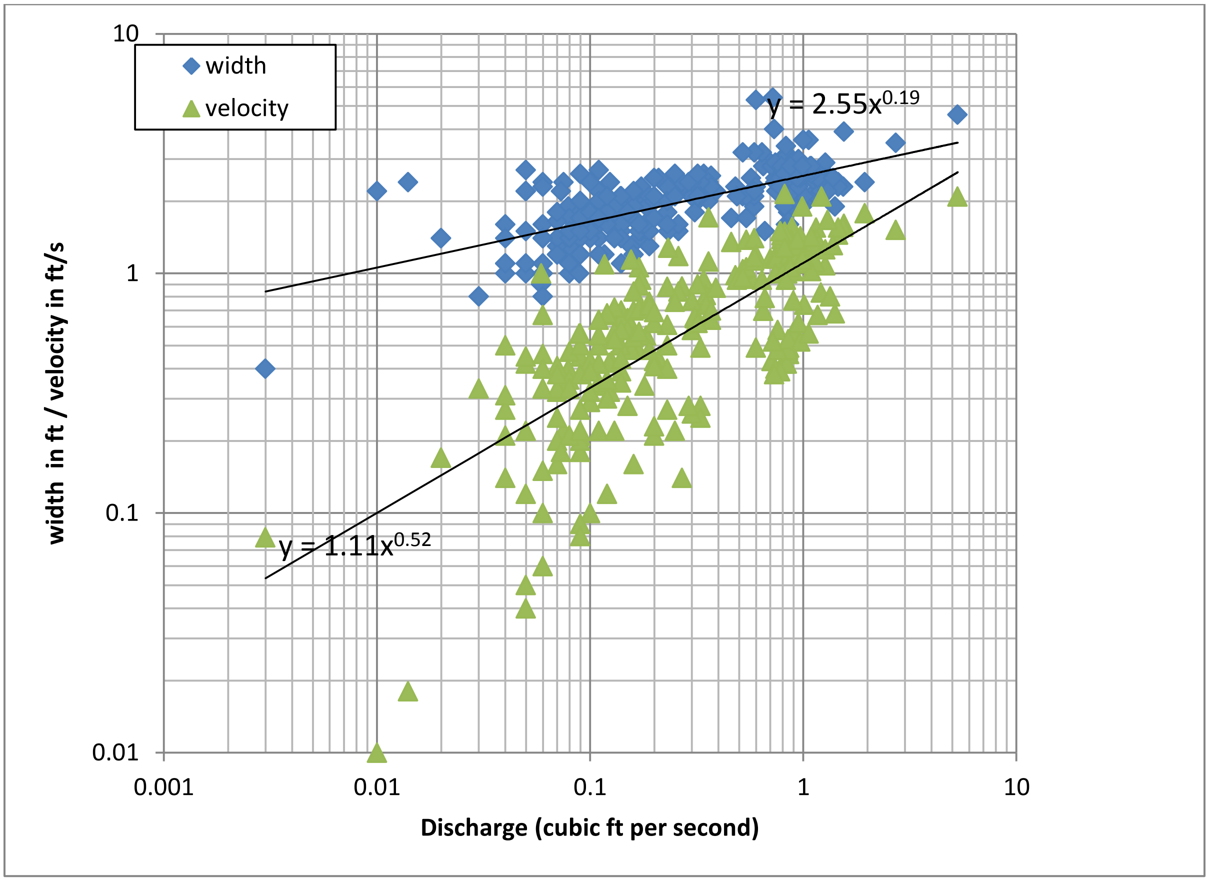


Figure 13: USGS hydraulic measurements that were ignored in Brown's analysis of Midnite Mine

Figure 14 shows photographs of the dominantly finer material found at the delta. More definitive evidence of this fact is provided from core samples obtained by Church et al. (2008) from one site on Midnite Mine tributary, two sites on Blue Creek downstream of the tributary confluence, and four sites on Blue Creek delta. Photographs and descriptions of these cores clearly indicate mainly fine grained sediments ranging from silts to medium sands, not coarse sands and gravel that dominate the material found in the waste rock piles that remain at the site. This again confirms that a substantial fraction of the waste material is deposited along the stream channel and is not transported downstream.

Figure 14: Sediment deposition and delta formation on Midnite Mine tributary creek indicating sediment transport is reducing along the stream.

4.2.5 TRAP EFFICIENCY CALCULATIONS

Simple Trap Efficiency Equations Do Not Account For Sediment Size

Using a simple trap efficiency relation such as Churchill (1948) is not sufficient to reliably estimate the amount of waste rock and tailings retained behind dams on the Pend Oreille River. This empirical equation was developed from observed rates of sedimentation on reservoirs operated by the Tennessee Valley Authority and does not explicitly account for the size of the sediments being transported. The method is only valid for rivers having similar sediment properties as the sites that were used to develop the equation. Vanoni (1977) pg. 590 reviewed two empirical trap efficiency equations (Churchill and Brune) and concluded:

Neither includes an analysis of sediment characteristics, and possibly for that reason some sedimentation specialists prefer to simply use a judgement factor.

No data were provided to suggest that manmade mine waste rock and tailings were similar to sediment produced by natural watershed processes. As shown below in Table 4, the particle size is a critical parameter in determining the settling characteristics of sediments in a reservoir. The particle size (D) transported in a natural river may include a very wide range of materials, including gravel (sediment coarser than 2 mm), sand (2.0 mm to 0.063 mm), silt (0.063 mm to 0.004 mm) or clay (finer than 0.004 mm). The particle settling velocity (w) is a measure of the rate at which sediment will fall through a water column. The values shown in column 3 and column 4 of Table 4 are taken from Vanoni (1977) pg. 25 Figure 2-2. The settling time (Ts) shown in column 5 and6, was calculated to indicate the time required for particles to settle out in a 50 feet deep reservoir (Ts = 50/w). These calculations simply show that the time required for sand particles to settle out is a small fraction of the time for silt particles. Therefore, the particular grain size characteristics of the sediment being transported into the reservoir needs to be properly represented and analyzed.

Table 4: Variation in settling velocity and settling time with particle size for a reservoir 50 ft deep.

Sediment	D (mm)	ω (cm/sec)	ω (feet/sec)	Ts (sec)	Ts (hours)
Gravel	10	75	2.46	41	0.01
Very coarse sand	2	27	0.89	113	0.03
Coarse sand	1	14	0.46	218	0.06
Med sand	0.5	7	0.23	435	0.12
Fine sand	0.25	2.7	0.089	1129	0.31
Very fine sand	0.1	0.65	0.021	4689	1.3
Coarse silt	0.062	0.31	0.010	9832	2.7
Medium silt	0.05	0.2	0.0066	15,240	4.2
Fine silt	0.016	0.018	0.00059	169,333	47.0

Hydraulic models such as SRH-1D were developed by the US Bureau of Reclamation to overcome the deficiencies of the simple empirical trap efficiency equations. A model such as SRH-1D uses the hydraulic characteristics in the reservoir to estimate the transport rate and deposition for each grain size fraction in the incoming sediment load. Since no grain size analysis was available at any of the sites or in the stream channels or the reservoirs, there is no way to accurately determine the amount that would be retained.

Inadequate Hydraulic Analysis of Reservoirs on Pend Oreille River

Brown did not make use of bathymetric surveys of the reservoirs or published reservoir storage volume – water level relations that have been prepared by the dam operators. This information is required to make reliable estimates of the mean velocity and residence time, which are needed for making accurate predictions of the trap efficiency. For example, the volume of Seven Mile Reservoir is estimated in Brown's spreadsheet Sedimentation-5.xls (row 124) to be 56.875 million cubic metres. The published reservoir volume (Canadian Dam Association, 2003) is 104 million cubic metres, nearly double, which means that Brown underestimated the actual trap efficiency.

Incorrect Analysis of Sediment Trapping in Lake Roosevelt

Eroded waste rock sediment and mill tailings were then assumed to be transported through the stream network until reaching Lake Roosevelt. The trap efficiency of Lake Roosevelt was estimated to be 80%. This value was used for all dates back to 1901 in the spreadsheet “Mine Waste Rock Sediment-20.xlsx, sheet 8 SED IN LR”. Filling of Lake Roosevelt due to construction of Grand Coulee Dam commenced in 1940. Therefore, assuming Grand Coulee Dam was in-place in 1901 over-predicted the amount of waste rock deposited in the reservoir.

4.3 SUMMARY OF FINDINGS

Brown used very oversimplified assumptions and methods to estimate the sediment discharges from mill tailings and mine wastes retained in the Columbia River. No actual field measurements or site specific surveys were used to calibrate or verify any of the computations and no site specific data or surveys was used to route the sediment through the drainage network from its source to the Columbia River. The methodology, data and analysis that were used to estimate the sediment inputs from mine waste rock and mill tailings are not comparable to the current state of the art practice by hydrologists and sediment transport specialists.

5 REVIEW OF REPORT BY DR. J. BRADLEY, P.E.

5.1 SUMMARY OF DR. BRADLEY'S OPINIONS

Dr. Bradley used a one dimensional sediment model (HEC-RAS) to assess the transport and deposition of slag, mine waste rock, mill tailings and natural sediments in Lake Roosevelt. Bradley stated he adapted an existing HEC-RAS hydraulic model that was initially developed by Hydro-Qual. Bradley produced a different model for each sediment type or source and then "aggregated" the results in order to assess the spatial distribution of sediment deposition. Bradley pg 13 listed the different models that were run:

1. Teck slag model – Extent: Birchbank to Grand Coulee Dates: 1930-2009

2. LeRoi slag model – Extent: Northport to Grand Coulee Dates: 1898 – 2009

3. Tributary Tailings models-Dates vary
   a) Pend Oreille River to Grand Coulee
   b) Deep Creek to Grand Coulee
   c) Onion Creek to Grand Coulee
   d) Young American Mill: RM 715.5 to Grand Coulee

4. Natural sediment model – Extent: Birchbank to Grand Coulee – Dates 1898-2009

In addition to these, a separate model was run which addresses the transport of finer materials (<0.064 mm).

Input data for the models included observed and synthesized stream flow records for the mainstem and some tributaries, river temperature, sediment properties (grain size and specific gravity) and channel topography (in the form of river cross sections). Bradley stated the bathymetry for the river was based on surveys by the US Coastal and Geodetic Survey in 1947-1949 along with more recent surveys of the floodplain. The origin of the topography along the Canadian portion of the river was not described. The Hydro-Qual model provided to NHC and described in Wands (2011) did not extend into Canada so the source of this data is unknown.

Bradley made several critical assumptions in the modeling:

- A "zero depth of scour" condition was applied for the entire reach of the river, which prevents the channel from lowering below its initial bed level;
- He assumed the Laursen sediment transport function was an accurate predictor of sediment transport for both the natural free-flowing river and in the reservoir.
- He relied on Brown's estimated sediment inflows to the Columbia River and Lake Roosevelt from mine rock waste and mill tailings sources.
- On pg. 19 he stated "Sediment loads for the Birchbank, Pend Oreille, and Spokane Rivers were estimated from measured suspended sediment load data from USGS sties". Presumably, Bradley meant the Columbia River at Birchbank, in this statement, which is a Water Survey of Canada gage site (08NE049)

located just upstream of Trail, British Columbia. Bradley relied on this data to establish the upstream boundary condition for his natural sediment model.

- Tributary sediment loads for the natural sediment model were estimated from a regional analysis of reservoir sedimentation rates using data from eight sites in Washington and Idaho. The grain size of the tributary sediment loads was based on soil surveys information in Ferry and Stevens County.

Bradley's opinions are given on page 49-66 of his report and are summarized briefly below.

Bradley predicted that 84% of the total slag mass entering at Trail was transported downstream across the International Boundary into the United States (located at RM 745) and 16% was retained in Canada. Of the material that was transported across the border, a large percentage of the slag deposited upstream of RM 720. The amount of Teck slag deposited downstream of RM 700 was minimal in comparison to the total deposits from other sources.

Bradley input over 2 million tons of LeRoi slag to the Columbia River between 1898 and 1909 and 400,000 tons of slag between 1916 and 1921 (all before Grand Coulee Dam). He reported that 41% of the total LeRoi slag passed the Grand Coulee boundary by 1940, which implies that 59% of the total LeRoi slag was deposited in the river channel upstream of Grand Coulee Dam site.

Bradley input 296,461 tons of mill tailings into the Columbia River from the Pend Oreille River, on the basis of information provide by Brown. Bradley predicted that approximately 71% of the total Pend Oreille mill tailings deposited in the Columbia River before RM 690 and a large portion was predicted to deposit near RM 700 (39%). Bradley claimed that the alleged Pend Oreille tailings would have dominated the total anthropogenic deposits downstream of RM 710. His explanationwas as follows:

1) The Pend Oreille tailings were discharged before Grand Coulee Dam was built and therefore had the opportunity to move further downstream before Lake Roosevelt was impounded;

2) The Pend Oreille tailings were much smaller in size (silt) compared to other anthropogenic sources and the resulting deposition occurred farther down into Lake Roosevelt.

5.2 OVERVIEW OF NUMERICAL MODELS, DATA REQUIREMENTS AND ACCURACY

Before commenting on Dr. Bradley's model results, I have summarized more general comments on the use and mis-use of numerical models to predict sediment transport and sedimentation in rivers and reservoirs. I have used the guiding principles in this section as a basis for critiquing the approach that was used to develop Dr. Bradley's model.

Cunge (2008), one of the founders of modern hydraulic modeling, provides a general critique on its present state. Extracts of his comments follow:

> *It is of the utmost importance to have the field-observed or laboratory measured data available for modeling… if a model does not behave as the observed nature, if its results are not like past observed data, it means that the model is either inadequate (equations) or incomplete. Hence, the importance and even absolute necessity of the data. But there are several types of data needed especially when we have mechanistic models in mind:*
>
> *For operational purposes we need the past-observed data to make sure that our models behave in general correctly.*
>
> *We also wish to have the field-observed data allowing for calibration of empirical (such as flow resistance) invariant coefficients. The data may be sometimes available but often they are polluted by all kind of other influences and sometimes they are not directly related to the calibration values.*
>
> *Then we need the data to check the hypotheses used to elaborate theories (equations) that are not confirmed yet. Indeed, one must not forget that our physical knowledge and its mathematical formulation are inadequate for recently promoted, marketed and widely used marketing tools! Eg. We can mention here turbulence, sedimentology problems, morphology problems, 3D formulations including turbulence etc. There are (many!) theories, equations and modeling tools built on these theories but they are dubious and at best, limited. And only the availability of the data oriented toward validation or invalidation of these hypotheses and theories can improve the situation.*

Power (1993) and Oreskes etal (1994) describe the critical importance and difficult challenge of validating numerical models when applied to the earth sciences and complex environmental systems. Calibration and validation of sediment models is essential because the sediment transport equations used in the models are fundamental to their performance, yet it is well known that sediment transport predictions may be very unreliable and very sensitive to errors in input data or calibration parameters.

Papanicolaou et al (2008) reviewed sediment transport modeling and wrote:

> *Transport of sediment is one of the most important and difficult classes of processes encountered by the hydraulic engineer. Despite the importance of the subject, it is probable that a greater differential exists between the information needed and the information available than in almost any other practical hydraulic engineering field.*
>
> *It has been pointed out that a mismatch exists in the theoretical foundations and performance of the hydrodynamic and sediment components of models. The disparity that exists between the hydrodynamic and sediment transport components is attributed to the fact that the principles of hydrodynamics and the fundamentals of turbulence theory and modeling have been established over the previous two decades, as compared with the fundamentals of sediment transport.*

Wilcock et al (2009) describe some techniques to estimate sediment transport to minimize errors in predictions. In their chapter "***Why Its Hard to Accurately Estimate Transport Rate***" they list three main challenges that induce errors in computations:

- The Flow. In many transport formulas …the flow is represented using the boundary shear stress τ, the flow force acting per unit area of stream bed. Stress is not something we measure directly. Rather, we estimate it from the water discharge and geometry and hydraulic roughness of the stream channel. It is difficult to estimate the correct value of τ because it varies across and along the channel and only part of the flow force acting on the stream bed actually produces transport.
- The sediment. Transport rate depends strongly on grain size. If we specify the wrong size in a transport formula, our estimated transport rate will be way off;
- The watershed. Because questions of sediment supply and alluvial adjustment intrude on the calculation of transport rates, an understanding of the dynamics and history of your watershed is needed in order to choose an appropriate study reach for analysis and to provide a basis for evaluating the results.

Wilcock et al (2009 pg. 71) recommended strategies to reduce uncertainties in predicting sediment transport.

> *Using a few transport samples to calibrate your transport estimate is the single most effective thing you can do to increase accuracy. The same problem applies to the prediction of Qc and transport rate: under typical conditions, uncertainty in boundary conditions is sufficiently large that the calculated results of a formula have very large uncertainties. If a good estimate is required, it must be determined from field observations.*

This advice is very similar to the advice quoted previously (pg.24) from the US Army Corps of Engineers "*Only those* (methods) *based on direct measurements are considered a rigorous approach; mathematical methods are trend indicators at best*". Predictions of sediment transport without site specific calibration should be considered "order of magnitude" estimates. Many previous studies have shown that a "good" prediction of sediment transport ranges from 2 times to ½ of the actual result. Yang (1996 pg 185) predicted sediment transport rate using several different equations and compared these with actual measurements by the US Geological Survey (**Table 5**).

Table 5: Comparison of predicted and measured sediment transport from Yang (1996)

Predictor	Predicted Sediment Concentration (ppm)	Ratio of Predicted to Measured
Yang	1910	1.01
Ackers and White	2400	1.26
Engelund and Hansen	3120	1.64
Shen and Hung	2400	1.26
Colby	1623	0.85
Bagnold	500	0.26
Laursen	800	0.42
Measured	1900	

The hydraulic information (depth, velocity, channel width) were measured values, which should minimize the uncertainties introduced from the hydraulic parameters. Although some equations came closer to the observed rate than others, there is no reason to suppose that they would perform as well at another site. In a sediment HEC-RAS model, the hydraulic variables are computed quantities and contain additional errors and uncertainties that will affect the accuracy of the sediment transport predictions. Due to the very non-linear nature of sediment transport relations, a small error in mean velocity or shear stress may translate into a much larger error in the sediment transport rate.

There are situations where sediment modeling may produce realistic results but there are certain prerequisites that are required for this:

- Reliable longterm hydrological records for all major rivers and tributaries in the watershed.
- Reliable sediment transport measurements (including the size distribution of the load) for calibrating and confirming sediment transport equations and for determining boundary conditions for all major rivers and tributaries in the watershed.
- Representative bed material samples (surface and sub-surface) in the study reach.
- Surveys of water surface profiles over a range of discharges to calibrate hydraulic computations.
- Repeated topographic surveys to describe the river channel and floodplain topography in the study reach. The surveys should be repeated over periods of years or decades to characterize trends and longterm rates of sediment deposition or degradation. Ideally, the repeat surveys should overlap with the hydrological and sediment transport data.

If this information was available, the following steps would need to be followed:

- A hydraulic model would be developed first using the hydrological data, river topography and water level profile data. The hydraulic model would be calibrated and validated.
- Test calculations would be made using the sediment transport measurements to calibrate and validate sediment transport equations. A decision would be made on the most appropriate equation for the project.
- The sediment model would be tested by attempting to reproduce patterns of deposition or degradation that have been observed by comparing historic topographic surveys. For example, in a reservoir simulation, predicted rates of sediment infilling over a period of years would be compared against observed rates of infilling. The reasonableness of the computations would be assessed and if necessary, adjustments would be made to model parameters.
- An independent validation run is often made (if the data are available) to check the stability of the calibration parameters. After interpreting and comparing the results, final adjustments to model parameters might be required.
- The model would then be run to predict various scenarios or future conditions.
- The predictions from the model would be compared against other methods (for example empirical methods or experience from other sites) as a check on their reasonableness.

I have used the general principles outlined in this section as a basis for critiquing the method of approach that was used by Dr. Bradley to develop, calibrate, validate and run his sediment model of the upper Columbia River. Dr. Bradley did not have sediment transport data for calibrating or validating his model, did not have repeat surveys of the reservoir or river channel to validate predictions of infilling (deposition) rates and did not make independent estimates of sediment infilling or transport rates using other methods as a check on his model predictions. On this basis, his results should be considered as "order of magnitude" estimates and are therefore, not suitable for making quantitative comparisons of sediment deposition from various sources.

5.3 MODEL TYPES AND LIMITATIONS OF 1D MODELS

Appendix D provides a detailed description of the physical processes that can be represented in models and the particular limitations that are associated with each type. This section highlights the most important aspects that apply to the Upper Columbia River.

Water or particles of sediment move in three-dimensions (3D): longitudinal (forward/backward), transverse (right/left) and vertical (up/down). Their movement is driven by a combination of what it is usually referred to as "primary" and "secondary" flows. In a river, the primary flow is caused by earth's gravity, which moves water from the mountains towards an ocean or lake. In secondary flow regions, the flow field is significantly different in both speed and direction to the primary flow. Secondary flows and eddies usually form when the primary flow is subject to a sudden change in direction.

The primary flow can be represented by simple one dimensional (1D) flow models, which assume that water moves only in the longitudinal or streamwise direction, ignoring the movement in the transverse and vertical directions. The HEC-RAS computer software developed by the US Army Corps of Engineers is a good example of a 1D flow model. HEC-RAS is used to predict the main features of the primary flow, such as average water depth and average flow velocity in a cross section. It can also model the movement of solid particles, such as natural sediment or slag by the primary streamwise flow. However, HEC-RAS, as any 1D flow model, cannot simulate the movement of sediment particles caused by secondary flows, as they are ignored by the 1D simplification.

A 1D flow model cannot realistically represent complex features such as rapids, bends, water falls, deep pools, riffles, local obstructions and abrupt expansions. Place names along the Upper Columbia River, such as Indian Eddy in Trail, Waneta Eddy at the confluence of the Columbia and Pend Oreille Rivers, Deadman's Eddy near Northport, China Bend, Elbow Bend, Coulee Bend and Hell Gate all illustrate common features along the Columbia River that produced strong secondary flows and eddies that are not amenable to 1D modeling. Prior to Grand Coulee Dam, the 24 major rapids listed in Table 2 also would have generated zones of strong secondary flows due to eddying and flow separation and again are not amenable to 1D modeling. Figure 15 shows the river near Black Sand Beach, located just upstream of Northport. This site is a good example of a deposition zone or sediment "sink" caused by a back eddy. In this case a natural bedrock spur extends out from the bank into the main flow, causing a zone of flow separation and eddy formation. This secondary circulation promotes Teck slag to drop out of suspension in the quiescent region in the lee of the rock spur. Included on the photo is a simplified 3D model representation of flow and eddying produced by an obstruction (for details of this see Appendix

D). A 1D model will not represent this process and will provide no useful information on rates of sedimentation in this section of the river.

Two dimensional models (2D) represent the longitudinal and transverse directions of flow and can represent the effects of sudden changes in direction or sudden expansions and contractions. Such models compute depth-averaged longitudinal and transverse directions of flow and velocity. Appendix E describes the development, calibration and preliminary results of 2D modeling (using the program Mike 21 developed by the Danish Hydraulics Institute) at two reaches of the Upper Columbia River.

Figure 16 shows an example of output from our 2D model near China Bend for a flow condition measured on the field during the March 2011 survey. The current speed along the channel is indicated by the color of the shading, with low velocity regions coloured blue and higher velocities regions shaded yellow and orange. Also shown are cross section lines from Bradley's one dimensional HEC-RAS model with labels indicated the computed 1D velocity. The hydraulic model (without sediment) was run for the same discharge and downstream water level as the 2D model in order to compare the predicted current velocities from the two different models and with the real field surveyed data. The river makes an abrupt expansion near the mouth of Flat Creek, causing two prominent eddies to form on both the north and south sides of the river. In these eddy zones, the flow separates creating slow moving back eddies, while the flow in the center of the channel contracts and accelerates to a maximum of 4 feet/second (ft/s) as measured during the field survey. The 2D predicted a slightly lower peak velocity around 3.5 ft/s, but the HEC-RAS model predicted an unrealistic constant velocity of 0.78 ft/s in the expansion since it assumed the entire width of the channel conveyed the flow.

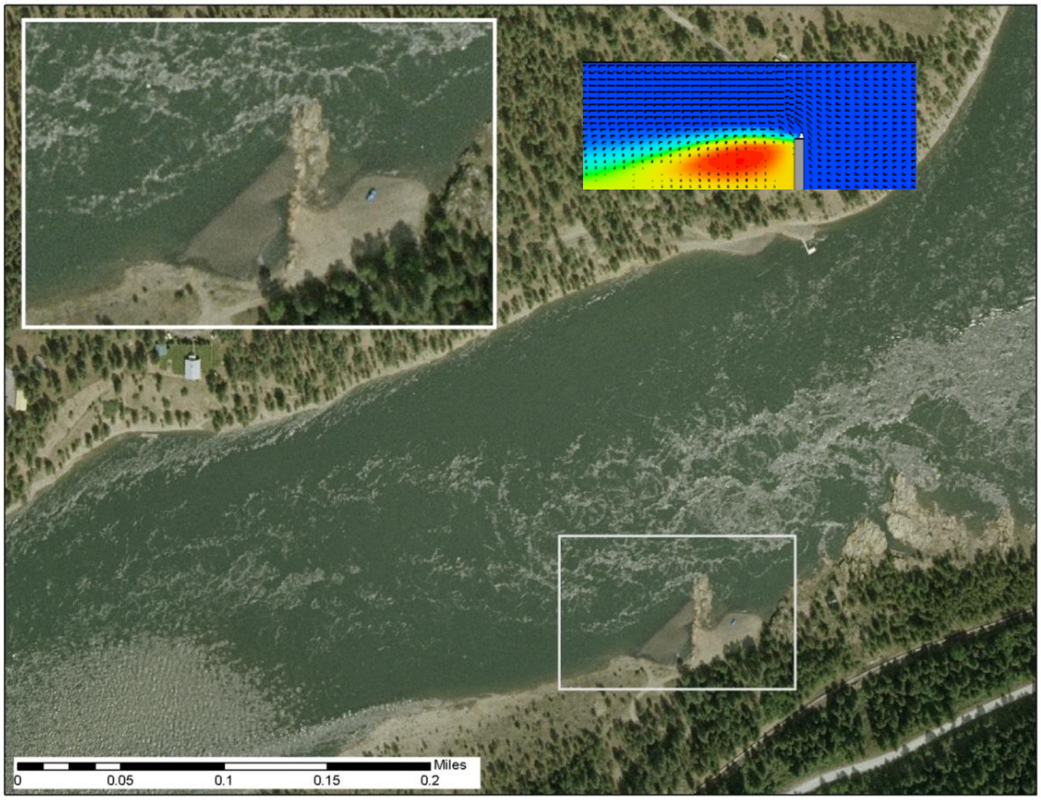


Figure 15. Eddy formation off a natural bedrock spur creating sediment deposition at Black Sand Beach

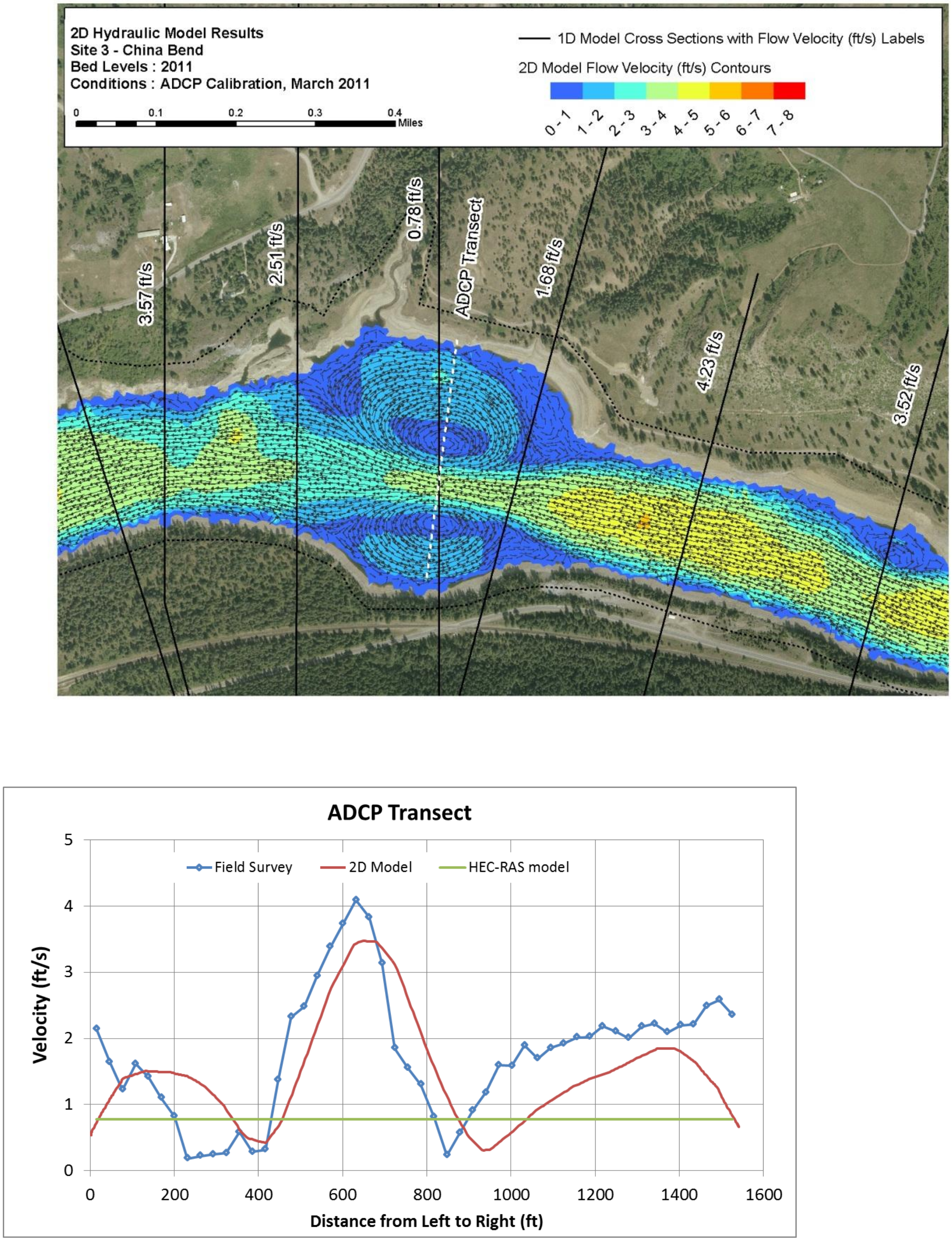


Figure 16. Comparison of 1D and 2D representation of flow in China Bend

A three dimensional (3D) model represents the motion of water or sediment particles in three-dimensions (3D): longitudinal (forward/backward), transverse (right/left) and vertical (up/down). Computational flow models have only recently been applied to large scale simulations of natural rivers and reservoirs. Appendix D summarizes the conceptual modeling of several complex channel features on the Upper Columbia River using the program FLO-3D (details of the model are contained in the Appendix). Figure 17 shows a detailed representation of the same site near China Bend described above in Figure 16. The plot shows the back eddies formed on the north and south sides of the channel and contraction of the flow in the middle of the channel. We have also prepared an animation showing the trajectories of suspended slag particles through China Bend (China Bend.avi is included with this report for viewing from a computer). In the 3D model the direction of flow near the bed will be different than at the surface. Since the concentrations of sediment is usually higher near the bed, the direction of sediment movement will be represented differently than in a 2D model.

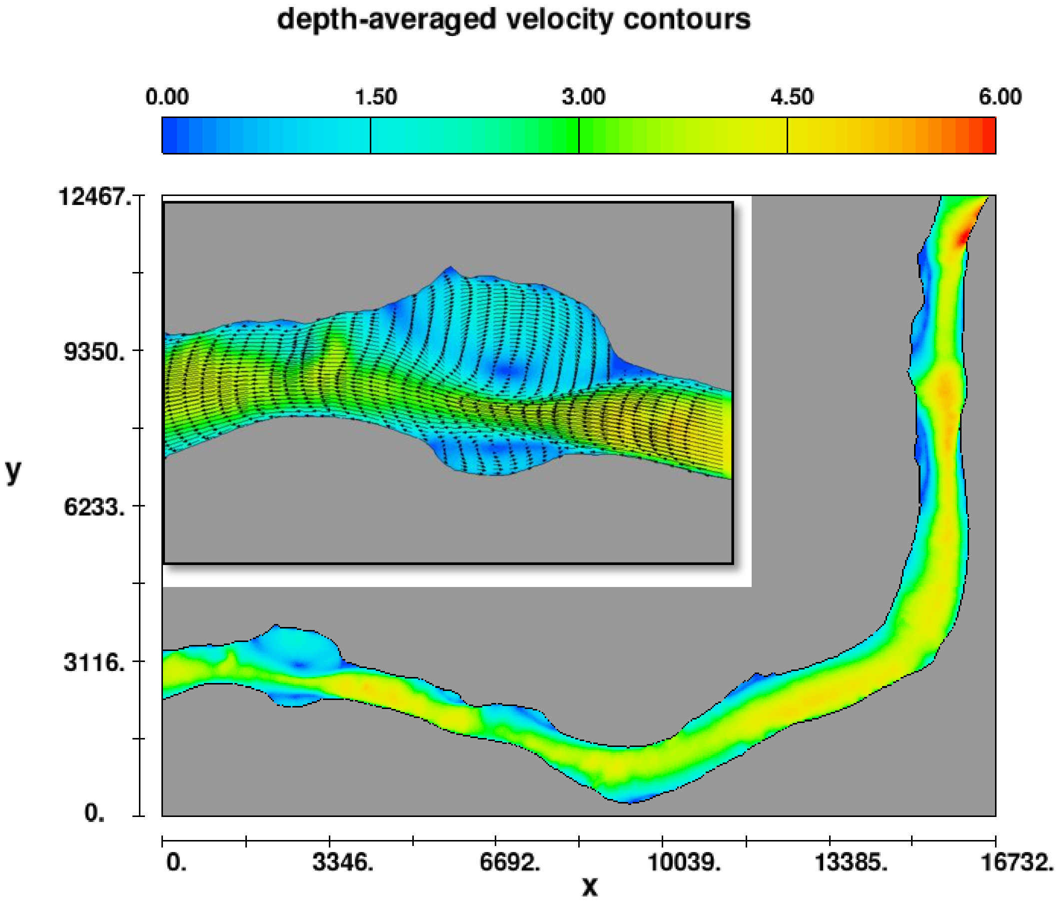


Figure 17. Eddy near Flat Creek in China Bend, Upper Columbia River

Selecting the type of model for a particular application usually involves making a trade-off between the requirements of the project, the available data and the time and resources available. For example, developing a 3D model of the entire Upper Columbia River from Grand Coulee Dam to Trail would probably not be practical at this time. If accurately formulated and calibrated, a 1D hydraulic model could represent the backwater effect from Grand Coulee Dam on the overall average hydraulic characteristics (the primary flow field) and could also represent the general trend of decreasing sediment transport capacity caused by the backwater from the dam. A properly formulated and calibrated 1D model could also be used to assess average hydraulic conditions over long reaches and make conclusions on sediment transport conditions – for example, whether the bed is immobile, whether it can transport sediment of a given size in suspension or as bedload. However, if information is required about local processes along the shoreline, in bends or sudden expansions, or behind obstructions then 1D models will not provide meaningful results.

5.4 CRITIQUE OF BRADLEY'S HEC-RAS MODEL FORMULATION

5.4.1 ORIGIN OF CANADIAN PORTION OF MODEL IS UNDEFINED

Bradley's HEC-RAS model extended for approximately 165 miles from Birchbank, B.C. to Grand Coulee Dam. Bradley (pg 30) stated the model was based on a previously developed HEC-RAS model from another Teck consultant, as part of the Upper Columbia River: RI/FS Workplan (HydroQual, 2007). NHC was provided with a HydroQual HEC-RAS model as part of our investigation of the upper Columbia River (McLean, 2010). However, neither the HydroQual model provided to NHC, nor that described in Wands et al (2010) included any portion of the river reach in British Columbia. Both models only included the Upper Columbia River from the International Boundary down to Grand Coulee Dam. Thus, it is unclear what data Bradley used to extend the model into British Columbia.

5.4.2 LIMITATIONS OF SEPARATE MODELS FOR DIFFERENT SEDIMENT SOURCES

Bradley ran separate independent models for seven primary sources of sediment and a fine sediment tracer model, spanning various time spans back as far as 1898 to the present:

1) Natural Sediment
2) Teck Slag
3) Le Roi (Northport) [1898; 1916]
4) Deep Creek [1956; 1968]
5) Pend Oreille [1953; 1966; 1967; 1976]
6) Onion Creek
7) Young American
8) Fines Tracer [natural sediment; slag]

The various sediment sources and sediment types (Teck slag, LeRoi slag, mill tailings, mine waste, natural sediments) could not be simulated in a single model because HEC-RAS cannot represent sediments having different specific gravities (only a single value is assigned). Also, the program cannot track the fate of sediments from different sources. Bradley assumed that separate sediment simulations could be made independently over periods of several decades for Teck slag, LeRoi slag, natural sediments and various mine waste products and that the results could then be compared by adding them together (as shown in Dr. Bradley's Figure 24). I disagree with this approach because sediments from different sources and different types (slag, natural, mine waste) all mix and interact. For example, as the reservoir fills in with natural sediments, the hydraulic conditions change (the depths decrease and velocities increase) allowing slag particles to be transported further downstream over time. This interaction is not represented in separate models. Furthermore, Bradley's method of aggregating results from separate models that have run for many decades will not provide a realistic basis for comparing the spatial distribution of deposits from the various sediment sources.

5.4.3 UNCERTAINTIES IN MISSING HYDROLOGICAL DATA

Flow data used in the HEC-RAS models are critical for estimating sediment transport rates and deposition. Bradley's sediment transport simulations require flow data back to 1898, the year in which the LeRoi smelter started operations. However, hydrometric records on the Columbia River extend back to 1937 at Birchbank and to 1913 at Trail. Discharge measurements from key tributaries such as the Pend Oreille, Kettle and Spokane River are also incomplete. Therefore, a number of assumptions were required to extend the records back to 1898. A review of the flow records, adopted input data and the basis for extending the records was carried out. These results are described fully in Appendix F. The following comments summarize the key findings from this review.

Bradley extended the observed flow data from the gage sites he relied on back to 1898 by a combination of techniques:

- estimating flows using data from another gage site which had a longer record;
- copying data from a later period of record at the same gage site.

Bradley's Figure 7 shows the periods of data reported to have been estimated or copied for each gage site he used. Bradley's approach to record extension by simply copying data from a later part of the record is rudimentary and is most unlikely to accurately represent the actual flow regime since it ignores the differing climatic conditions from one period of record to another. Furthermore different periods of record were apparently copied at different gage sites. For example, according to Bradley (page 17),

"The Kettle River flow for years 1898 through 1929 were assigned the same records of flow as the years 1930 to 1960," while

"The records for the Colville River during the years 1898 to 1922 were assigned the same discharge values as years 1922 to 1946 …"

This approach leads to inconsistencies in the assumed early records since, for example, 1898 would be presented by one of the driest years on record (1930) on the Kettle River (and regionally) but by an average or moderately wet year regionally (1922) on the Colville. Curiously, Bradley states that records for 1898 on the Colville were assigned the same values as 1922, however the USGS published record on the Colville did not actually start until November 1922.

Bradley's hydrologic analysis appears to have overlooked flow records from a number of USGS stream gages which were operating in the Columbia River basin before 1930. These gages are listed in Table 1 of Appendix F. Data from these sites demonstrate the uncertainty and errors inherent in Bradley's approach to record extension for the early part of the simulation period, from 1898 through the 1920's, which relied on copying of data from a later period of record.

Estimation of flows for the early part of the simulation period (from 1898 until the 1920s) is hampered by the scarcity of observed data. Some data are nevertheless available back to 1898 and earlier. Available USGS flow data from Columbia River at The Dalles and the Spokane River at Spokane from 1898 through 1943 demonstrate with reasonable certainty that Bradley's approach to estimating flows will understate actual flows in the early part of the simulation period. Available observed flow data from the Columbia River at Kettle Falls, which lies in the study reach, conclusively demonstrates significant underestimation of flows in Bradley's LeRoi HEC-RAS model for the period 1916 through 1922.

5.4.4 INCORRECT ANALYSIS OF NATURAL SEDIMENT INFLOWS

Suspended sediment loads published by Water Survey of Canada (WSC) for the site "Columbia River at Birchbank" (08NE049) were used to set the upstream sediment boundary condition for the natural sediment model. The suspended sediment measurements were collected by WSC during the period 1965-1981. The size distribution of the sediment load was not measured. The data were described and analyzed in McLean (2010 section 2.3 and 3.3). Miscellaneous water quality samples collected along the Columbia River indicate the suspended load consists of a wide range of sediments, from sand to clay (Aquatic Resources, 2001), with most of the suspended load consisting of fine sand, silt and clay. However, these samples were not collected using depth-integrated sediment samplers or using approved methods for measuring sediment loads and were not intended for quantifying sediment loads by particle size.

According to Bradley (pg 19) a second order polynomial equation was fit to the published data to represent the sediment rating curve (i.e. relationship between suspended sediment transport rate and discharge) at the upstream boundary. No information was provided on the grain size distribution that was assumed, although this assumption will greatly affect any predictions about the spatial distribution of deposition in a reservoir. For example, if it was assumed that most of the suspended load consisted of sand, sediment deposition would be expected to occur near the upstream end of the reservoir in response to the decrease in stream velocities caused by backwater effects. If it was assumed most of the sediment was clay, then much more of the sediment would be flushed down to the dam (or possibly over the dam). No information was provided about whether the natural sediment HEC-RAS model even modeled fine sediment (silt and clay) and if so, no information was provided on critical parameters governing settling or re-entrainment.

We contacted Water Survey of Canada in Vancouver, BC in January 2011 and enquired about the history of suspended sediment measurements on the Columbia River. After conducting a review we were informed by email that the actual field measurements were made in Trail at the former gage site (Columbia River at Trail, 08NE003), downstream of the Teck smelter. The discharge at the time of sampling was obtained from the active hydrometric station further upstream at Birchbank. This was described previously in McLean (2010 Section 2.2 pg. 4). Therefore, the sediment loads input into Bradley's natural sediment model included the slag discharges from Teck and actually did not represent the natural sediment load. This would have overestimated the contribution from natural sediments in his final summary and all subsequent interpretations in other reports, such as Johns (2011).

5.4.5 LACK OF TRIBUTARY SEDIMENT INFLOW DATA

The natural sediment input from tributaries was estimated from regional estimates of the sediment yield (tons/square mile), which were then multiplied by the drainage area of each tributary to produce an annual load. No information was provided on how the annual sediment load was distributed over the year to generate daily loads. However, on smaller tributaries, sediment production will be governed by local runoff conditions and may not follow the same temporal pattern of discharge as the mainstem river (particularly since it is regulated by upstream hydro dams).

It was indicated the regional sediment yield was estimated from records of sedimentation in reservoirs (USGS Reservoir Sedimentation Survey System). Bradley selected eight reservoirs in Northern Washington and Idaho from a national reservoir database thought to represent the forested mountain terrain around Lake Roosevelt, and computed the average unit sediment yield, given as 30.1 tons/year/square mile. This value is misleading because it included a high outlier value that biased the calculation. If the median value was adopted, the sediment yield would have been reduced to 13 tons/year/square mile, which would have reduced their natural sediment contributions by 57%.

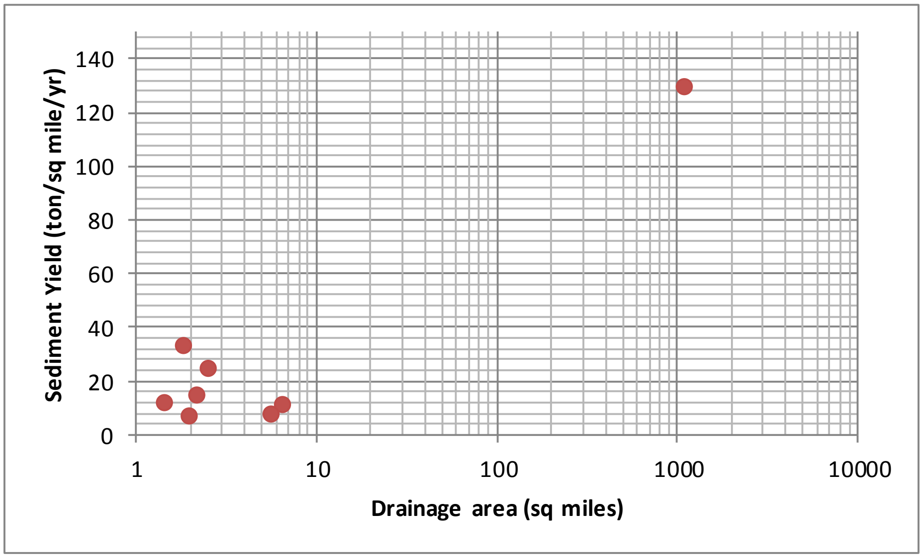


Figure 18: Regional sediment yield data used to estimate tributary sediment inflows

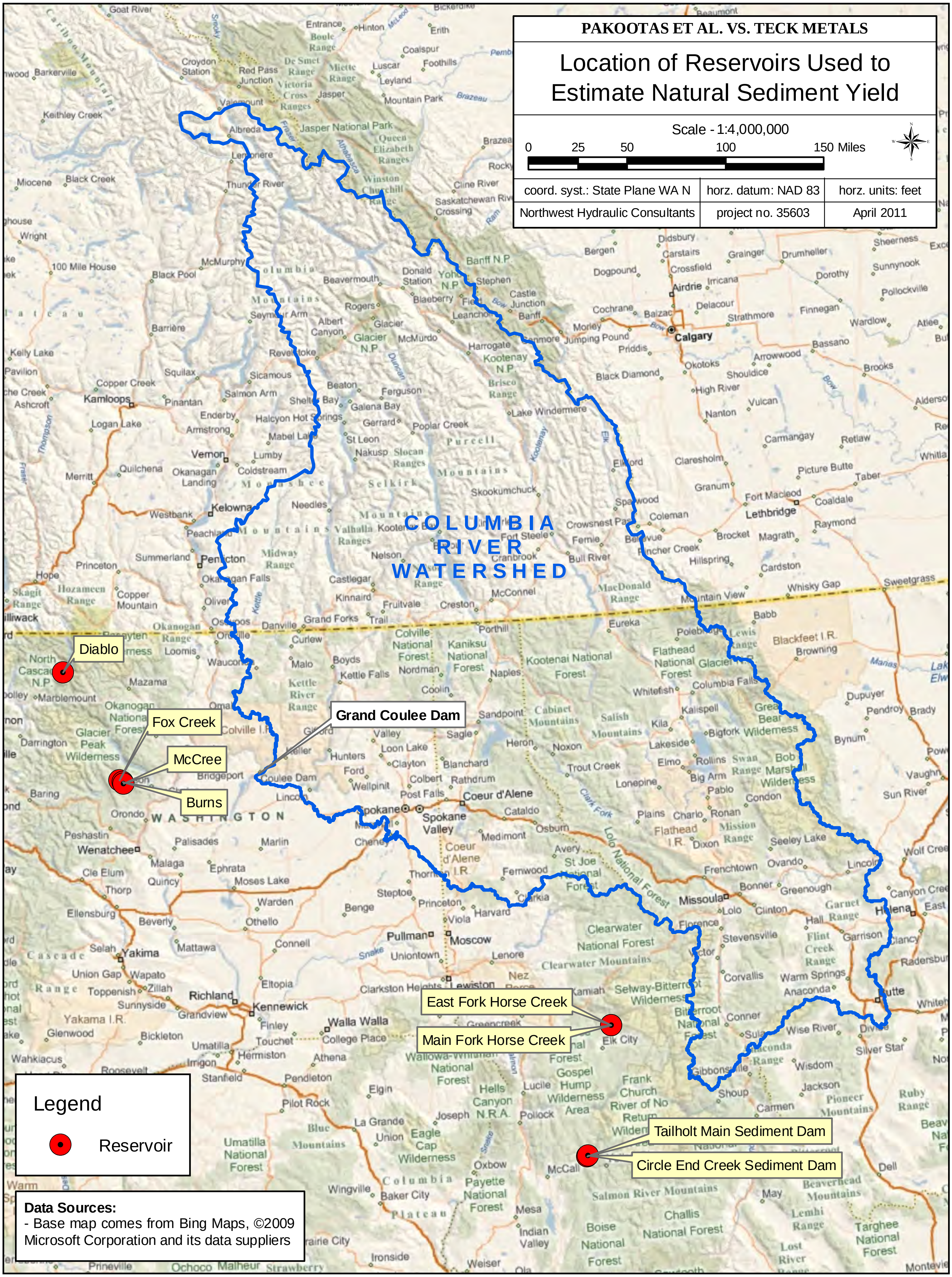
Bradley assumed that the average sediment yield of 30.1 tons/year/square mile was appropriate for estimating the tributary input for the entire Columbia watershed upstream of Grand Coulee Dam. The reasonableness of this assumption was never verified (by comparing predicted sediment loads with observed loads on test sites) and the significance of the assumptions on the model predictions was never assessed.

One important limitation of the analysis was that none of the eight reservoirs are even within the Upper Columbia River watershed (Figure 19), so they likely do not represent typical conditions throughout the entire watershed. In addition, seven of the chosen reservoirs drain an area smaller than 7 square miles, and several of these are clustered close together, so effectively represent the same physical processes. Results from a few mainly small watersheds are not apt to be representative of a range of drainage basin sizes that extend over several orders of magnitude. The disequilibrium of sediment yield with basin size is well known for formerly glaciated regions (Church and Slaymaker, 1989).

Watershed sediment production is influenced by a complex set of geomorphic processes that vary over time and space (USACE, 1994). The spatial variability in sediment yield that is expected is demonstrated by Church et al. (1999) for rivers in British Columbia. Records of suspended sediment transport collected by the Water Survey of Canada and British Columbia Hydro for the period 1966-1985 were used to investigate areal patterns of fluvial sediment yield.

For stations within the Columbia River watershed, specific annual yield ranged from 1.6 t/km^2/yr to nearly 300 t/km^2/yr (roughly 4 to 836 tons/yr/square mile) at roughly 20 sites. The authors found that specific sediment yield increased with drainage area up to 30,000 km^2, then declined for larger basins as sediments are stored on floodplains and channel islands. These results confirm that Bradley's approach of applying a single value of specific sediment yield over a large spatial area including a large range of drainage areas is incorrect.

The size distribution of the tributary sediment loads was represented by soil samples from fields in two counties in Washington State. It is not clear why the size distribution of the suspended load and bed load from tributary streams would correspond to the soil samples. The accepted method to determine the size distribution of the suspended sediment load is to measure it directly in each stream channel, using a standard USGS depth-integrated sediment sampler.



PAKOOTAS ET AL. VS. TECK METALS

Location of Reservoirs Used to Estimate Natural Sediment Yield

Scale - 1:4,000,000

coord. syst.: State Plane WA N	horz. datum: NAD 83	horz. units: feet
Northwest Hydraulic Consultants	project no. 35603	April 2011

Legend

● Reservoir

Data Sources:
- Base map comes from Bing Maps, ©2009 Microsoft Corporation and its data suppliers

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Figure 19

5.4.6 LIMITATIONS OF AVAILABLE BATHYMETRIC DATA

Cross sections of the Columbia River were input to the HEC-RAS model to represent the river and reservoir geometry. The US portion of the model was based on bathymetric surveys made between 1947 and 1949 as well as other more recent topographic data to represent the floodplain and higher ground. The topography was then used to represent conditions dating back to as earlier as 1898 to predict sedimentation patterns along the river and reservoir. Bathymetric surveys represent conditions at a particular point in time and it is not clear how surveys from 1947-1949 can be assumed to represent conditions in 1898 (which was done for the LeRoi slag model).

On the Columbia, mileage is measured from the mouth where the river discharges into the Pacific Ocean. River miles are often shown on maps and charts such as those produced by the U.S. Geological Survey (USGS) and National Ocean and Atmospheric Administration (NOAA). Despite their use on such products, there are some ambiguities associated with river miles. River miles shown on NOAA navigation charts of the upper Columbia River only show delineations at 5 mile increments with no defined stream "centerline" between. Without a specific path from which to measure distance, ambiguities arise when determining precise RM locations between markers. On the upper Columbia River, for instance, the NOAA charts show the Grand Coulee Dam being near RM 597 and the International Boundary near RM 745.

A review was made of the cross sections in the models and it was found that the River Mile identifiers on the cross sections often did not match the actual geographic locations. For example, the International Boundary, which is located at RM 744.9 on the published NOAA chart was indicated to be at RM 744.0767 in the model. Differences in river mile stationing typically varied by between 1 to 2 miles along portions of the upper Columbia River.

5.5 CRITIQUE OF BRADLEY'S MODEL OUTPUT AND RESULTS

5.5.1 WORK CARRIED OUT TO ASSESS BRADLEY'S RESULTS

NHC and NW Hydro conducted field investigations between March 22 and March 29 2011 on the Upper Columbia River between China Bar and Deadman's Eddy (RM 722 to 740). The work included bathymetric surveys and measurements of velocities and flow patterns. Appendix C provides details of the survey methods and results. We used the data to conduct additional detailed hydraulic and sediment transport investigations in selected reaches of the river. We also used the data to check predictions from Bradley's HEC-RAS model.

A follow-up reconnaissance was carried out between April 18-19, 2011. Photos are observations from this trip are also included in Appendix C.

5.5.2 COMPARISON OF PREDICTED AND OBSERVED PATTERN OF SEDIMENTATION

Repeat surveys in the UCR contradict Bradley's predicted pattern of deposition

Bradley's results (his Figure 24) purport to show that there was considerable deposition of natural sediments, mine and mill tailings and slag between RM 720 and the International Boundary near RM 745. For example, Bradley claimed nearly all of the Teck slag that crossed the border was contained within this reach. Bradley further claimed that 52.1 million tons of material (from all sources) was deposited between RM 730 and RM740. If this deposition had actually occurred and were evenly deposited along the entire 10-mile section of river, it would have an average thickness (T) of nearly 17 feet (assuming the bulk density of sediment (γs) is approximately 100 pounds/cubic foot).

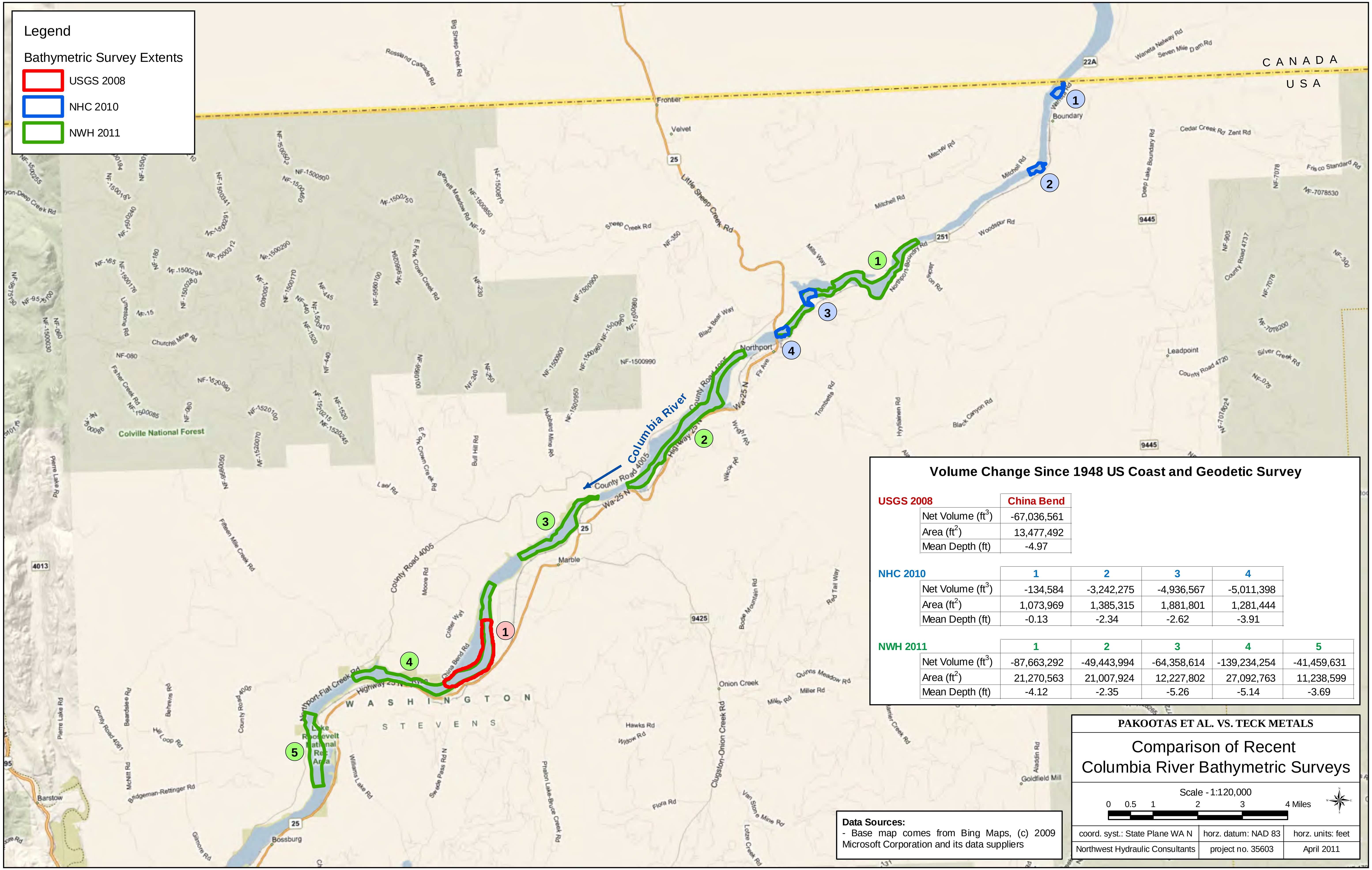
$T = M/(\gamma s\ L\ W)$ where L is the reach length (10 miles or 52,800 feet), W is the average width (1,100 feet)

We assessed Bradley's predictions of deposition in the UCR by using actual surveys of the river bed from the 1940's and recent surveys undertaken by the USGS (Weakland, 2008) and NHC in 2011 to determine the actual changes that have occurred. Details of the survey information are contained in GIS file format attached to this report.

Since the original post-reservoir surveys completed in the late 1940's there has been no complete re-survey of the entire river by any Federal authority. The USGS collected detailed bathymetric soundings in 2008 at Marcus flats and China Bend (Weakland, 2011). The data at Marcus Flats covers a strip of channel, but the data at China Bend cover the complete low-flow channel (see **Figure 20**). China Bend roughly extends from RM 723 to RM 725. This survey was differenced from a 10-m (32.8 feet) resolution grid produced from the 1940s survey. Corpscon software from the USACE was used to convert the vertical datum of the 1940s survey to NAVD88 to be compatible with the more recent USGS survey. This analysis reveals a net loss of 67 million ft^3 of bed sediments since the late 1940s, for a total mean loss (degradation) of 5 feet. For comparison, Bradley estimated a total deposit more than 3 feet thick between RM 720-730. *It should be emphasized that degradation (overall bed lowering) does not mean that deposition has not occurred in portions of the channel. For example, slag and other sediment may have deposited behind obstructions or in slack water areas, while the main channel has lowered.*

In 2010 NHC collected bathymetric data at several pools between Northport and the Canada / US border (**Figure 20**). These surveys included sites with deep pools and are locations where sediment would be expected to deposit. Comparison with the surveys from the 1940's indicated a net loss of 135,000 ft^3 near the border, increasing to roughly 5 million ft^3 for two pools near Northport (as summarized on **Figure 20**). The degradation at each pool averages 0.13 feet near the border, and increased downstream to a maximum of nearly 4 feet nearest Northport. The measured pattern of bed degradation is consistent with the findings at China Bend and contradicts the predictions of Bradley's HEC-RAS model.

NHC and Northwest Hydro undertook additional surveys at five reaches between Northport and Bossburg in March, 2011 (**Figure 20**). Site 1 and Site 2 encompass nearly all of the reach between RM 730 -740, while Site 3 and Site 4 encompass most of the RM 720s. As with the other datasets, topographic models of the bed were created for each location and compared with the original surveys from the 1940s. These comparisons also indicated net bed degradation at all five locations, ranging from 2.4 to 5.3 feet in average thickness. The range of bed degradation is consistent with the results of the previous survey comparisons. The sum of degradation at Sites 1 and 2 is 137 million ft^3, or 3.2 feet on average which can be directly contrasted with Bradley's figure of 17 feet average deposition. This result very clearly demonstrates that Bradley's model results are not credible – and in fact are not even close to reality. A similar analysis for Sites 3 and 4 produced a total degradation of nearly 204 million ft^3, or 5.2 feet on average compared to Bradleys modeled estimate of more than 3 feet mean deposition between RM 720-730. The final site (5) degraded by 41.5 million ft^3, or 3.7 feet on average, while Bradley shows a very modest (near zero) bed deposition in the corresponding RM 710s. Taken together, the consistent findings of bed degradation upstream of RM 718 since the late 1940s demonstrate that Bradley's HEC-RAS model results are not believable.



Volume Change Since 1948 US Coast and Geodetic Survey

USGS 2008	China Bend
Net Volume (ft^3)	-67,036,561
Area (ft^2)	13,477,492
Mean Depth (ft)	-4.97

NHC 2010	1	2	3	4
Net Volume (ft^3)	-134,584	-3,242,275	-4,936,567	-5,011,398
Area (ft^2)	1,073,969	1,385,315	1,881,801	1,281,444
Mean Depth (ft)	-0.13	-2.34	-2.62	-3.91

NWH 2011	1	2	3	4	5
Net Volume (ft^3)	-87,663,292	-49,443,994	-64,358,614	-139,234,254	-41,459,631
Area (ft^2)	21,270,563	21,007,924	12,227,802	27,092,763	11,238,599
Mean Depth (ft)	-4.12	-2.35	-5.26	-5.14	-3.69

Data Sources:
- Base map comes from Bing Maps, (c) 2009 Microsoft Corporation and its data suppliers

PAKOOTAS ET AL. VS. TECK METALS

Comparison of Recent Columbia River Bathymetric Surveys

Scale - 1:120,000

0 0.5 1 2 3 4 Miles

coord. syst.: State Plane WA N	horz. datum: NAD 83	horz. units: feet
Northwest Hydraulic Consultants	project no. 35603	April 2011

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Figure 20

5.5.3 MODEL INSTABILITY NEAR THE LITTLE DALLES

Errors in initial model topography created unrealistic waterfalls in the stream profile

We made an initial review of Bradleys HEC-RAS model output using the HEC-RAS results viewer that animates the computed water surface profiles and evolution of the bed. Through this viewer, changes to the water and bed surface profiles could be reviewed at yearly time steps. An abnormality was observed in the results from the "Natural Sediment" model. Figure 21 shows a screen capture from Bradley's model output. Figure 22 illustrates this abnormality by comparing the bed and water surface profiles from the "Natural Sediment" model, between Kettle Falls and Birchbank, B.C., at the beginning (1898) and end (2009) of the model run. This figure shows an abrupt sediment deposit over 100 ft tall is predicted to develop just downstream of the Little Dalles, near RM 727, causing a near 30 foot tall waterfall and a significant backwater upstream past the International Boundary. These results indicate an instability or error in Bradley's hydraulic and sediment transport model computations. Thus it was decided to investigate the Little Dalles reach in more detail.

In addition to the unrealistic and inaccurate results computed by the Bradley (2011) "Natural Sediment" and "Teck Slag" sediment transport models, the basic concept of the summation of results from individual sediment transport models to predict transport patterns and timing is flawed. This method was used by Bradley in an effort to distinguish the transport and fate from individual sediment sources. Figure 23 shows the change in computed bed elevation over time for the "Natural Sediment", "Teck Slag", and both the 1898 and 1916 "Le Roi" models. The bed elevation computed by the "Natural Sediment" model steeply rises at the beginning of the run in 1898 and by 1940, i.e. at the beginning of regulation of the river at Grand Coulee Dam, has already grown over 90 ft. This result indicates that regulation by Grand Coulee Dam has little to do with deposition in this area, but it also illustrates how unrealistic the "Teck Slag" model is. The "Teck Slag" model begins in 1930 at a bed elevation of approximately 1187 ft, NAVD-88, but based on results from the "Natural Sediment" model the bed has already almost 90 ft by this time at this location. This bed aggradation is not accounted for in the initial condition of the "Teck Slag" model.

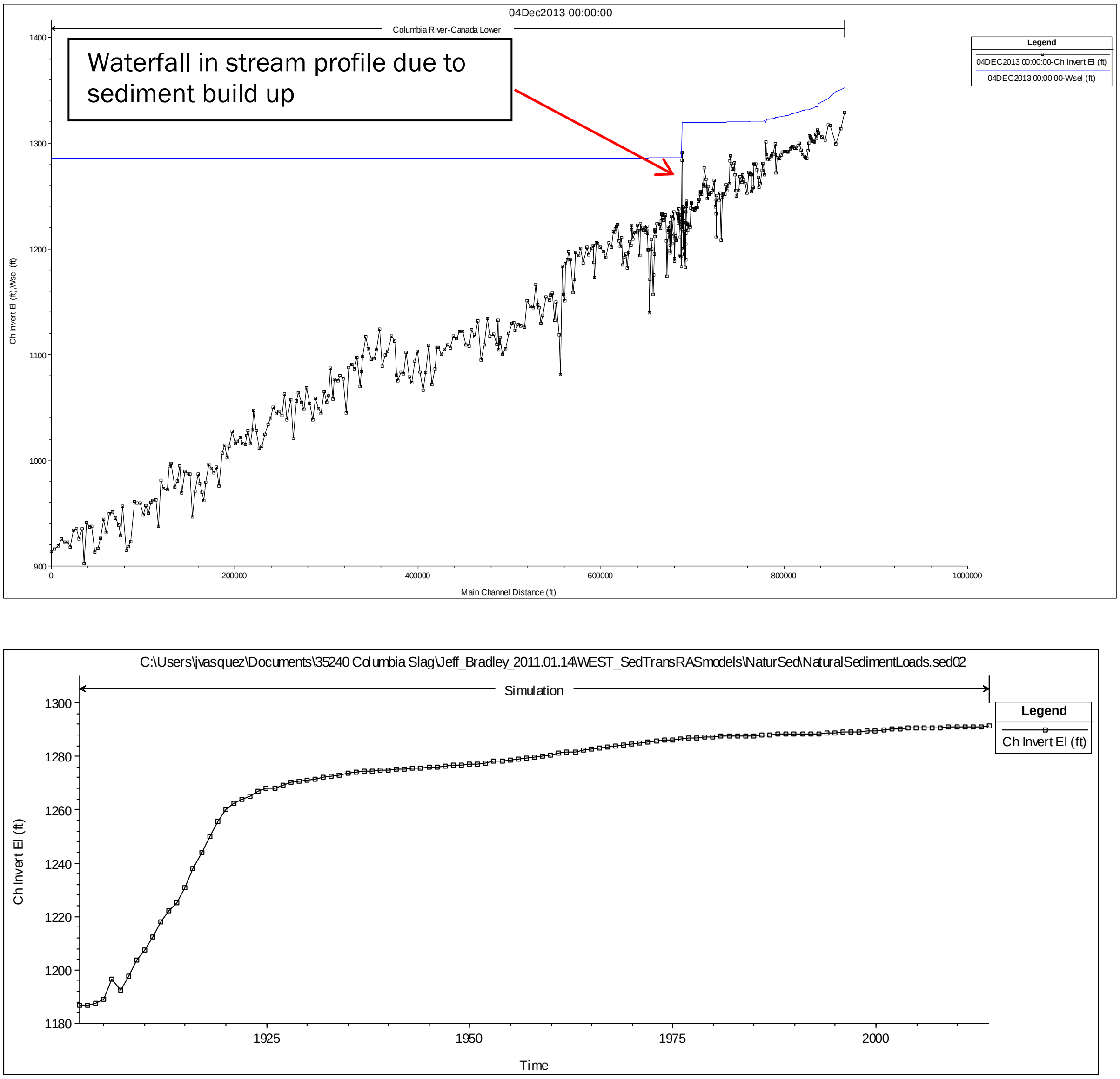


Figure 21. HEC-RAS output screen from Bradley's Natural Sediment model

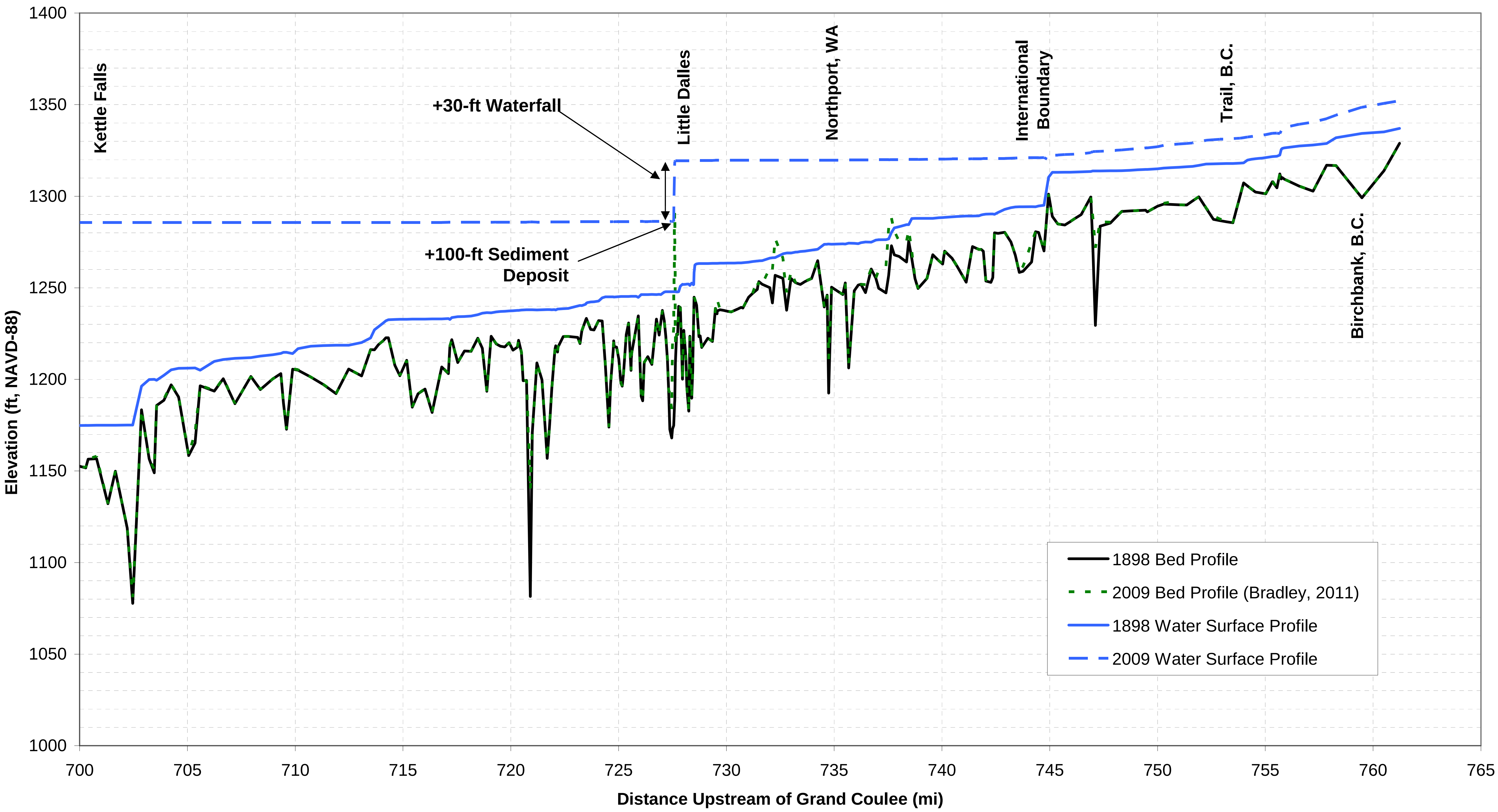


Figure 22. Computed bed and water surface profiles at the beginning (1898) and end (2009) of the "Natural Sediment" HEC-RAS model (Bradley, 2011).

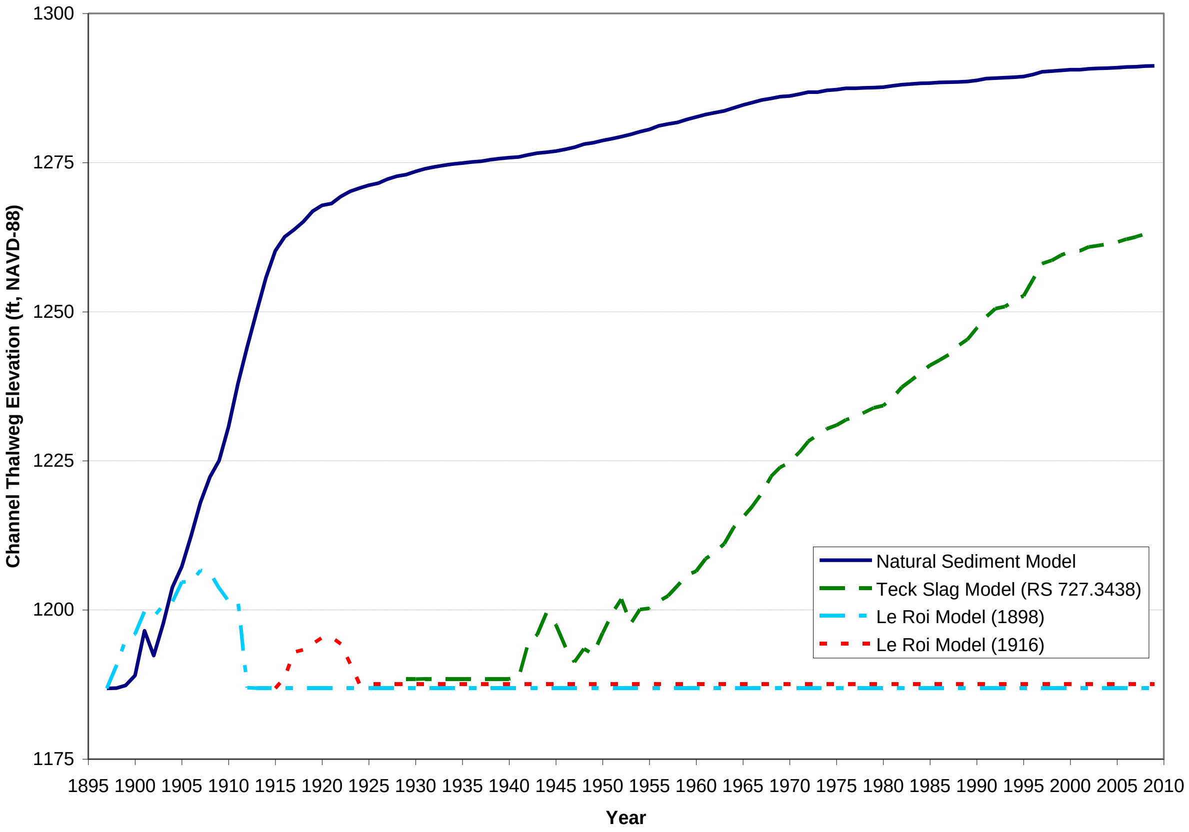


Figure 23: Change of bed elevation over time at RS 727.3334 and 727.3438 computed by Bradley's "Natural Sediment", "Teck Slag", and "Le Roi" (1898; 1916) models

Source of model errors at the Little Dalles

The Little Dalles is a natural constriction of the river located near RM 728 and approximately six miles downstream of the town of Northport. Immediately upstream and downstream of the Little Dalles, the Columbia River ranges in width from 750 to 800 feet, but narrows to approximately 350 feet as the river flows through a 2,000 foot long, bedrock canyon. During construction of the Grand Coulee Dam, the corridor through the Little Dalles was widened by blasting the adjacent bedrock outcrops. This work was apparently conducted to improve flooding conditions along the upper river as stated in Williams (1941, pg. 754):

> *"Since Grand Coulee Dam backs up the water to the Canadian boundary, one might think that flood damage in the upper valley would be increased. But our engineers, removing obstructions in the Little Dalles, have actually lowered the flood level."*

Figure 8 (on page 14) illustrates the work conducted within the Little Dalles in the late 1930s by comparing aerial photos from 1930, i.e. prior to the modification, and 2009. Comparison of these images partially illustrates the modifications to the river channel that occurred after the blasting; however, inundation by Lake Roosevelt partially obscures some of the shoreline in the latter image. The estimated 2009 water line is overlaid on the 1930 photo to assist in the comparison. These images suggest that much of the blasting occurred along the upstream 1,500 feet of the canyon, where the channel was widened approximately 200 to 500 feet along the left bank. A remnant of this widening is apparent from recently conducted bathymetric surveys through the reach. compares the channel geometry used by Bradley and that developed using the 2011 bathymetry at five cross-sections through the reach. These data show that a submerged bench is located along the left bank of the canyon and a trench up to 150 ft deep and 150 ft wide along the right bank. The latter is likely a remnant of the original channel prior to blasting. A comparison of this newly collected channel geometry with that in the Bradley model indicates that the latter greatly underestimated the depth of the channel through the Little Dalles.

NHC reviewed the original bathymetric data from the 1949 U.S. Coast and Geodetic Survey (USCGS) that was used in developing the original HEC-RAS models (Bradley, 2011). Agreement between the 1949 data and Bradley (2011) model geometry were confirmed; however, there is no obvious explanation for why the original USCGS data were incomplete in representing the full channel geometry. Bathymetric data in this area is relatively sparse compared to other portions of the river, thus it could be presumed that high flow velocities in the area during the survey made data collection difficult.

Considering the significant inaccuracies in channel geometry linked to the 1949 bathymetry data used in the Bradley model, it was decided to revise the model in the vicinity of the Little Dalles using 2011 bathymetric data. Validation of the modified model could then be conducted using observed water surface elevations collected during the survey. Channel geometry was revised at seven cross-sections between RS 727.8596 and 728.3554. Five of these cross-sections are those shown in Figure 24.

Boundary conditions for NHC's revised model were obtained online from three different agencies. Discharges at Birchbank, B.C. and the International Boundary were collected from the Water Survey of Canada (WSC) and USGS, respectively. Lake Roosevelt water levels at Grand Coulee Dam were obtained from the U.S. Bureau of Reclamation (USBR). Since the bathymetric and water surface surveys were conducted over a weeklong period, from March 22-29, 2011, some variation in downstream lake level and upstream discharges were observed at each of the gage sites. To simplify the analysis, time-averaged values of lake level and discharge were estimated at each location. Table 6 summarizes the discharges and water levels used in the revised model.

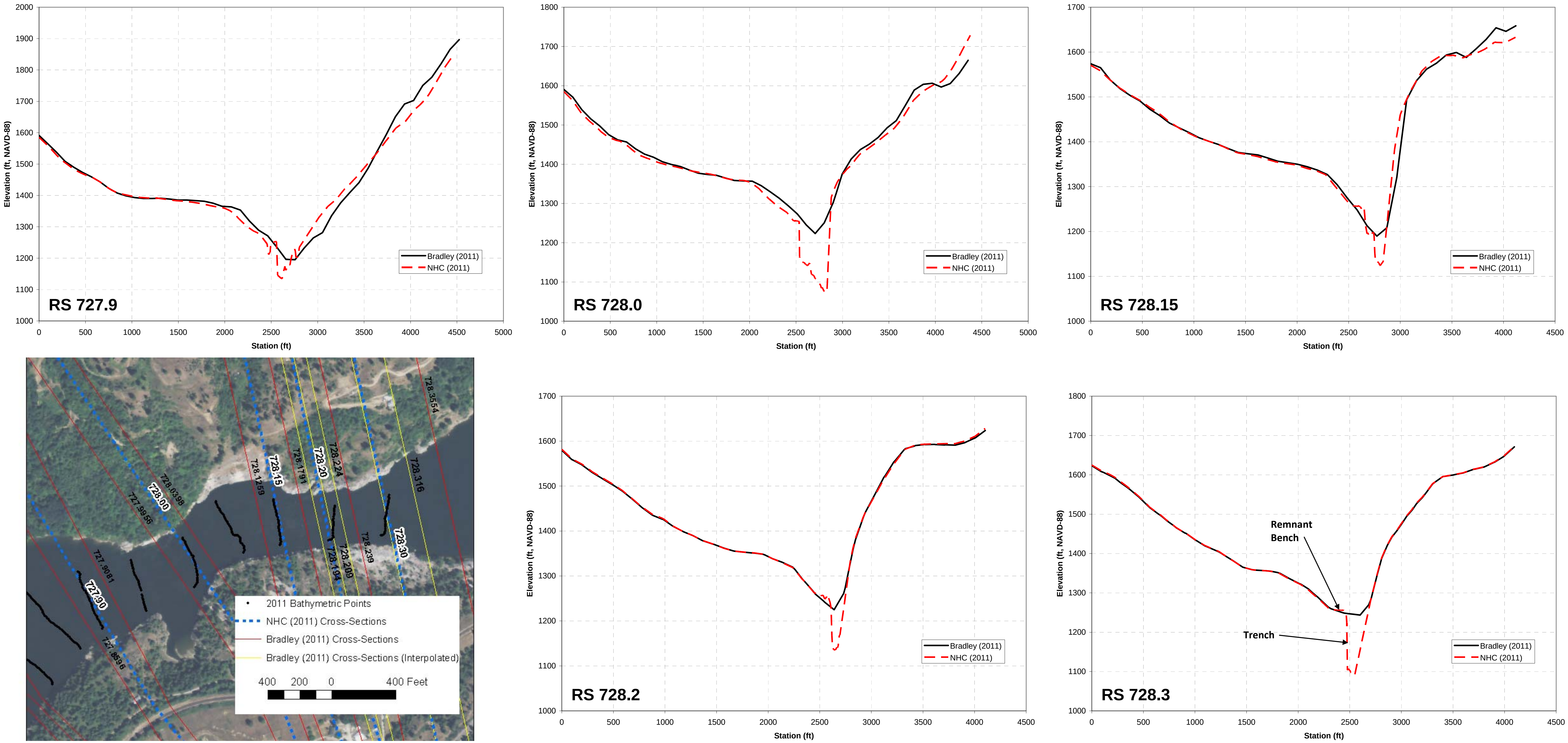


Figure 24. Comparison of HEC-RAS cross-sections at the Little Dalles based on 1949 USCGS bathymetric data (Bradley, 2011) and bathymetric data obtained in March 2011.

Table 6. Summary of discharge and water level (22-29 March 2011)

Location	Maximum	Minimum	Average
Birchbank, B.C.[1]	72,000 cfs	66,000 cfs	69,000 cfs
International Boundary[2]	104,000 cfs	73,000 cfs	96,000 cfs
Lake Roosevelt at Grand Coulee[3]	1256.2 ft, NAVD-88	1254.4 ft, NAVD-88	1255.4 ft, NAVD-88

[1] http://www.wateroffice.ec.gc.ca/index_e.html, [2] http://waterdata.usgs.gov/usa/nwis/uv?site_no=12399500

[3] http://www.usbr.gov/pn-bin/arcread.pl?station=GCL

Measured cross sections were overlain with Bradley's predicted cross section output at RS 727.3334 in **Figure 25**. Included is the initial cross-section bed profile from the Bradley model based on the 1949 USCGS bathymetry. Also included are the cross-section bed profiles showing computed deposition from the "Natural Sediment", "Teck Slag", "Pend Orielle-1953", and "Le Roi-1898" models at the end of their respective runs (2009). At RS 727.3334, over 100 feet feet of sediment deposition is computed by the "Natural Sediment" model. Immediately upstream at RS 727.3438, a similar deposit of over 75 feet is computed by the "Teck Slag" model. Relatively modest deposits of approximately only 13 feet and 3 feet were computed by the "Pend Orielle-1953" and "Le Roi-1898" models, respectively. For comparison, Figure 25 also illustrates the bathymetry and water surface elevation surveyed by NHC in March 2011. The 2011 bathymetric data does indicate that 30 to 40 feet of sediment deposition has occurred since 1949 in the back eddy located on the left side of the channel, which would be expected under these hydraulic conditions. However, the water surface elevation of 1259.8 ft, NAVD-88 observed in March 2011 is located over 30 feet below the computed bed elevation from the "Natural Sediment" model and over 3 feet below the computed bed elevation from the "Teck Slag" model.

Figure 26 shows a series of photographs taken in the vicinity of the Little Dalles during the March 2011 survey. During this survey, neither the significant sediment deposits predicted by Bradley (2011) nor abrupt drops in water surface, i.e. waterfalls, were observed near the Little Dalles.

Direct observations contradict model predictions

These direct observations demonstrate conclusively that the sediment deposition computed by Bradley, particularly by the "Natural Sediment" and "Teck Slag" models, are unrealistic and inaccurate.

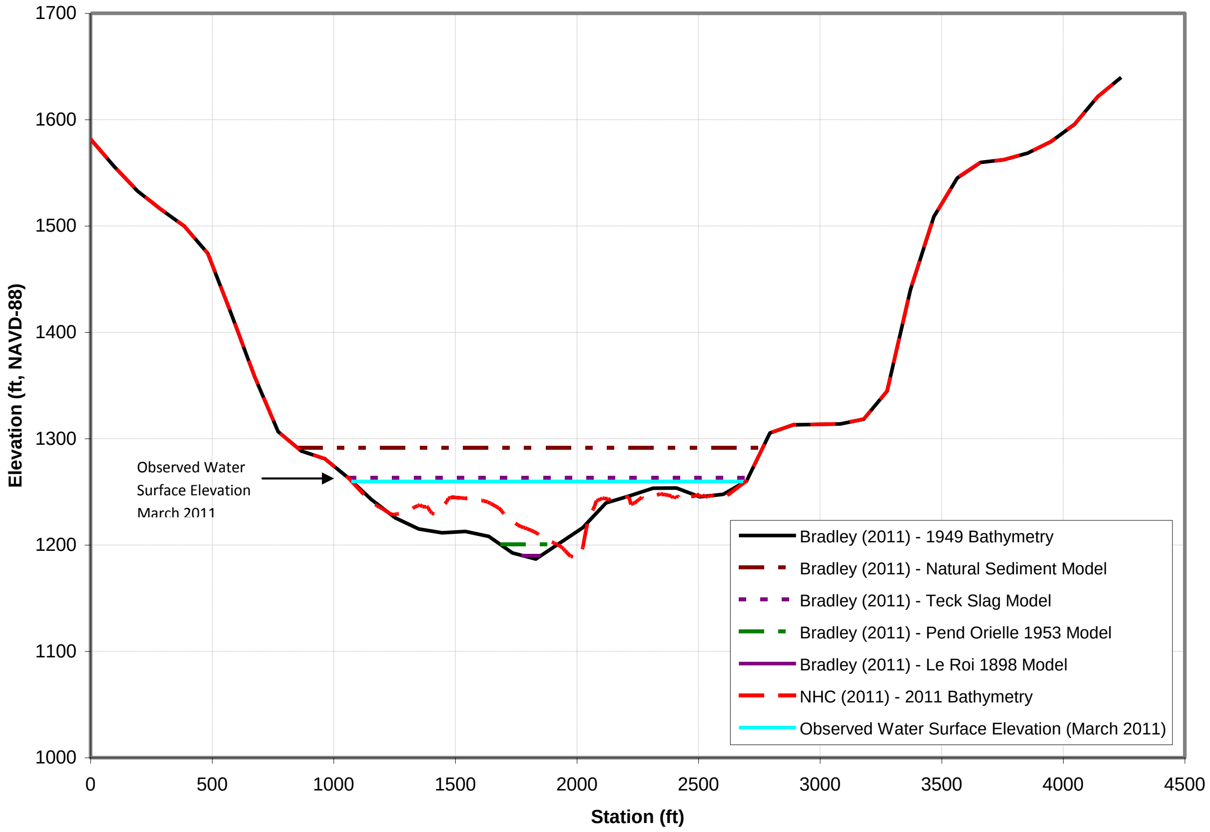


Figure 25. Comparison of cross-section bed profiles and observed water surface elevation downstream of the Little Dalles at RS 727.3334.

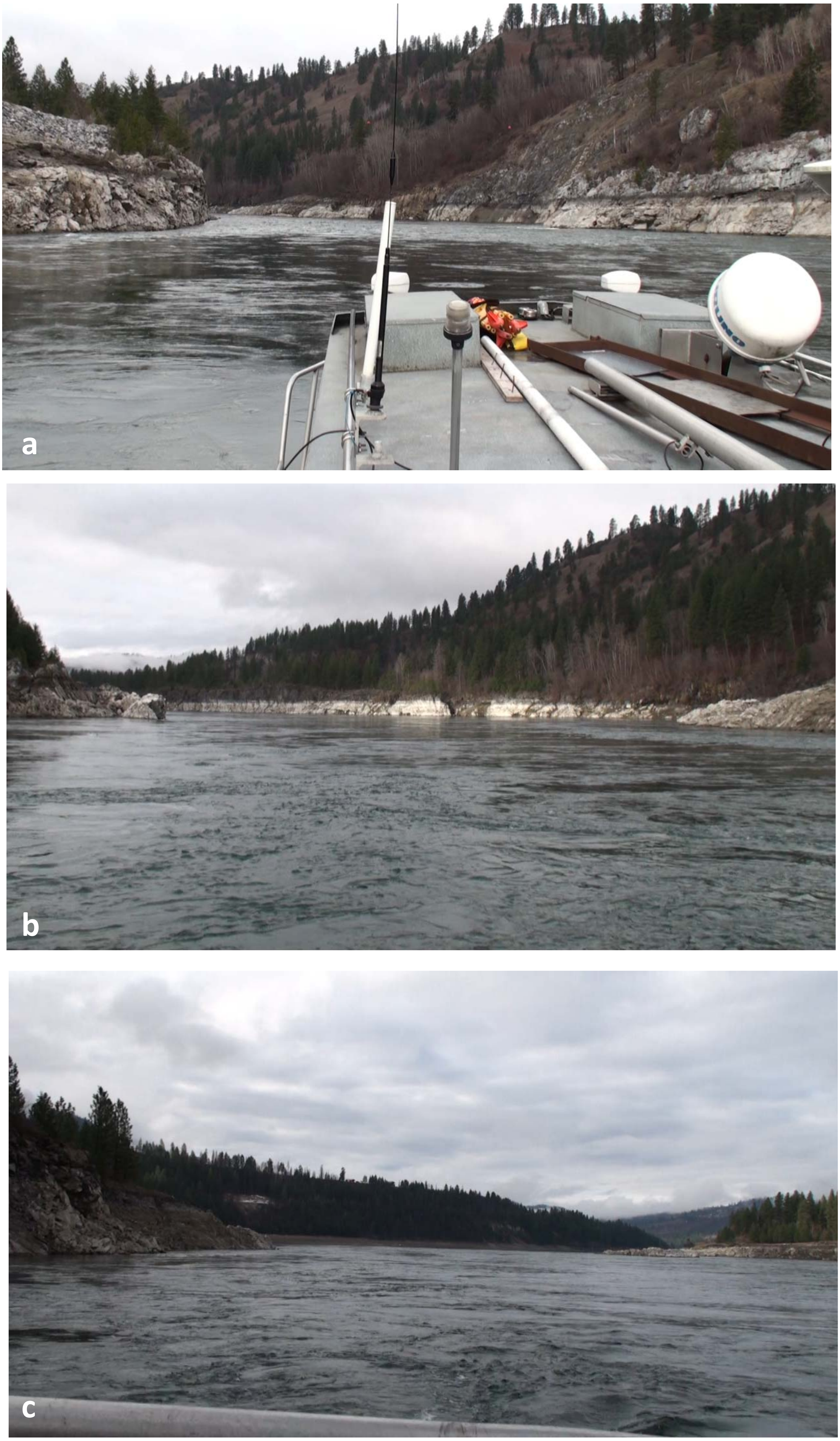


Figure 26. Downstream facing photographs of the Little Dalles reach taken during site visit on March 26, 2011: a) upstream reach of the Little Dalles near RS 73554, b) mid-reach near RS 727.9956, and c) downstream near RS 727.3438. Note relatively smooth water surface throughout reach and no apparent sediment deposits within channel in 6c.

5.5.4 MODEL INSTABILITY NEAR WANETA EDDY

Similar problems exist as the Little Dalles

Waneta Eddy is located in British Columbia, approximately 0.25 miles upstream of the International Boundary (RM 745.3), at the confluence of the Columbia and Pend Oreille Rivers. The water surface profiles computed by Bradley's HEC-RAS model show an abrupt, approximately 15 feet drop in water surface elevation of the Columbia River just upstream of the confluence with the Pend Oreille River (Figure 22). A feature such as this would resemble a small waterfall or cascade with significant turbulence and whitewater; however, no such feature was observed during either a field investigation conducted in 2010 (McLean, 2010), or on aerial photos.

To evaluate conditions at Waneta Eddy a HEC-RAS model previously developed by NHC was compared with the results from the Bradley "Natural Sediment" model. The NHC model extends from Northport (RM 735) to Birchbank, B.C. (RM 762), and was developed as part of the original UCR analysis (McLean, 2010, Appendix B). The channel geometry downstream of the International Boundary was obtained from the HydroQual (2007) model provided to NHC, thus based on the 1949 USCGS bathymetric data. Upstream of the International Boundary, NHC used a model originally developed by B.C. Hydro, then augmented with bathymetric data collected by the WSC in 1989 (McLean, 2010, Appendix B). Figure 27 compares bed profiles and computed water surface elevations from both the NHC (2010) and Bradley (2011) models using March 2011 hydraulic boundary conditions. Observed water surface elevations at both the USGS's auxiliary (RM 742.5) and main gages (RM 744.2) at the International Boundary, and the WSC's Birchbank gage (RM 762.2) are shown as additional calibration points.

Comparison of the computed water surface profiles downstream of the International Boundary and upstream of Trail, B.C. show reasonable agreement between the two different models, but in the vicinity of the Waneta Eddy, the abrupt water surface rise in the Bradley model deviates from the computations of McLean (2010). Here, the NHC model predicts a relatively smooth water surface profile along the reach.

Comparison of the bed profiles, however, does indicate potential errors in the channel geometry data used by Bradley (2011). Downstream of the International Boundary, agreement between the bed geometries is generally good, with some differences likely caused by changes Bradley (2011) made to the original base HydroQual (2007) model, particularly, changes to cross-section alignments. Upstream of the International Boundary, bed elevations from Bradley (2011) are consistently lower than those in the McLean (2010) model with the acceptation occurring in deep pools. Here, Bradley underestimates pool depths by as much as 55 ft.

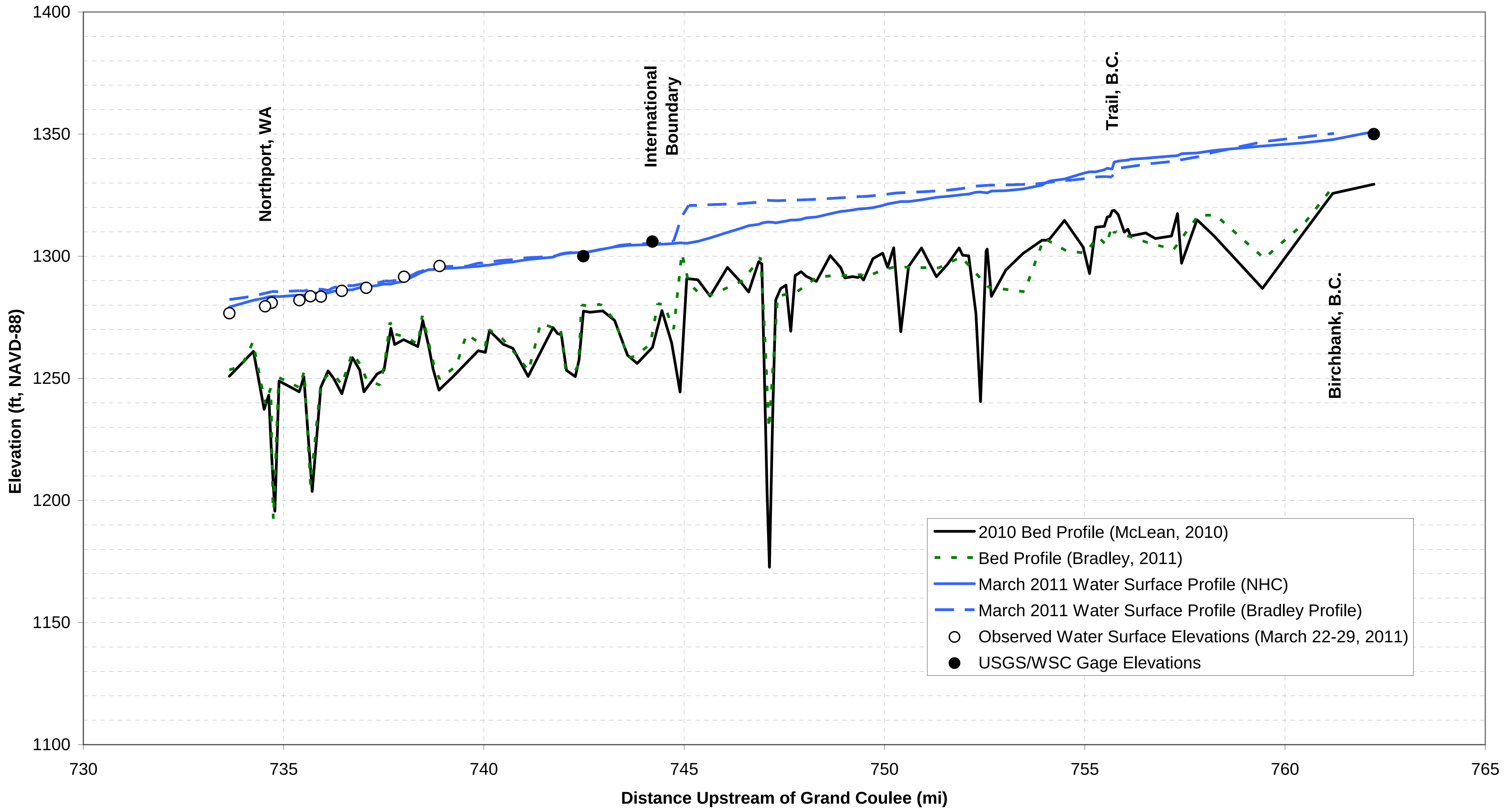


Figure 27. Computed bed and water surface profiles, and observed conditions from March 22-29, 2011 from RM 730to 762.

Figure 28 compares the channel geometry used by Bradley and that from the 1989 WSC bathymetry used by NHC (McLean, 2010, Appendix B) at three cross-sections through the reach. Although cross-section locations are slightly different between the two models, this cannot explain the nearly 55 ft difference observed at the upstream edge of the pool (RS 18.11/744.6796) Again, it is difficult to comment on why this occurs since the origin of the channel bathymetric data used by Bradley on the Canadian side of the border is unknown.

Further evidence of inaccuracy or error in the Bradley model is shown in the photograph pictured in **Figure 29**. This photograph was taken at Waneta Eddy on January 21, 2010, by NHC staff during a field investigation. In the foreground, the turbulent inflow from the Pend Oreille River can be seen, but in the background upstream, the Columbia River surface is relatively smooth. The estimated discharge at Birchbank on this day was nearly 48,000 cfs, or approximately 21,000 cfs lower than the discharge modeled. Despite the reduced discharge, no evidence of a water surface drop is apparent.

Predicted falls at Waneta do not exist

Based on the comparison of cross-section data and photographic evidence, the water surface elevation computed by Bradley's model is inaccurate near Waneta Eddy. Similar to the Little Dalles, this inaccuracy in hydraulics invariably leads to further inaccuracies related to sediment transport computations.

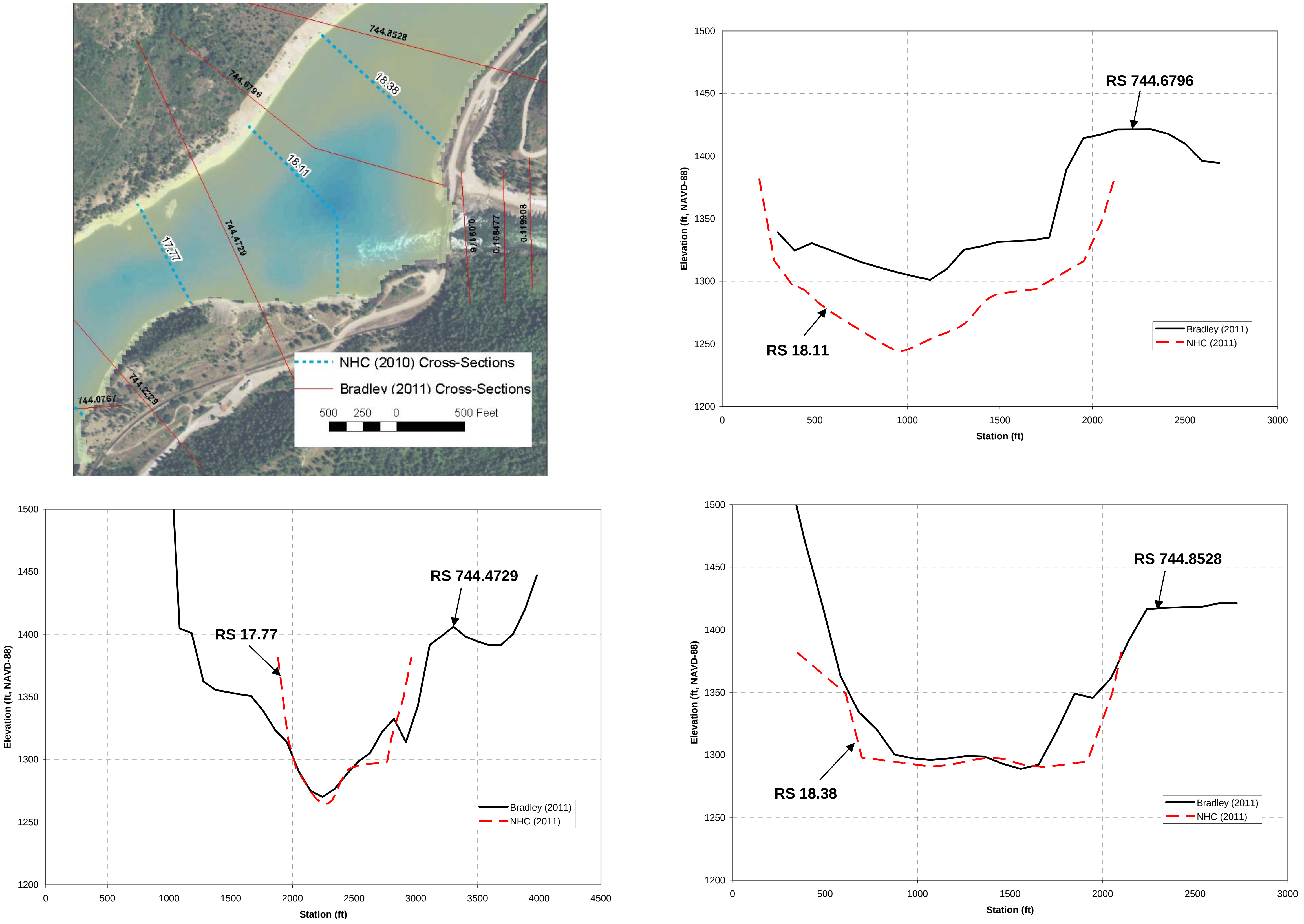


Figure 28. Comparison of HEC-RAS cross-sections at Waneta Eddy based on 1949 USCGS bathymetric data (Bradley, 2011) and 1989 WSC bathymetric data (McLean, 2010).

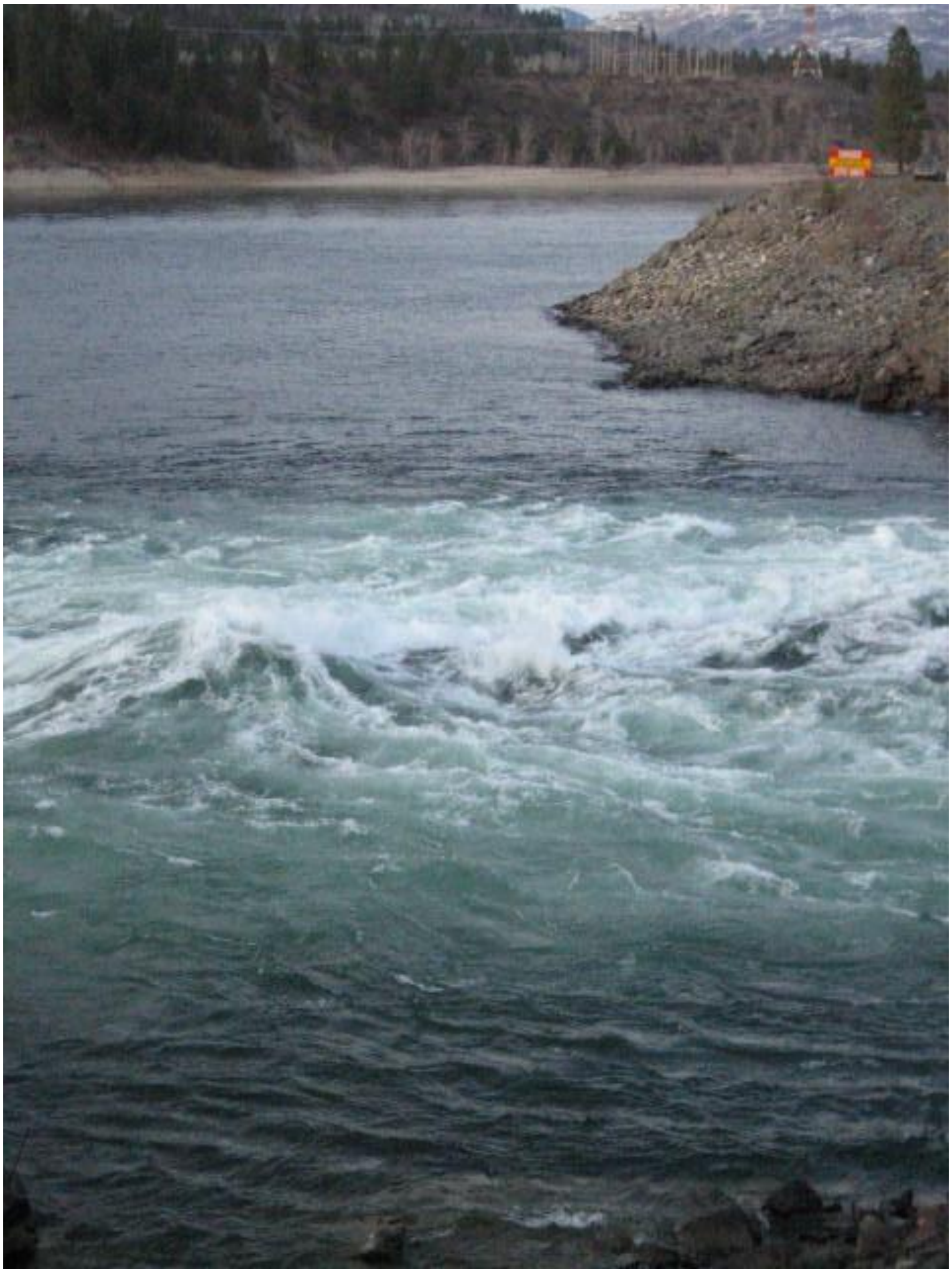


Figure 29. Photograph of the confluence of the Pend Oreille and Columbia Rivers at the Waneta Eddy (facing northeast) showing absence of waterfall.

5.5.5 MODEL PREDICTIONS NEAR ELBOW BEND

An evaluation of the Bradley HEC-RAS model was conducted in the vicinity of Elbow Bend between RM 660 and 670. Located approximately 35 miles downstream of Kettle Falls, this portion of the Columbia River is inundated by Lake Roosevelt even at the low pool levels. As a result, we could not perform a field investigation of the site as it would be underwater, but rather relied upon historic data to evaluate conditions along the reach.

Three figures (**Figure 30**, Figure 31 and **Figure 32**) illustrate the lower, middle, and upper portions of Elbow Bend, respectively. Included in each figure are panels showing the USACE 1898 chart and 1930 aerial photo mosaic overlaid with cross-sections from the "Natural Sediment" HEC-RAS model (Bradley, 2011). The third panel in each figure illustrates the bed and computed water surface profiles from the Bradley (2011) model for typical low and high discharges conditions prior to regulation in 1940. Low flow discharges were estimated from gage records prior to 1940 with records averaged between January and March, i.e. typical low flow periods. High flow discharges were estimated by averaging gage records prior to 1940 for the month of June, i.e. typical high flow period. The low flow and high flow discharge correspond to approximately 41,000 and 298,000 cfs in this reach, respectively.

The Bradley model computes water surface drops at RS 661.9772 and 664.8647 of 10-18 ft during low flow and 10-16 ft during high flow. For comparison, with the original geometry of Bradley, the water surface drops at low and high flow at the Little Dalles for these discharges are approximately 15 and 26 ft, respectively. Although some constriction of the channel may occur near RS 6661.9772 (**Figure 30**) neither the 1898 chart nor the 1930 aerial photo show significant turbulence or whitewater in the vicinity. The former does note a measured flow velocity of 6 miles per hour (9 fps) near this area. At RS 664.8647 (Figure 31) however, there is no apparent constriction or whitewater, and the 1898 chart notes a flow velocity of 1.5 miles per hour (1.8 fps). The historical data, particularly the 1898 charts, were presumably developed for navigation, thus it's unusual that the Bradley hydraulic model is predicting features that would pose significant barriers where none were noted. Conversely, at the upstream end of the reach near Spencer's Bar (**Figure 32**), both the 1898 chart and aerial photo indicate rapids occurring, while the Bradley model indicates a relatively flat water surface profile.

5.5.6 MODEL PREDICTIONS OF DEPOSITION PRIOR TO GRAND COULEE DAM

Bradley's model appears to greatly over predict deposition of LeRoi slag, mill tailings and mine waste during the period prior to Grand Coulee Dam. For example, the model predicted 59% of the LeRoi slag was deposited in the river, even though all of these discharges took place before Grand Coulee Dam was constructed. My historical assessment of the Columbia River prior to Grand Coulee Dam showed the river was a fast-flowing and powerful with rapids, boulders, falls and eddies and would have transported sand-sized sediment (including slag , mill tailings and mine waste in suspension as wash load. Only a small fraction would have been trapped in the gravelly bed and on sandy and gravelly bars along the margins of the channel in back eddies.

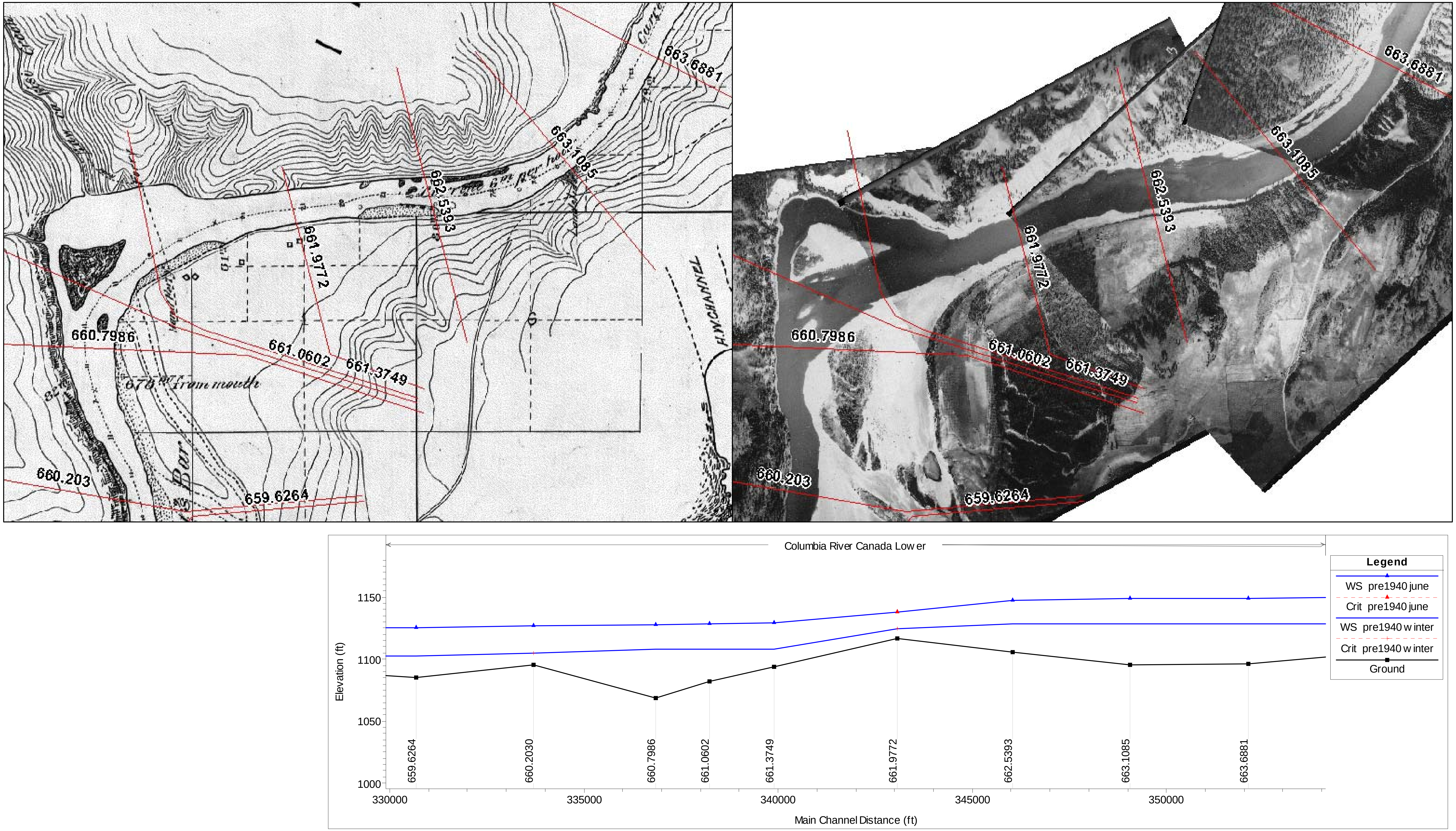


Figure 30. USACE 1898 chart, 1930 aerial photo, and computed water surface profile at the downstream end of Elbow Bend.

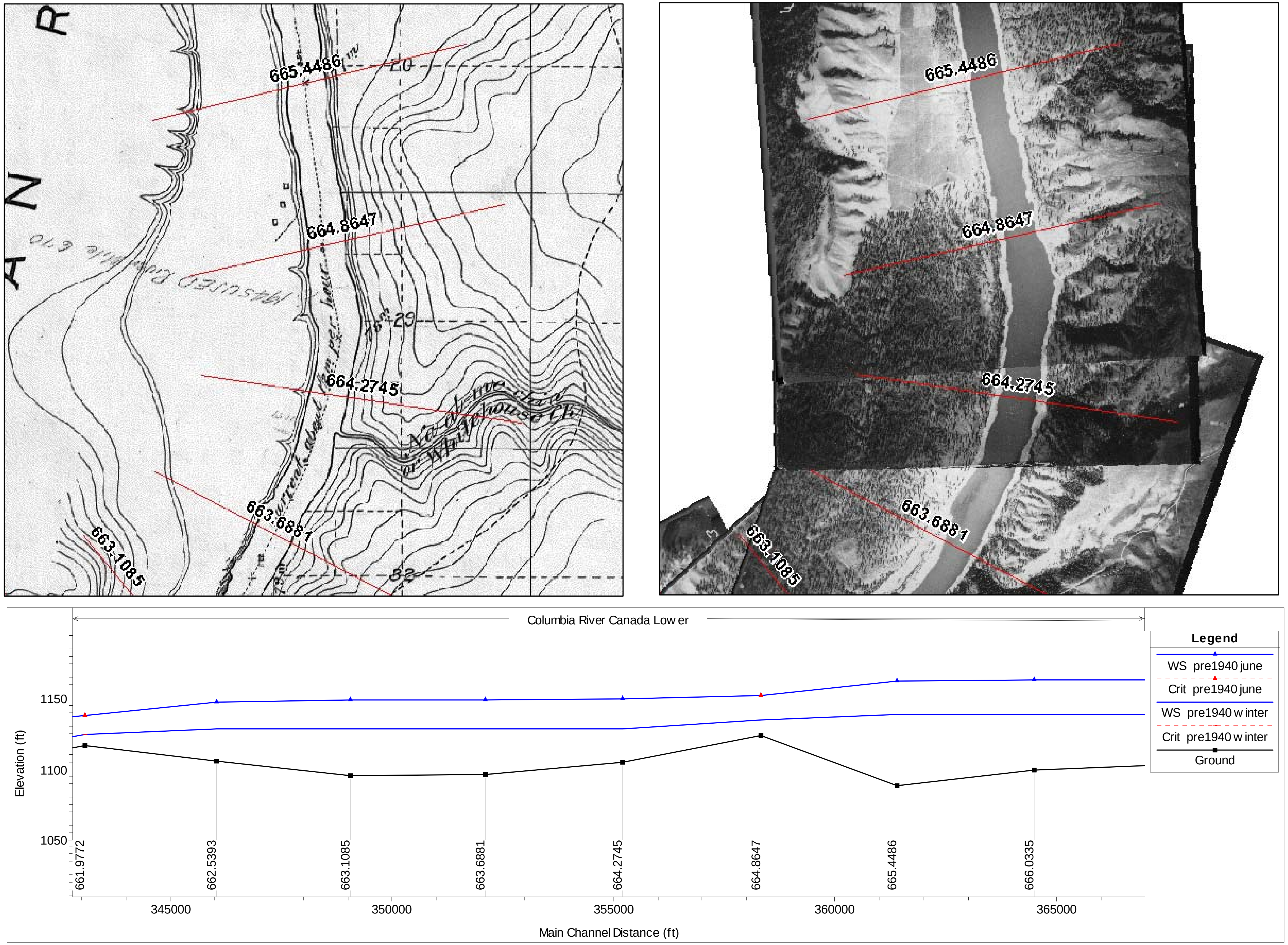


Figure 31. USACE 1898 chart, 1930 aerial photo, and computed water surface profile midstream at Elbow Bend.

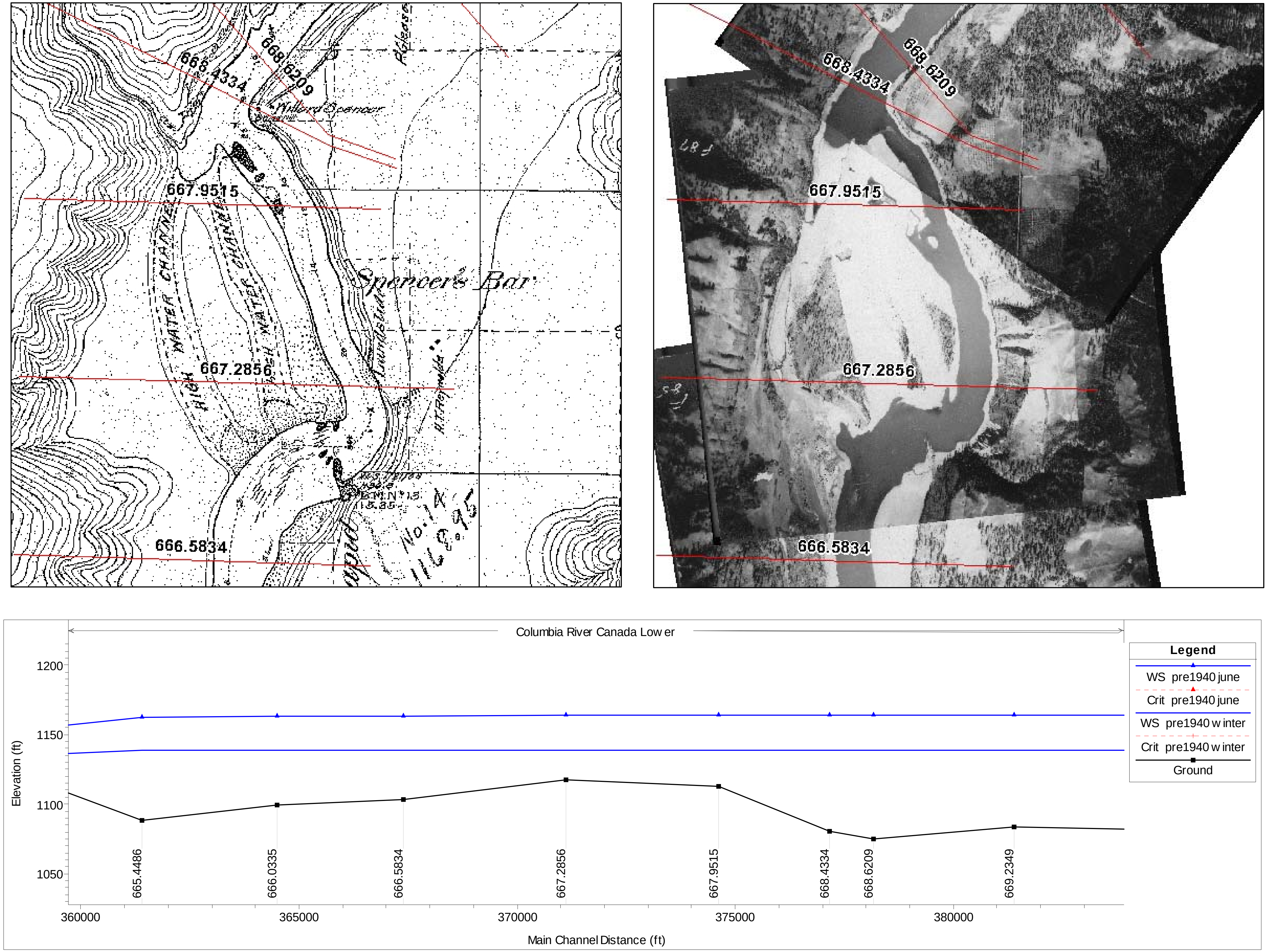


Figure 32. USACE 1898 chart, 1930 aerial photo, and computed water surface profile at the upstream end of Elbow Bend.

5.6 SUMMARY OF FINDINGS

Bradley's model cannot be used to quantify the distribution of sediment deposits in the Upper Columbia River or the relative contributions of deposits from various sources (slag, alleged mill tailings and mine waste and natural sediment) since it was not validated against measurements of sediment transport or historical sediment deposition patterns. Uncertainties and errors in key input data (such as sediment inflows from tributaries, mill tailings and mine waste and channel topography) are very large and make quantitative comparisons unreliable. Furthermore, errors in the assumed channel geometry generate instabilities in the hydraulic and sediment computations, which produce unrealistic conditions (waterfalls that do not exist and massive build-ups of sediment that do not occur).

6 REVIEW OF REPORT BY DR. A. RIESE

6.1 SUMMARY OF RIESE'S OPINIONS

Riese provides opinion on whether slag discharged at the Trail smelter and found within the UCR releases CERCLA hazardous substances and whether there are other CERCLA hazardous substances.

6.2 CRITIQUE OF OPINIONS

Riese stated that McLean (2010) underestimated the specific gravity of Teck slag, but did not provide any reference or any supporting data. This issue was discussed in Appendix A.

In Opinion 1, Riese discussed characteristics of slag from Fort Shepherd eddy, but provided no information on who collected this material, how much was collected, how it was collected, when it was collected, and who analyzed the samples. There is an accompanying memo from Teck that mentions Fort Shepherd samples, but it is unclear if this is the correct reference. In Opinion 3, Riese stated that the mass of each element gained or lost per unit time has not reduced to account for slag still present in Canada, but does not explain why this was ignored.

In Opinion 4, Riese stated that slag from Northport can be distinguished from Teck slag. He quoted McNulty in providing the historic slag production at Northport. McNulty listed additional sources of slag, and other Teck experts (i.e. Brown) also refer to other smelters. Riese did not discuss these even though he acknowledged that they exist and even provided a map (his Figure 7) showing other sources. There is no explanation as to why these other mills and smelters are not discussed any further. In general, it is not clear why each of Teck's experts is not discussing a consistent set of mines, mills and smelters, or why they include some that contribute an insignificant fraction of total releases from all sources.

Riese compared particle sizes between Northport slag and other sources but provided no citations for source of information.

On page 61 of his report Dr. Riese made calculations to estimate the residence time of river and lake waters in contact with bottom sediments. This somewhat involved calculation concluded that the residence time corresponded to the time for water to travel 1 meter along the lake. The average velocity (U) in the reservoir was estimated to be 0.0525 m/s (0.17 feet/sec). The "residence time" (Tr) was computed simply as the inverse of the velocity:

$$Tr = 1/U = 19 \text{ seconds}$$

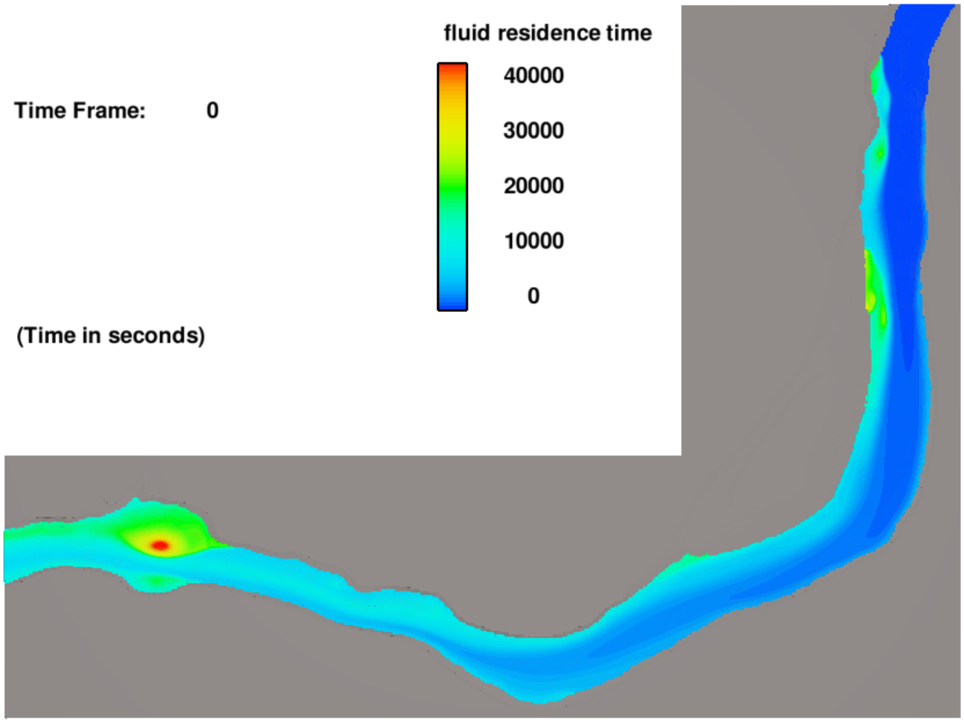
This value does not represent the residence time for water or suspended sediment to move through the reservoir, it simply represents the time required to travel a distance of 1 meter. The parameter has no other physical significance. The actual residence time for water flowing through the reservoir is expressed as:

Tr = Vol/Q where Vol is the total volume of water contained in the reservoir and Q is the mean annual discharge.

The total storage volume of reservoir (V) is about 9.4 million acre-feet. The average annual flow (Q) on the Columbia River is approximately 98,840 cfs. The average residence time (Tr) of the reservoir is approximately 47 days assuming steady flow conditions. This represents the average time a particle of water would spend travelling through the reservoir before being discharged through Grand Coulee Dam. The distance from Northport near the head of the reservoir to Grand Coulee Dam is about 138 miles. Therefore, the average speed of the water is 138 miles/47 days = 2.94 miles/day or 0.18 feet/sec. During this 47 day period water and suspended particles would undergo continuous mixing throughout the water column due to turbulence, secondary currents and other processes. There is no relation between the average time for water to travel a distance of one meter (Riese's "residence time") and the time that water will be "in contact" with the bed of the river or reservoir.

As demonstrated in Appendix D, fluid residence time is sensitive to the complexity of the river channel. Water particles entrained into eddies can spend a considerable amount of time rotating inside them, therefore increasing significantly their overall residence time. The 3D model of China Bend shown previously in Figure 17 was also used to compute the fluid residence time. Figure 34 shows that residence time at center of the large eddy near Flat Creek is considerable larger than in the main channel. Also, solid particles simulating slag were fed at the upstream inflow of the model to observe their movement. Figure 34 shows two snapshots of particles at the beginning and 20,000 seconds after being released upstream. The solid particles concentrate where the fluid residence time is higher, such as eddies.

Finally Riese provided opinions on the formation of alteration rims by hydration on Teck slag and its alleged role in the release of metals. I have no comment on the chemistry aspects. However, my observations are that slag is easily broken and friable. During sediment transport in the gravel cobble environment of the Upper Columbia River, I expect that slag particles will be subject to abrasion and will breakdown. Abrasion and attrition of sediment particles is well documented along rivers. Attal and Lave (2009) reviewed abrasion rates of pebbles and reported typical attrition rates (expressed as % mass loss/km of river length) of 0.1 to 10. Over long distances this will cause a significant wearing of the particles, creating new fresh surfaces that are exposed to the flow. This abrasion process is not accounted for in either Riese or Johns.



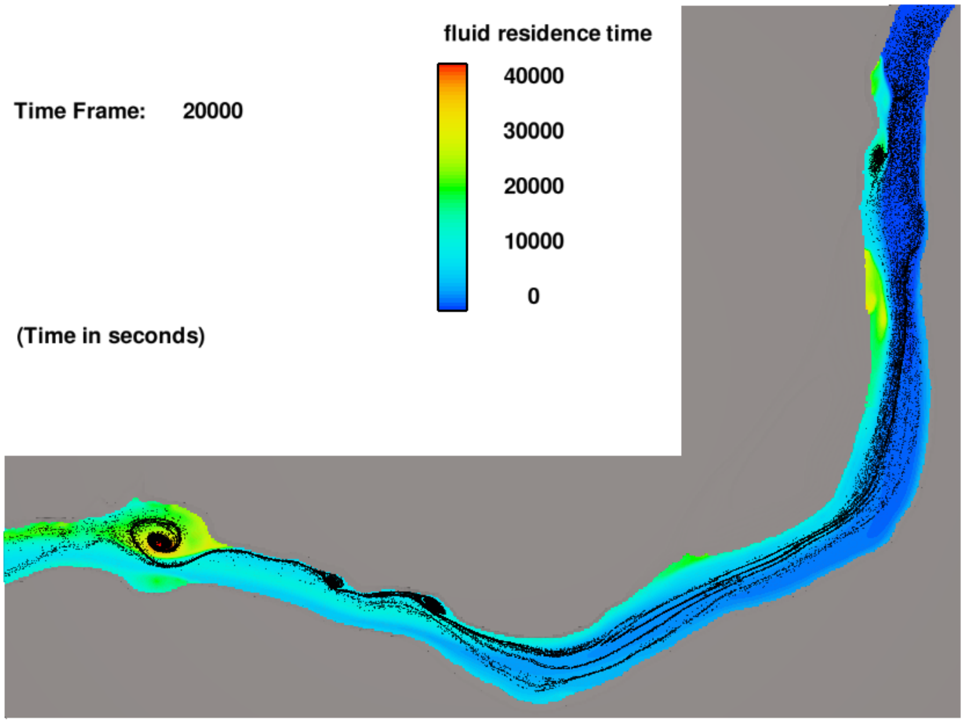


Figure 34. Residence time and slag particles computed by 3D model at China Bend

7 REVIEW OF REPORT BY DR. M. JOHNS

7.1 SUMMARY OF DR. JOHNS'S OPINIONS

Dr. Johns opinions are as follows:

The harm in this case is the extent of sediment contamination by hazardous substances released at the site. This harm can be apportioned and is divisible based on the relative proportion of metals released at the site by different sources.

He alleged that the primary sources of sediment identified were landslides (49%) and tributary sediment loads (25%) with the remainder contributed by mines, mills and smelters, including Teck smelter.

7.2 CRITIQUE OF DR. JOHNS' OPINIONS

I have provided opinions only on issues directly relating to hydraulics, erosion and sediment transport, particularly on his assumptions that were made concerning sediment discharges and sediment deposition along the Columbia River and in Lake Roosevelt.

7.2.1 RELIANCE ON SEDIMENT DISCHARGES FROM BROWN AND BRADLEY

Dr. Johns' analysis relied on results from other studies for determining discharges of sediments and waste rock from mines, mills and smelters and the quantities of sediment retained in Lake Roosevelt. As previously noted, the uncertainties in Brown's sediment discharges from mill tailings and mine waste are very large and over-predict the discharges to the Columbia River. Bradley's one dimensional sediment model was never validated against actual sedimentation rates and contains several inherent errors that make it unsuitable for quantifying sediment volumes from various sources.

7.2.2 SEDIMENT INPUTS FROM LANDSLIDES

Johns looks at the contributions of metal-bearing sediments from a variety of sources and estimated the total volume delivered to Lake Roosevelt was 82.3 million tons, of which 40.7 million tons (49%) was delivered from landslides alone.

In an effort to determine whether the erosion volume estimates presented by Johns are reasonable, two of his reported landslide volume estimates (for Monaghan Grade and Reed Terrace) were independently computed following the same general approach described in his report. Johns also cites a bulk density of 1.67 g/cm^3 in his appendix text (Exhibit E) which is slightly larger than the value reported in the main text (1.64 g/cm^3). The 1948 USGS topographic maps for Hunters and Kettle Falls (provided in Johns' facts and data considered) were rectified by digitizing 4 lat/long coordinates and re-projecting the map in ArcMap GIS from Geographic coordinates (Nad27) to UTM Zone 11N (Nad83). Comparison of the reservoir shoreline on the projected map showed very close correspondence to a recent (2007) orthophoto. The contours that encompassed the slide areas (based on the more recent orthophoto) were digitized to

ensure that the entire slide area / volume was captured and elevations were converted to NAVD88. A boundary was defined around the contours and a digital elevation model (DEM) was constructed using the Topogrid function in Arc/Info. A second DEM was constructed from the most recent National Elevation Dataset (NED) using the same spatial boundary. The cut/fill function was used to determine erosion, deposition and net volume changes.
Results of the analysis reveal a net loss of 307.6 million cubic feet of sediment at Reed Terrace, somewhat less than the 396.6 million cubic feet reported by Johns. At Monaghan 1, a net loss of 5.4 million cubic feet was calculated, which is actually greater than reported by Johns (3.9 million). The difference was much greater at larger Monaghan 2 site where the calculated net loss is 90.1 million cubic feet, nearly 3 times greater than reported by Johns (33.7 million). These differences – despite nearly identical analytic procedures – illustrate limitations of Johns analysis. This occurs because small errors in geo-registration of the old maps and deviations in digitizing the old contour lines (i.e. horizontal errors), can produce large differences in volumetric calculations where vertical changes in surface are large or slopes are steep.

This analysis indicates that the total estimated input of landslide material Johns reports is not reliable. The main problem with Johns analysis is that all sediment estimated to have been eroded from the surface above full reservoir pool is considered to have entered Lake Roosevelt and mixed with sediments derived from other sources. This assumption is misleading, and in some cases, incorrect. The large deposits of unconsolidated Pleistocene terraces common along reservoir margins are comprised of glacio-lacustrine sands, silts and clay, glaciofluvial deposits, fluvial sand and gravel, alluvial fan deposits and wind-blown sand (Jones, 1961). Cobbles and large material may be found inter-bedded with these other materials. Only the finer fractions of material eroded from landslides will necessarily move to the deeper parts of the reservoir depending on the local underwater topography. The underwater profile of the reservoir can be determined from the late 1940s available hydrographic survey completed by US Coast and Geodetic Survey, but Johns ignores this information in his analysis.

The different combinations of available sediments result in the different type of landslides that are known to commonly occur, including slump-earthflows, multiple alcove landslides, slip-off slope landslides and mudflows (Jones et al., 1961). Carpenter (1984) points out that landslide type refers to the form of movement, including sliding, falling or flowing and that the slope mass can move as intact material, broken blocks or as a viscous liquid. Although Johns acknowledges that many different slide types exist, he treats the fate of eroded material exactly the same in each case, which is not correct. For some type of landslides, eroded sediments or blocks of material may slide underwater and remain largely intact adjacent to the reservoir margins at the toe of the slide. As Jones does not discriminate between different types of landslide sediment, and fails to quantify the volume that remains at the toe of the submerged landslides, he over-estimates the volume of material – hence metals – transported to depth in Lake Roosevelt and mobilized by reservoir currents.

7.3 SUMMARY OF FINDINGS

Given the inadequate field data and validated results, the relative contribution from the various sources is presently unknown, and indeed is probably unknowable at the present time.

8 CONCLUSIONS

Based on my review of the available data and the actual analysis carried out by other Teck experts, I conclude that the available information and data are inadequate to develop a reliable, quantitative sediment budget of the Upper Columbia River and Lake Roosevelt.

Methods used to estimate the sediment discharges from mill tailings and mine wastes retained in the Columbia River were oversimplified and expected to significantly overestimate the actual sediment loads discharged to the river. No field measurements or site specific surveys were used to calibrate or verify any of the computations although this could have been carried out. The quantities should be considered as “order of magnitude” rather than as quantitative estimates.

Bradley’s model cannot be used to quantify the distribution of sediment deposits in the Upper Columbia River or the relative contributions of deposits from various sources (slag, alleged mill tailings and mine waste and natural sediment) since it was not validated against measurements of sediment transport or historical sediment deposition patterns. Model predictions do not agree with field observations and produce unrealistic conditions (waterfalls that do not exist and massive piles of sediment that do not occur).

Given the lack of direct field measurements and absence of validated results, the relative contribution of sediment from the various sources is presently unknown, and indeed is probably unknowable at the present time.

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PHOTOGRAPHS

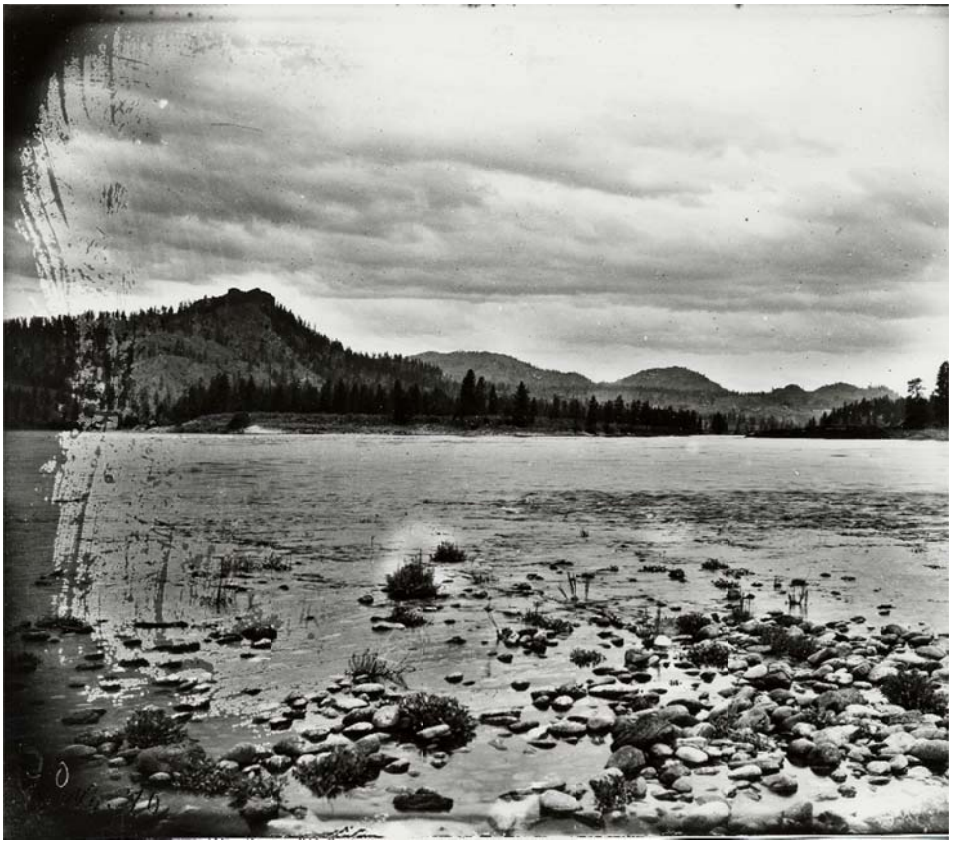

Photo 1: Elbow Rapid

River Mile 600

(all photos taken in 1892)

Photo 2: Turtle Rapid

River Mile 605

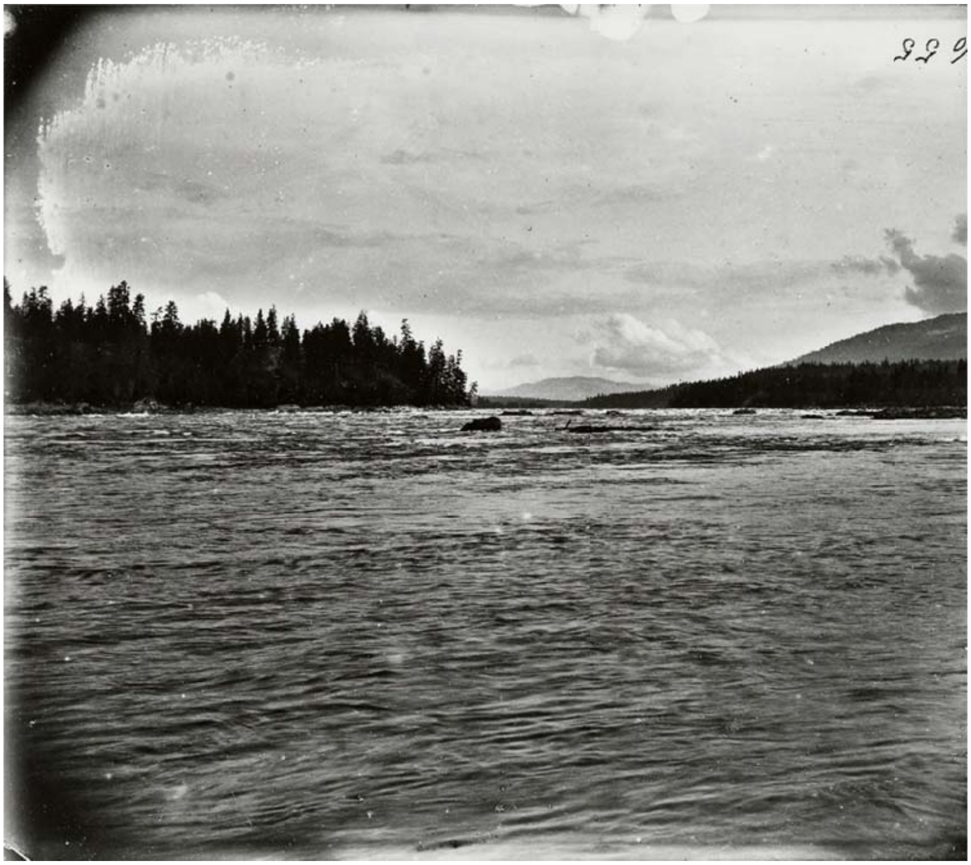

Photo 3: Grand Rapids

River Mile 650

Photo 4: Kettle Falls

River Mile 670

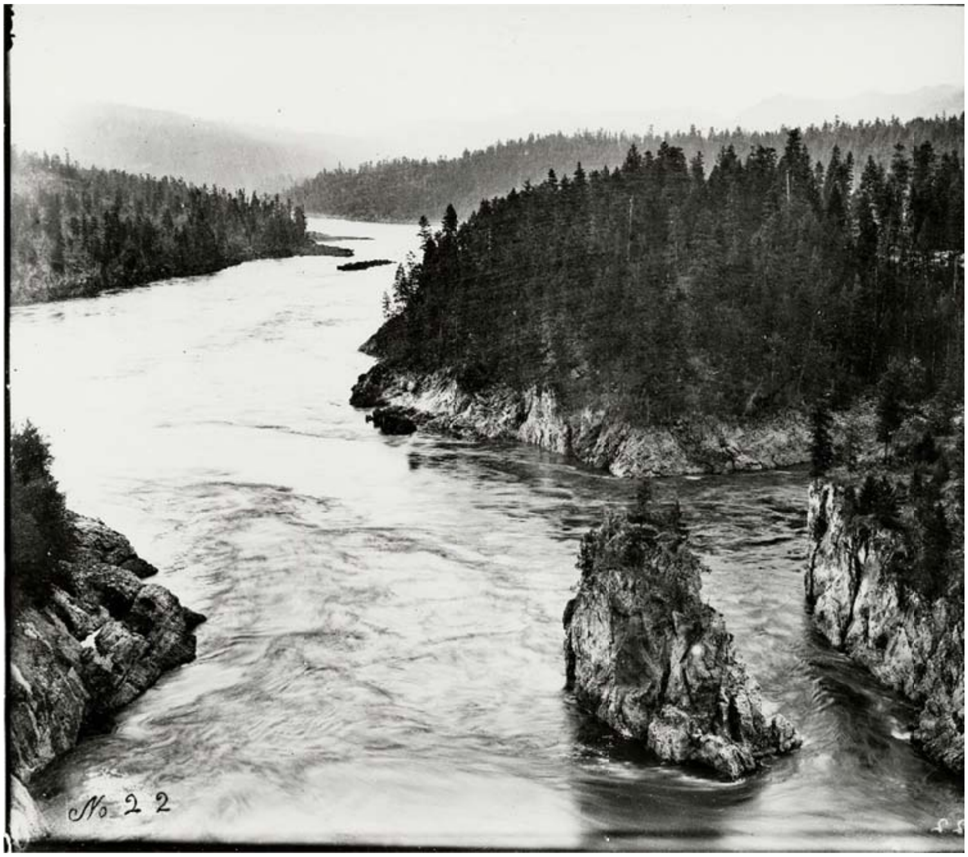

Photo 5: Little Dalles

River Mile 728

Photo 6: Murphy's Rapid

River Mile 743