IDENTIFICATION OF RELICT FLOODPLAIN AREAS ALONG THE UPPER COLUMBIA RIVER

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INTRODUCTION

Studies are underway to examine potential impacts that metallurgical waste (slag) from a smelter has on the upper Columbia River (UCR), from the U.S.-Canadian border (U.S. Geologic Survey [USGS] river mile [RM] 745) downstream to Grand Coulee Dam (USGS RM 596). Slag is present in some areas of the river bed and may also occur in periodically inundated floodplain areas. The potential occurrence of slag in floodplain areas is influenced by water surface extents during floods. However, river flow regimes during the period of slag release have been extensively modified as a result of dam construction and flow regulation. As a consequence of flow modification, flood extents have changed over time. One-dimensional (1-D) hydraulic analyses were conducted to estimate water surface elevations and relict floodplain extents along approximately 240 kilometers (km) (~150 miles) of the site. Analyses were conducted using a number of geographic information system (GIS) and hydraulic analysis tools, including: ArcGIS 9.3 (ESRI 2008), HEC-GeoRAS 4.2.93 (USACE 2008a), and HEC-RAS 4.0 (USACE 2008b). Geostatistical methods were used to interpolate river bathymetry and cross-sectional characteristics based on site-specific data. Results of bathymetric analyses provide information to perform water surface elevations and hydraulic calculations. Parameter values for water surface elevation calculations were determined by calibration to stage, and verification with cross-sectional area, and velocity measurements. Analyses were then conducted to estimate historical (relict) and present-day (active) floodplain extents. It is anticipated that these analyses will help to identify relict floodplain areas where samples would be collected to determine the potential occurrence of slag and any associated environmental risks.

DEVELOPMENT OF A SITE-SPECIFIC DIGITAL ELEVATION MODEL

River channel characteristics, particularly shoreline extents and river bed, island, and land surface (floodplain) elevations must be defined before hydraulic calculations can be performed. Site-specific data sources describing UCR channel, island and floodplain characteristics include the following:

- ♣ River and island shorelines based on aerial images from the U.S. Department of Agriculture (USDA) National Agriculture Imagery Program (NAIP);
- ♣ Water depth measurements (soundings) collected by the U.S. Coast and Geodetic Survey (USCGS);
- ♣ Channel cross-section measurements collected by the U.S. Geological Survey (USGS) at a monitoring station near the US-Canadian border;

- ♣ Land surface (island and floodplain) elevations from the USGS National elevation Dataset (NED); and
- ♣ Land surface (island and floodplain) elevations collected using Light Detection and Ranging (LIDAR).

Geostatistical methods and geographic information system (GIS) software were used in conjunction with these site-specific data to define shoreline extents and channel characteristics. Descriptions of the data analysis process follow. The end result was digital elevation model (DEM) that provides a continuous representation of river bottom, island, floodplain, and land surface elevations. The horizontal datum was the North American Datum of 1983 (NAD-83) and the vertical datum was the North American Vertical Datum of 1988 (NAVD-88).

Shoreline Extents

River bank and island shoreline locations were determined from digital aerial images obtained from the USDA NAIP. Images for the area were collected in 2006. River bank and island shorelines in these images were digitized using GIS software. In subsequent DEM development steps, shorelines from NAIP images were used as boundaries to determine which data source would provide elevation data for site features (e.g. river bed, islands, and floodplain or upland areas).

River Bed Elevations

Water depth measurements (soundings) from the U.S.-Canadian border to Grand Coulee Dam were collected by the USCGS as part of an extensive set of hydrographic surveys completed from 1947 to 1949 (USCGS 1950). The average distance between any sounding and its nearest neighbor is less than 30 m (100 ft) and the maximum distance between two adjacent soundings is approximately 420 m (1,400 ft). These data provide the basis for present-day National Oceanic and Atmospheric Administration (NOAA) nautical charts for the site (i.e., Charts 18551 and 18553). Soundings were converted to bed elevations by subtracting reported depths from their applicable reference water surface elevations and converted to the NAVD-88 datum using U.S. Army Corps of Engineers (USACE) CORPSCON software.

These discrete bed elevation measurements were interpolated by kriging to generate a continuous bed elevation surface. Kriging and associated GIS operations were performed using ArcGIS 9.3 (ESRI 2008) with the Spatial Analyst and Geostatistical Analyst Extensions.

Kriging parameters were optimized by iteratively determining the root-mean-square (RMS) error of bed elevation cross validation calculations. With the final kriging parameter values, the RMS error for bed elevation was 3.14 m (10.3 ft).

Island and Land Surface Elevations

Island and land surface elevations were obtained from the USGS NED DEM as well as LIDAR measurements reported by Watershed Sciences, Inc. (WSI) (WSI 2007). The USGS NED provides elevations for the entire site with a 30 meter (~100 ft) (1 arc second) resolution and are reported in the NAVD-88 datum. NED data were acquired from the USGS National Map Seamless Server (http://seamless.usgs.gov/index.php). The LIDAR system was comprised of two aircraft-mounted lasers that were flown over the site. The LIDAR data were collected during October and November, 2006 and are highly detailed, covering an area of more than

99,000 acres with a density of more than 8 measurements per square meter (WSI 2007). These data were processed by WSI into a DEM with a 30 m resolution (~100 ft) resolution and are reported in the NAVD-88 datum. The vertical accuracy of LIDAR measurements was ± 0.05 m (0.16 ft) as determined by comparison to ground-based survey measurements (WSI 2007). In terms of distance along the river, the region over which LIDAR data exist runs from approximately RM 737 to a point just downstream of RM 690 and includes land surface areas along river shorelines (Figure 1).

Because of their high accuracy, LIDAR measurements were preferentially used to assign island and land surface areas in areas where LIDAR measurements existed. Outside of the LIDAR coverage area, island and land surface elevations were assigned using NED values. Islands and seasonally emergent rocks within river shorelines are defined based only on features visible from NAIP aerial images, LIDAR measurements, or otherwise captured in NED data.

Site Specific Digital Elevation Model

River bed, island, and land surface elevations were used in conjunction with shoreline extents to generate a site-specific DEM with a 30 m (~100 ft) resolution. Interpolated (kriged) river bed elevations were used to define elevations for all areas within the river shorelines, exclusive of islands. Islands and land surface areas within the area of LIDAR data coverage were assigned LIDAR elevation values. Islands and land surface areas outside the LIDAR coverage area were assigned NED elevation values. The site-specific DEM combining river bed, island, and surrounding upland elevations is displayed in Figure 1. A close-up display of the site-specific DEM in the area near RM 735 (Northport, WA) is presented in Figure 2.

1-D HYDRAULIC ANALYSES

Set-Up

One-dimensional, steady flow hydraulic analyses were performed using HEC-RAS 4.0 (USACE 2006) software. River channel and floodplain geometry for the analyses were generated from the bathymetric surface using the HEC-GeoRAS 4.2.93 (USACE 2008a) extension to ArcGIS. From RM 745 to 596, a total of 414 cross-sections with a typical spacing of 500 to 750 m (1,600 to 2,500 ft) were defined and exported from ArcGIS using HEC-GeoRAS. This information was imported into the HEC-RAS geometry editor. Within HEC-RAS, 8,108 additional cross-sections were interpolated to ensure proper computation of water surface elevations. The maximum spacing between interpolated cross-sections was 30 m (~100 ft). In an area immediately adjacent to RM 729, the maximum spacing for interpolated cross-sections was 10 m (~33 ft). The resulting total number of specified and interpolated cross-sections in HEC-RAS was 8,522.

Calibration

For this analysis, flow was assumed to be steady and subcritical. The primary calibration variable is the flow resistance coefficient (Manning n). Calibration data included flow and water depth measurements collected by the USGS at the international border between 1985 and 2006, water surface elevation measurements reported by Survey Solutions, Inc. during a December 2006 limited topographic survey near RM 743, and Acoustic Doppler Current Profiler (ADCP) measurements collected by the Washington Department of Fish and Wildlife (WDFW) near RM

734 and 735. These data sources provide a total of 94 cases for calibration, focused on the upper 20 km (12 miles) of the site.

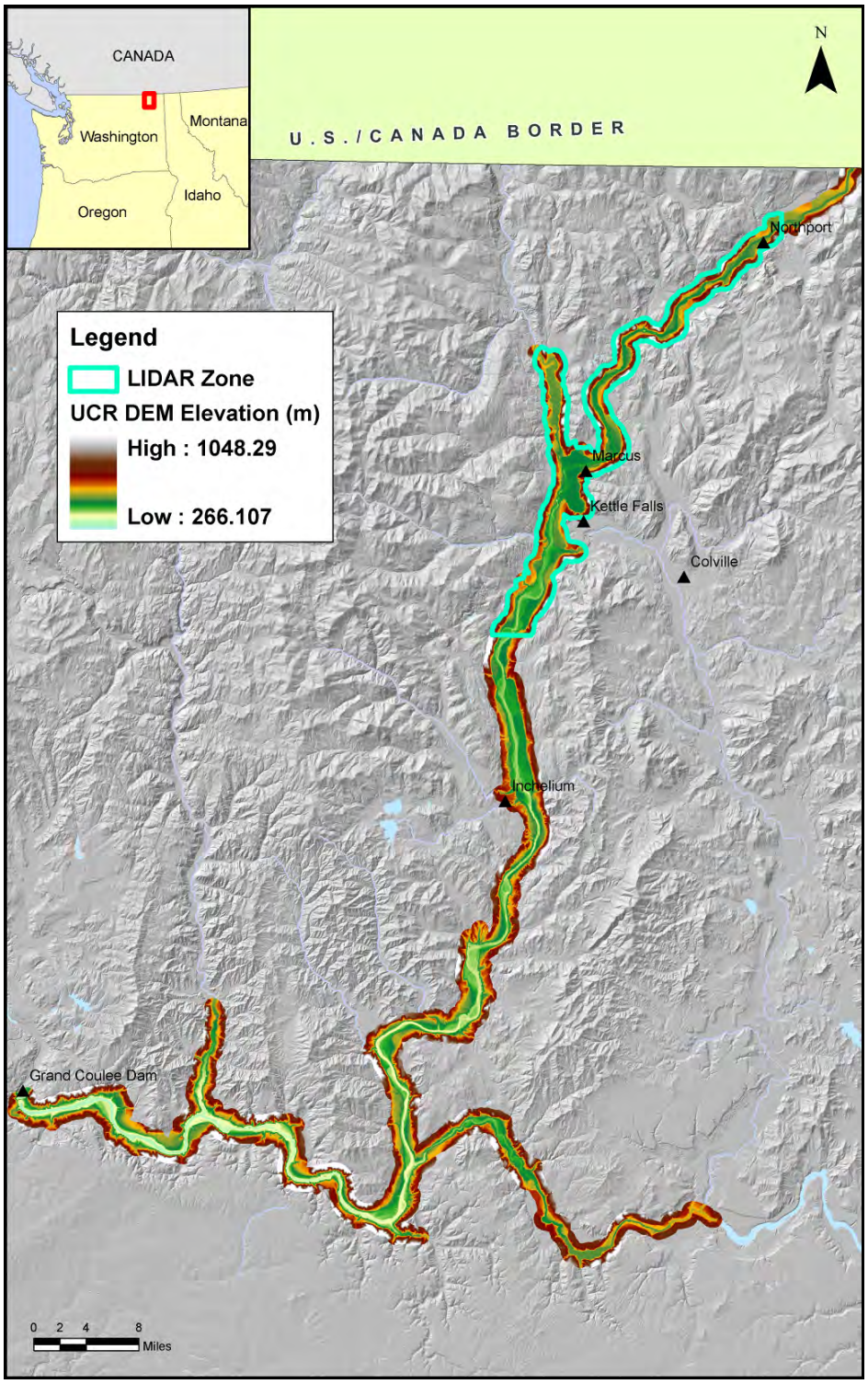

Figure 1 Site-Specific Digital Elevation Model: Upper Columbia River from U.S.-Canadian Border to Grand Coulee Dam.

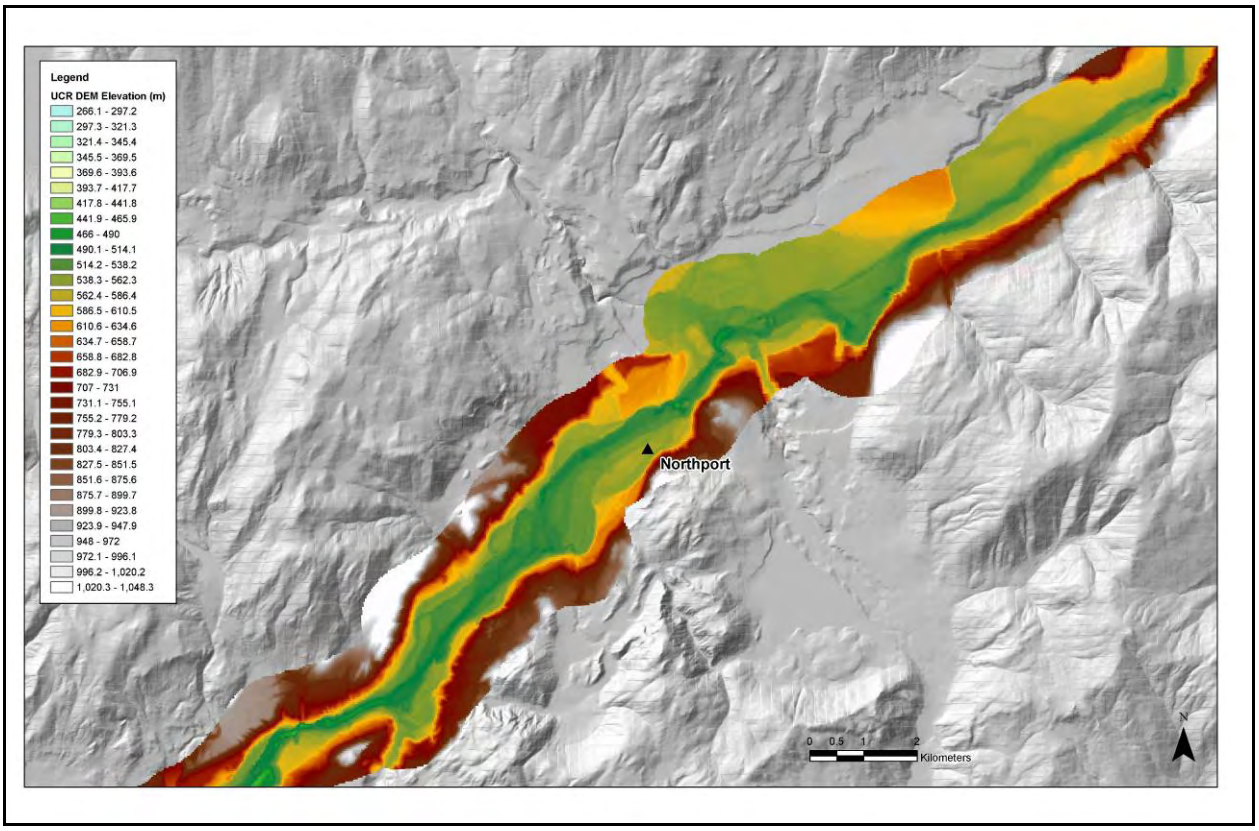

Figure 2 Site-Specific Digital Elevation Model: Upper Columbia River: near RM 735; Northport, WA.

Flow resistance was calibrated by iteratively comparing calculated water surface elevations to measurements and calculating the average RMS error for each Manning n value examined. During calibration, Manning n values were assumed to be constant for all cross-sections (i.e. spatially uniform) and were incrementally varied from 0.024 to 0.044. HEC-RAS calculations were performed for each Manning n value assessed and average RMS errors between calculated and measured water surface elevations. A summary of calibration results is presented in Table 1. A Manning n value of 0.032 generated the minimum RMS error.

Table 1 Summary of HEC-RAS Calibration Results.

Manning n	*Root Mean Square Error (m)*	*Notes*
0.024	0.854	
0.030	0.224	
0.032	0.136	
0.032 u/s, 0.024 d/s	0.136	Manning n values differ upstream (u/s) and downstream (d/s) of RM 729
0.033	0.188	
0.034	0.270	
0.038	0.644	
0.044	1.198	

Results

Comparisons of calculated and measured water surface elevations at the U.S.-Canadian border are presented in Figure 3. The average RMS error between calculations and measurements was approximately 0.14 m (0.45 ft). Comparisons of calculated and measured flow velocities and cross-sectional areas at the RM 744 (USGS Cableway) and RM 734-735 (WDFW ADCP) transects are presented in Figures 4 and 5, respectively. A representative downstream water surface profile is presented in Figure 6. Results are shown for flow and pool conditions that occurred on June 10, 1997, corresponding to a flow condition approximately equal to the largest post-1973 flood.

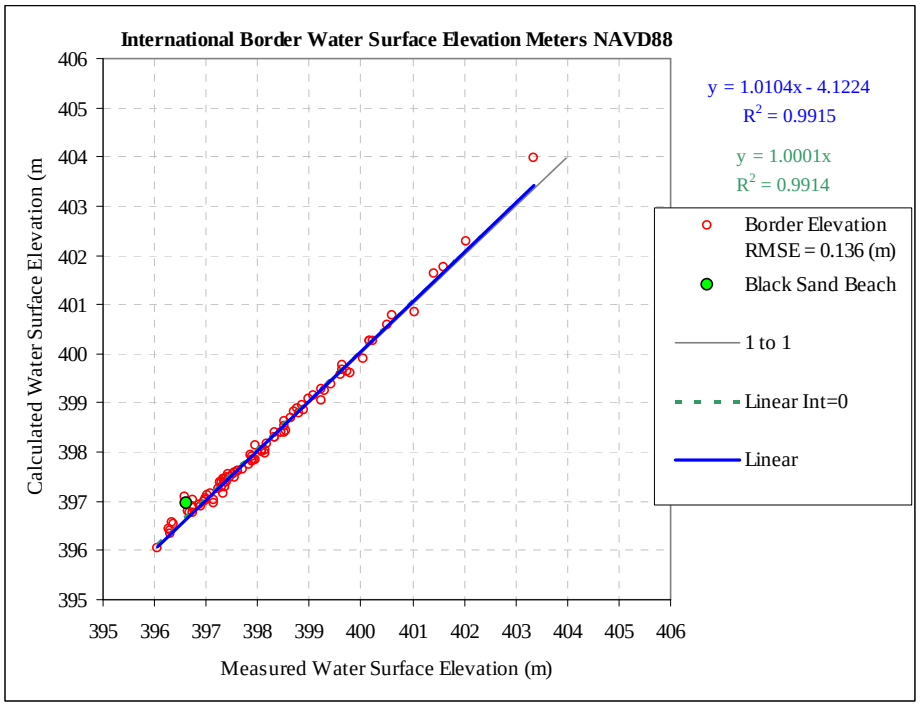

Figure 3 Calculated versus measured water surface elevation at the U.S.-Canadian border and including measurements at RM 743. Note: regression equations are shown for cases where the intercept of the regression is assumed to be zero (dashed green line) or allowed to be non-zero (solids blue line). The 1-to1 line represents perfect agreement.

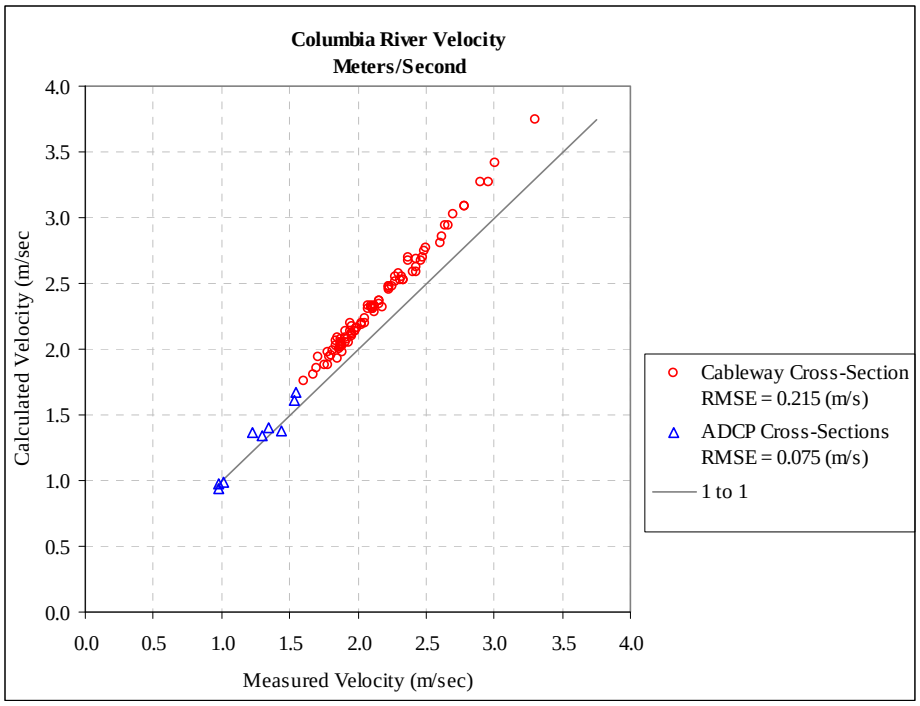

Figure 4 Calculated versus measured velocity in the areas of the RM 744 (USGS Cableway) and RM 734-735 (WDFW ADCP) transects.

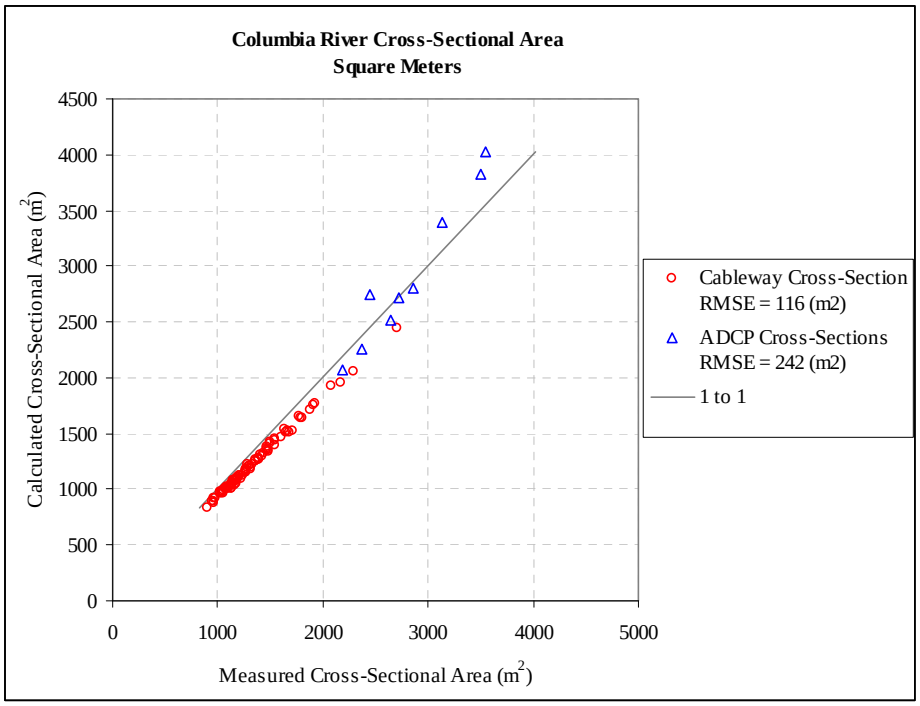

Figure 5 Calculated versus measured cross sectional area in the areas of the RM 744 (USGS Cableway) and RM 734-735 (WDFW ADCP) transects.

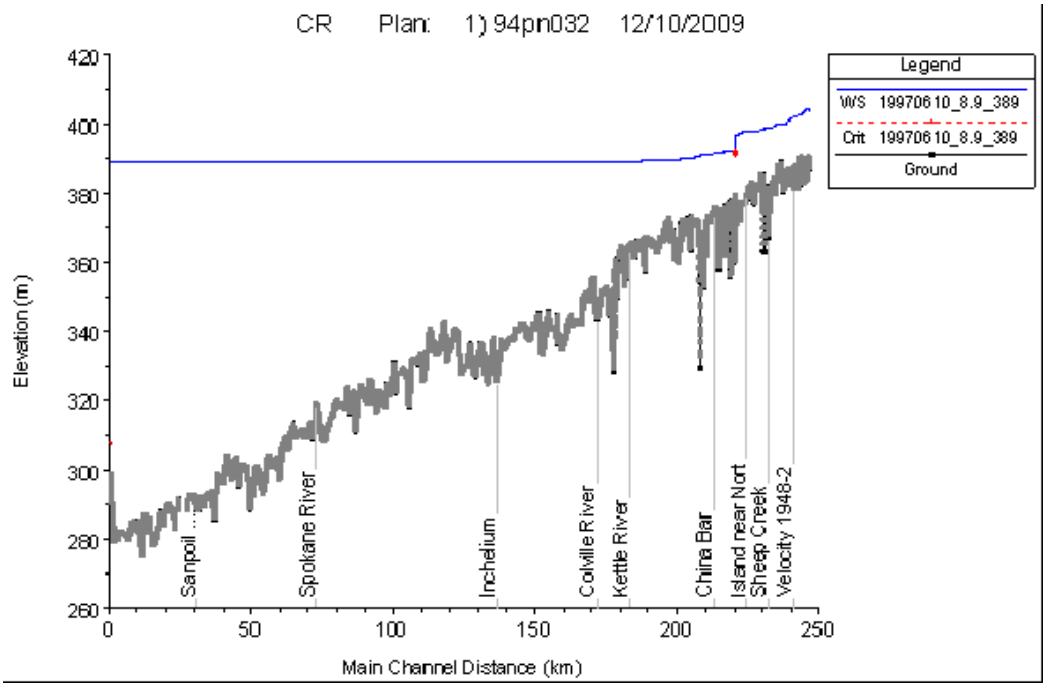

Figure 6 Example HEC-RAS Water Surface Elevation Profile: U.S.-Canadian Border to Grand Coulee Dam for June 10, 1997. Flow at border was 8,948 m^3/s (316,000 cfs) and elevation at Grand Coulee Dam was 389.08 m (1276.5 ft) (NAVD-88) [388.3 m (1,274 ft) (USBR-37)].

FLOODPLAIN DELINEATION

The areal extent of the UCR water surface for a range of flood conditions was estimated using HEC-RAS. Given changes in upstream flow regulation that began in 1973, flood magnitudes were separately considered for the pre-1973 (pre-regulation) and post-1973 (regulated) periods. Water surface extents were developed for six different flow conditions in descending order of magnitude:

1. The projected 1-in-100-year flow based on pre-1973 flows
2. The maximum recorded pre-1973 flood (June 1948)
3. The projected 1-in-100-year flood based on post-1973 flow data
4. The maximum recorded post-1973 flood (June 1997)
5. The average annual post-1973 flood
6. The average daily flow based on post-1973 flow data.

Estimation of Flood Flows and Magnitudes

Reported annual peak flow data were used to calculate summary statistics (i.e., mean, standard deviation, and skewness) for the pre- and post-1973 periods. This information was used to construct frequency distributions that represent the likelihood of a discharge as a function of recurrence interval (exceedance probability). The standard procedure to determine the recurrence interval associated with a flow event involves fitting stream flow measurements to a probability distribution that is used to extrapolate conditions for the upper tail of the distribution. The choice of probability distribution to use for this extrapolation requires careful consideration

of how well a distribution fits the upper tail of the data as well as the length of the annual flood record. The five probability distributions evaluated for this flood frequency analysis were:

- Normal distribution
- Log-normal distribution
- Gumbel distribution
- Log-Pearson Type III distribution
- Flow duration curve approach (Julien 2002).

Flood magnitude estimates for the six conditions examined using the above-listed probability distributions are presented in Table 2. The appropriateness of any distribution to estimate flood magnitudes depends on the underlying distribution of data and whether the flood record is long enough to reliably estimate larger, less frequent floods. For the UCR, flood records for pre- and post-1973 periods are relatively short (approximately 30 years). In general, limitations of a short flood record can be counteracted by using a distribution that yields a more conservative (i.e., larger) estimate when extrapolating flows for large floods.

Table 2. Estimated and measured flows for UCR floodplain delineation (m^3/s).

Distribution Type	*Pre-1973*		*Post-1973*		
	1-in-100	*Peak Flow*	*1-in-100*	*Peak Flow*	*Average*
Normal Distribution	15,000		8,200		
Log-Normal Distribution	16,400		8,600		
Type I Extreme Value (Gumbel) Distribution	17,948		9,809		
Log-Pearson Type III Distribution	16,033		9,600		
Flow Duration Curve Approach (Julien, 2002)	13,196		9,656		
Measured		15,577		8,637	2,762

The procedure used for the frequency analysis was adapted from standard procedures used by the USGS (Riggs 1968; USGS 1982). As described by the U.S. Interagency Advisory Committee on Water Data (USGS 1982), the Log-Pearson Type III distribution is the recommended approach for flood frequency analysis. However, flood estimates for 100- and 500-year flood events based on the Log-Pearson Type III distribution are smaller than estimates based on the Type 1 extreme value (Gumbel) distribution (Table 2). Given that the short record used for the analysis might not have been sufficiently long to accurately estimate 100- and 500-year flood events, a more conservative approach is appropriate. Therefore, flood magnitude estimates based on the Gumbel distribution were chosen over the other techniques.

Floodplain Delineation Extents

Estimated (or measured) flows for the seven specified flood conditions were entered into HEC-RAS and water surface elevations were calculated. These results were exported from HEC-RAS and imported into ArcGIS for further analysis using the HEC-GeoRAS extension. Floodplains

for each of the seven flood conditions were then delineated. The accuracy of the water surface and floodplain extent calculations was assessed by graphical comparison to floodplain limits for the UCR published by the Federal Emergency Management Agency (FEMA). Calculated flood extents for the estimated post-1973, 1-in-100-year flow were compared to the FEMA 1-in-100-year floodplain. Calculated flood extents are in very close agreement with the published flood zones. Given potential differences in channel bathymetry, flow resistance parameterization, and flow condition used to represent the post-1973 1-in-100-year flood, the correspondence between these two independent analyses suggests that UCR HEC-RAS water surface calculations provide a reasonable basis to estimate flood extents for other flood conditions.

Identification of Active and Relict Floodplain Areas

A primary goal of floodplain analyses was to identify relict floodplain areas along the UCR. For this analysis, a relict floodplain is defined as an area that may have been subjected to flooding under past flow conditions but that is not expected to be flooded under present flow and pool level management controls. Five flow conditions are relevant to this analysis: 1) average daily post-1973 flow at low pool; 2) average daily post-1973 flow at high pool; 3) average post-1973 annual flood; 4) maximum reported post-1973 flow; and 5) maximum reported pre-1973 flow. Water surface extents for the average daily post-1973 flow at low pool define the minimum area expected to be under water at all times (i.e. areas that are always flooded). Water surface extents for the average daily post-1973 flow at high pool defines the area expected to be periodically flooded (i.e. areas that are sometimes flooded) during the year. The average annual post-1973 flood defines the typical limit of the present-day floodplain and represents the area expected to be inundated once a year. The maximum post-1973 flow defines the area expected to have been flooded once since upstream flow regulation began. The maximum reported pre-1973 flow was 15,577 m^3/s (550,100 cfs) and occurred on June 12, 1948. Water surface extents for the June 1948 flow define the largest area where flooding may have occurred since record keeping began in 1938. The area between floodplains for the maximum post-1973 flow and maximum pre-1973 flow defines a lower bound for relict floodplain extent. The area between floodplains for the average annual post-1973 flood and maximum pre-1973 flood defines maximum relict floodplain extent.

A map showing calculated floodplain extents for daily average flow conditions, annual average flood, and as well as relict floodplain extents for the area around RM 735 is presented in Figure 7. These results indicate that in many locations the pre-1973 maximum floodplain was no larger than present-day floodplain extents. However, in a few locations (e.g., RM 737) the relict floodplain is larger than the present-day floodplain. Based on this analysis, relict floodplain areas exist mainly upstream of approximately RM 729. Downstream of RM 729, relict floodplain areas are expected to be inundated by the Lake Roosevelt pool.

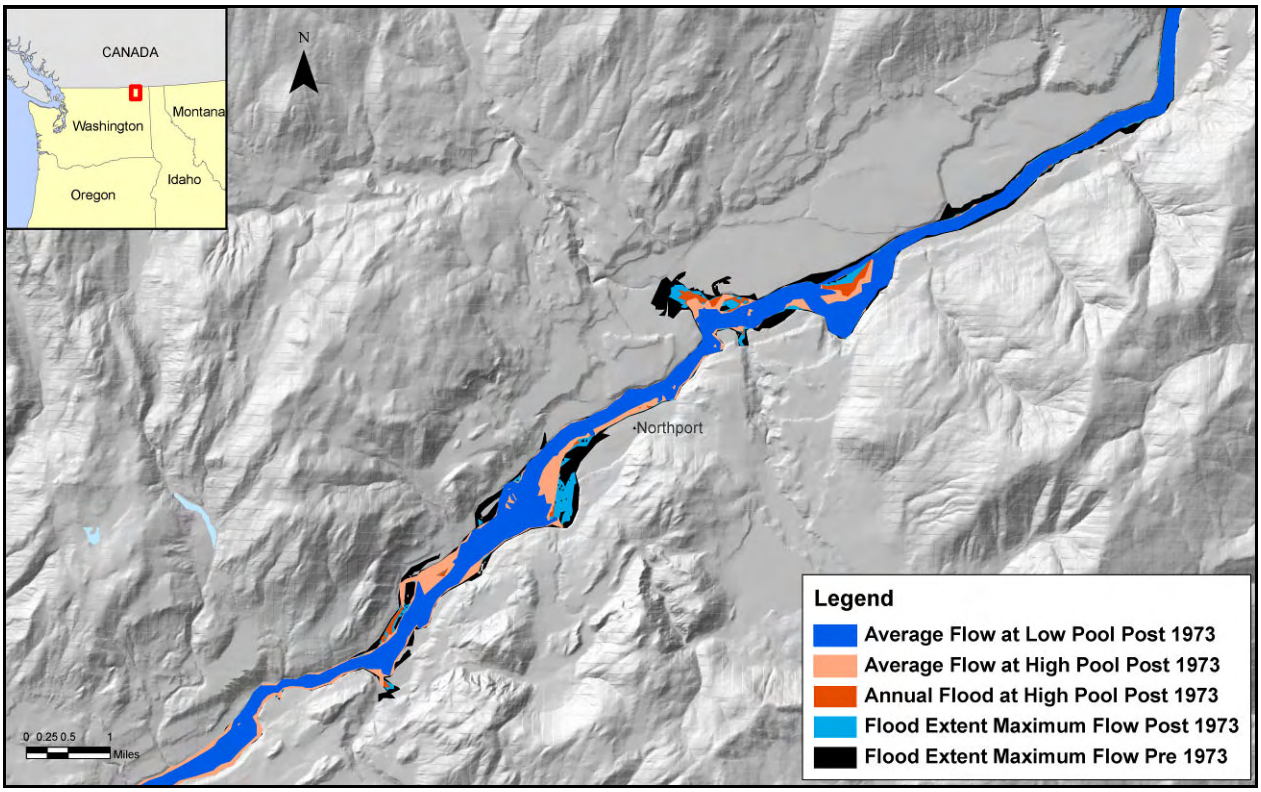

Figure 7 Calculated floodplains for post-1973 average daily flow and pre-1973 maximum flow conditions: area near RM 735 (Northport, WA).

SUMMARY

Relict floodplain extents for the Upper Columbia River were determined by using HEC-RAS to perform a series of water surface elevation calculations. An extensive bathymetric dataset along with NED and LIDAR land surface elevations allowed for the development of a continuous, site-specific DEM for the ~150 mile site. The site-specific DEM was developed to specify channel cross-section properties and adjacent floodplain elevations. HEC-GeoRAS was used to develop inputs and process outputs. HEC-RAS was calibrated by adjusting flow resistance coefficients to minimize the difference between calculated and measured water surface elevations. HEC-RAS was then used to determine water surface extents for floods that reflect differences in historical (pre-1973) and contemporary (post-1973) flow and reservoir pool management conditions.

Identification of relict floodplain areas is relevant to ongoing environmental investigations and will be used to help direct sampling programs that evaluate potential risks to human health and wildlife. These analyses suggest flood extents that occurred under historical flow and pool management constraints were larger than contemporary flood extents in some areas of the river. Specifically, relict floodplains exist between the international border (RM 745) and Little Dalles (approximately RM 729). However, downstream of Little Dalles, relict floodplain areas are expected to be inundated by the Lake Roosevelt pool as controlled by Grand Coulee Dam.

REFERENCES

ESRI. 2008. ArcGIS 9.3. Environmental Systems Research, Inc., Redlands, CA.

Gumbel, E.J. 1958. Statistics of extremes. Columbia University Press, New York, NY.

IJC. 1941. Order of Approval. International Columbia River Board of Control, International Joint Commission.

Julien, P.Y. 2002. River Mechanics. Cambridge University Press, New York, NY. 434 p.

Legleiter, C.J., and Kyriakidis, P.C. 2006. Forward and inverse transformations between Cartesian and channel-fitted coordinate systems for meandering rivers. Mathematical Geology, 38(8):927-958.

Riggs, H.C. 1968. Techniques of water-resources investigations, Book 4, Chapter A2: Flood frequency curves. U.S. Geological Survey, Denver, Colorado. 21 p.

USACE. 2008a. HEC-GeoRAS, GIS tools for support of HEC-RAS using ArcGIS User's Manual, Version 4. U.S. Army Corps of Engineers Institute for Water Resources, Hydrologic Engineering Center (HEC), Davis, CA.

USACE. 2008b. HEC-RAS, river analysis system, user's manual, Version 4.0. U.S. Army Corps of Engineers, Hydrologic Engineering Center (HEC), Davis, CA.

USCGS. 1950. Descriptive reports (hydrographic surveys for Lake Roosevelt): HO7691, HO7692, HO7693, HO7694, HO7695. U.S. Coast and Geodetic Survey, Department of Commerce, Washington, D.C.

USGS. 1982. Guidelines for determining flood flow frequency, Bulletin 17-B of the Hydrology Subcommittee. U.S. Interagency Advisory Committee on Water Data, Office of Water Data Coordination, U.S. Geological Survey, Reston, VA. 183 p.