Appendix 4: ENTRIX: Final Draft Technical Memorandum: Topographic Survey, Hydraulic Modeling and Design Assessment of Proposed Carbon River Road Flood Damage Reduction Measures (October 2008) (detached)

This detachment is available on the park's website located at http://www.nps.gov/mora and on the Planning, Environment and Public Comment (PEPC) website located at http://parkplanning.nps.gov/mora.

ENTRIX

FINAL TECHNICAL MEMORANDUM

TOPOGRAPHIC SURVEY, HYDRAULIC MODELING AND DESIGN ASSESSMENT OF PROPOSED CARBON RIVER ROAD FLOOD DAMAGE REDUCTION MEASURES

PROJECT # 4194803

OCTOBER 2008

FINAL TECHNICAL MEMORANDUM

TOPOGRAPHIC SURVEY, HYDRAULIC MODELING AND DESIGN ASSESSMENT OF PROPOSED CARBON RIVER ROAD FLOOD DAMAGE REDUCTION MEASURES

October 2008

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1. Executive Summary

In response to flood damage in 2006-2007, a site assessment and design was proposed by GEOMAX to repair and protect the Carbon River Road adjacent to Carbon River in Mount Rainer National Park. Protection measures included rock barbs, check dams, and other flood damage reduction measures. These measures were put forward with the intention of providing techniques for river stabilization and flood damage resistance in the event that a decision is made to re-open the road corridor.

Multiple factors contribute to flooding and damage of the road. One major factor appears to be the lack of capacity of existing culvert crossings. These culverts can become partially filled with sediment and debris. Accordingly, as flows overtop and flow down the road, they exceed culvert capacity and cause damage to the roadway. Another factor relates to the high stream energy and sediment loads which frequently lead to dramatic changes in the river's course. These factors have resulted in dozens of road washouts over the past decade. Furthermore, additions of sediment associated with glacial recession directly impact the Upper Carbon Road. These problems are associated with processes inherent to the Carbon River watershed, result in chronic problems with the road, and are unlikely to diminish over time.

ENTRIX assessed the likelihood of success of the measures proposed protect the road and trail by GEOMAX. Specifically, the efficacy of each structure was examined using hydraulic, sediment transport, and channel response analyses. Results of this evaluation indicates that the Upper Carbon Road is currently is aggrading and within an unsustainable location that will continue to be subjected to chronic hazards and these conditions are unchanged by the proposed GEOMAX structures. The hydraulic and sediment transport analysis conducted clearly demonstrates that the Carbon River Road is at serious risk of chronic failure regardless of measures taken for protection. These results were further confirmed by the re-survey of several cross-sections which show continued aggradation of the channel rendering several of the proposed measured ineffective, especially for the long-term. In fact, some proposed measures such as barbs were shown to offer only minimal benefit; only one location along the existing rock revetment just up stream of the FR 7810.

Therefore, the best possible solution for the Carbon River Road would be to move sections of the road to areas outside hazard zones. To determine if such a stable road route can be identified, a complete topographic and channel-migration assessment needs to be conducted. This includes obtaining LiDAR topography for the Upper Carbon River that will support an extensive hydraulic analysis. This work combined with a complete road assessment is necessary to identify locations outside of chronic hazard areas to which the road can be relocated for long-term stability.

2. Introduction

This investigation was conducted to better understand the hydraulics, sediment transport, and channel response necessary to evaluate plans to protect and manage the Upper Carbon River Road and trail. After flood damage in 2006-2007, a new set of flood protection alternatives was proposed to repair and protect the road (GEOMAX 2008). This study estimates the likelihood of success of those flood protection measures, given the natural dynamics of the Carbon River. The investigation also re-occupied a series of river cross-sections done in 1994 (Riedel 1997) to determine the rate and magnitude to which the river may have aggraded within the project reach. This technical memorandum also summarizes a hydraulic and sediment-transport assessment of the proposed flood protection measures. To complete this assessment a detailed set of topographic surveys, including river cross-sections and profile of the Upper Carbon River Road was conducted.

The hydraulic analysis was done to estimate flow depths and shear stress conditions along the Upper Carbon River to evaluate fluvial processes at known problem sites. A one-dimensional HEC RAS model was used for the hydraulic analysis. Estimates of the sediment loads supplied and transported through the project reach were also studied. Shear stresses at structure locations were used to estimate the mobile grain size and the recurrence interval of the critical discharge. Sediment transport rates were used to determine the efficacy of the proposed flood protection measures.

2.1. Glaciers

Glaciers are among the most conspicuous and dynamic geologic features on Mount Rainier in Washington State. They erode the volcanic cone and are important sources of stream flow for several rivers, including some that provide water for hydroelectric power and irrigation. Together with perennial snow patches, glaciers cover about 36 square miles of the mountain's surface, about nine percent of the total park area, and have a volume of about 1 cubic mile. (Driedger and Kennard, 1986). The streams of Mount Rainier can be expected to continue to aggrade because retreating glaciers expose vast amounts of unconsolidated sediment. The newly uncovered sediment from the presently receding glaciers, such as the Nisqually is a large source for inevitable transport downstream.

Associated with glacial erosion is the flooding within Mount Rainier which is largely attributable to the sediment aggrading in streams and overflowing their banks. Flooding impacts along the Carbon River occur during high flow events typically related to rain on snow events where periods of intense rainfall are combined with rapidly melting snow. Due to the flow energy associated with large flow events, the river may also transport large concentrations of material, including rock, sediment and woody debris. This material adds to the dynamic nature of the river by creating depositional areas and debris jams. Furthermore, debris flows have a tendency to block and reroute stream alignments through new flow routes. High sediment and debris loaded streams can avulse, chute cutoff, and create debris blockage causing them to reroute themselves down the hydraulically smooth corridor of roads.

2.2. Connection to Climate Change

Geomorphic evidence from Mount Rainier provides an illustration of how glacial river systems are responding to the warming climate and some of the implications to fluvial ecosystems and human infrastructure such as roads. Glacial recession and thinning has resulted in the disappearance of approximately 25% of Mount Rainier's glacial volume between 1913 and 1994 (Nylen, 2005). This is exposing large volumes of unconsolidated, over steepened and unvegetated sediment. These new sources of sediment and increases in frequencies of highly erosive debris flows are exponentially increasing sediment supply to downstream rivers. The increased sediment supply is accelerating channel aggradation which in turn is causing dramatic alteration of alluvial landforms within the receiving river valleys (Beason et al. 2006, Beason 2007). Re-occupation of channel surveys after the November 2006 floods indicated that even this record setting event that delivered 46 cm of rain in 36 hours did not provide sufficient runoff to transport sediment inputs and most channels continued to aggrade. The warming climate is thus exaggerating the sediment supply and may be also leading to more frequent high magnitude peak flows further contributing to flooding and channel aggradation (Abbe et al.2008).

In the 2006 flood, channels raised an average of about 1 meter, something that would take 20 years based on historic aggradation rates. This channel response diminished conveyance capacity and exaggerated flood impacts. Total damage to roads, trails, campgrounds, and buildings exceeded anything that the park has experienced in its 108-year history, and the Park was closed for six months. It will take over $36 million dollars and several years to repair the devastation.

River aggradation is altering entire valley bottoms, burying old growth riparian forests and overwhelming infrastructure constructed with assumptions about flow, sediment and wood regimes that are no longer valid. The geomorphic response under the new climate regime will be complex since we can expect that sediment budgets will eventually diminish and trigger a period of channel degradation. Successful habitat restoration depends on setting realistic goals in the context of landscape response to human development and climate change. Successful design will accept and integrate change by giving rivers response space and the elements necessary to maintain habitat. This includes consideration of alternatives that move roads segments to locations outside significant hazard areas.

2.3. Carbon River Road

The Upper Carbon River Road is an important visitor access road into the Northwest portion of Mt. Rainier National Park. The road terminates at the Carbon River trail, which offers a relatively easy hike to the terminus of the Carbon Glacier, a major Park attraction. But the same natural attractions that entice visitors also create a very dynamic landscape. High stream energy and sediment loads lead to frequent and dramatic changes in the river's course that plague the Upper Carbon River Road and have resulted in dozens of washouts over the past decade. These problems are unlikely to diminish and the addition of sediment associated with glacial recession will also directly impact the Upper Carbon Road.

3. Background

3.1. Carbon River Road

Carbon River Road is located at Mile Post 1.5 at 121°53'17.527"W, 46°59'44.277"N (Figure 1). In 2007, the Carbon River Road was determined by the National Park Service to be 1 of 10 priority sites associated with repeated road damage from natural hazards. In the flood of 2006, the flood torrent from an adjacent hillslope clogged culverts and flowed down the Carbon River Road washing out large portions of the road. The necessary repairs to the river bank exceeded approximately $0.5 million. The primary mechanism that washed out the road was the clogging of several culverts upstream that lead to a build up of flowing water on the road sufficient to ultimately scour out large portions of road.

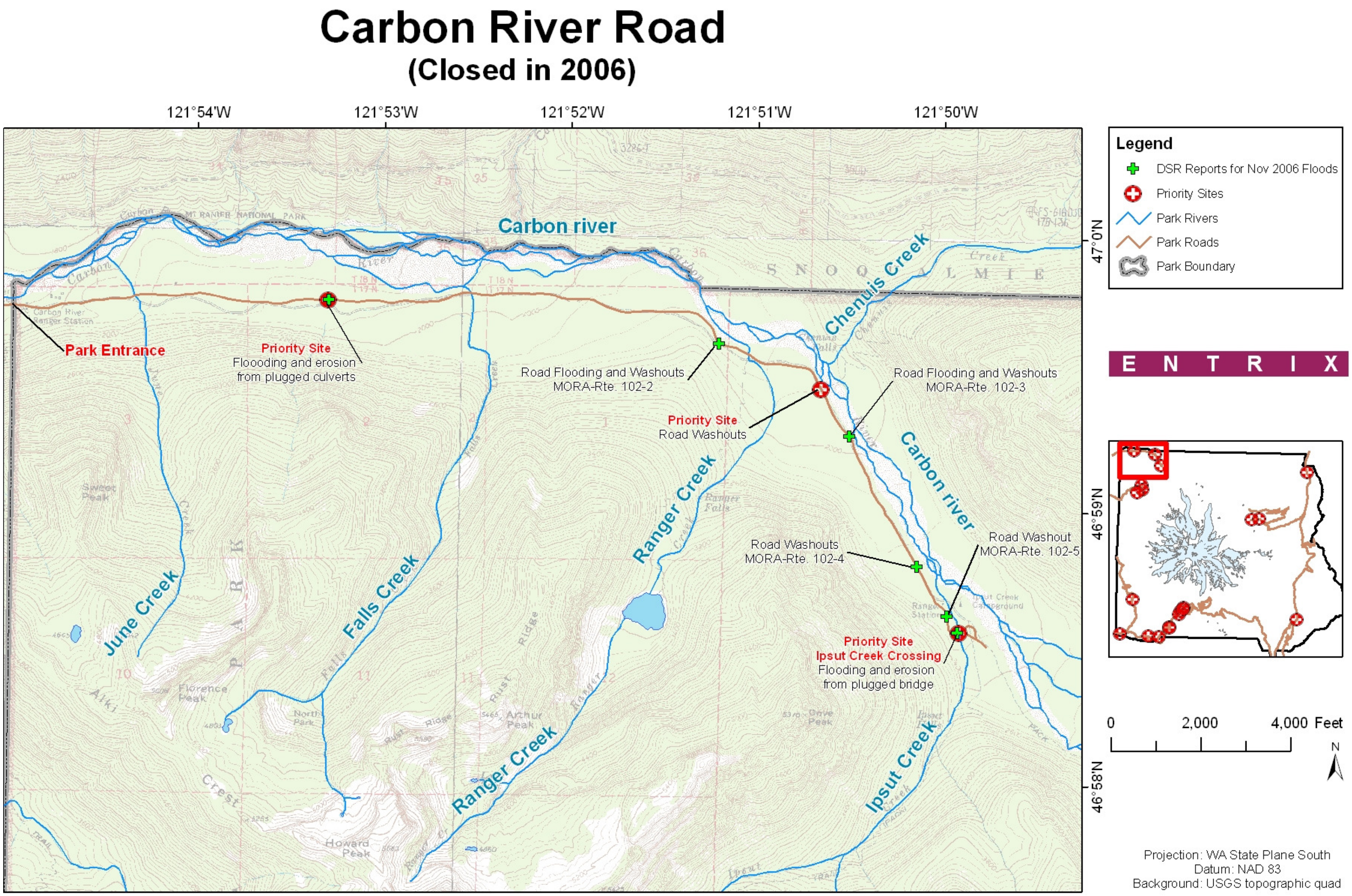

Figure 1. **Carbon River Road 2006 Damage Survey Reports (DSR) and designated 2007 priority sites.**

3.2. GEOMAX Structures

After flood damage in 2006-2007, a site assessment and design was proposed to repair and protect the road (GEOMAX 2008). Protection measures including rock barbs, check dams, and other flood damage reduction measures were proposed for the Carbon River Road. These were put forward with the intention of providing techniques for river stabilization and flood damage in the event that a decision is made to re-open the road corridor. The specific measures proposed are described in detail below.

GEOMAX (2008) proposed 15 bank barbs and several other grade and flood control structures throughout the 7 miles of the old Carbon River Road (Figure 1). Other structures include culvert trash racks, road flood dips, a ring dike section, rock grade control, and road hump/X-valley dikes. A total of approximately 3,400 cubic yards of rock was recommended for the construction of all structures.

Beginning at the Carbon River entrance of the park, four bank barbs were proposed downstream of the entrance to the park to divert flow away from the bank. All barbs were designed to be 16 ft wide at the bank and tapered to 10 ft at its tip in the river. They were also designed to be spaced 200 ft apart along the bank. Directly at the entrance, a culvert trash rack and a road flood dip was recommended at the existing large culvert. At the Carbon River Ranger station and upstream shed, a bank barb and ring dike section was proposed for the protection of the infrastructure. GEOMAX (2008) suggests that the proposed structures could fail. Furthermore, GEOMAX recommended that, should these structures fail, the relocation of the Carbon River Ranger station was a next possible measure to address the flooding issues. No hydraulic, force balance, sediment transport, geomorphic analysis or risk assessment is included in the design report to explain the basis for the proposed structures (GEOMAX, 2008).

Approximately 4,200 ft above the entrance, GEOMAX proposed a road flood dip for improved flood drainage. Two grade control structures were proposed approximately 3 miles above the entrance. Upstream where the road bank is exposed to the river, four bank barbs were proposed at 200 ft spacing. For about 1,000 ft above the bank barbs, two sets of grade control structures, one road flood dip and four road hump/X-valley dikes were proposed. Where the road bank is exposed again upstream, six bank barbs were proposed at 200 ft increments.

The Chenuis Falls parking area is located upstream of the last upstream barb. GEOMAX recommended that the road be permanently terminated due to GEOMAX's belief that the area above Chenuis Falls parking lot is not feasibly sustainable. Nonetheless, GEOMAX proposes a grade control structure and a culvert trash rack to protect the culvert, an X-valley dike, and a road flood dip above the parking area. Nor does GEOMAX discuss whether other options were considered to create a sustainable roadway upstream of the Chenuis Falls parking lot or why they believed fluvial processes would allow the road to be sustained downstream, but not upstream of this location.

Above Chenuis Falls, GEOMAX proposes the relocation of the trail from within the floodplain to above the floodplain on the hillside. The proposed relocation continues through Ipsut Creek campground of which they also recommend relocating above the floodplain.

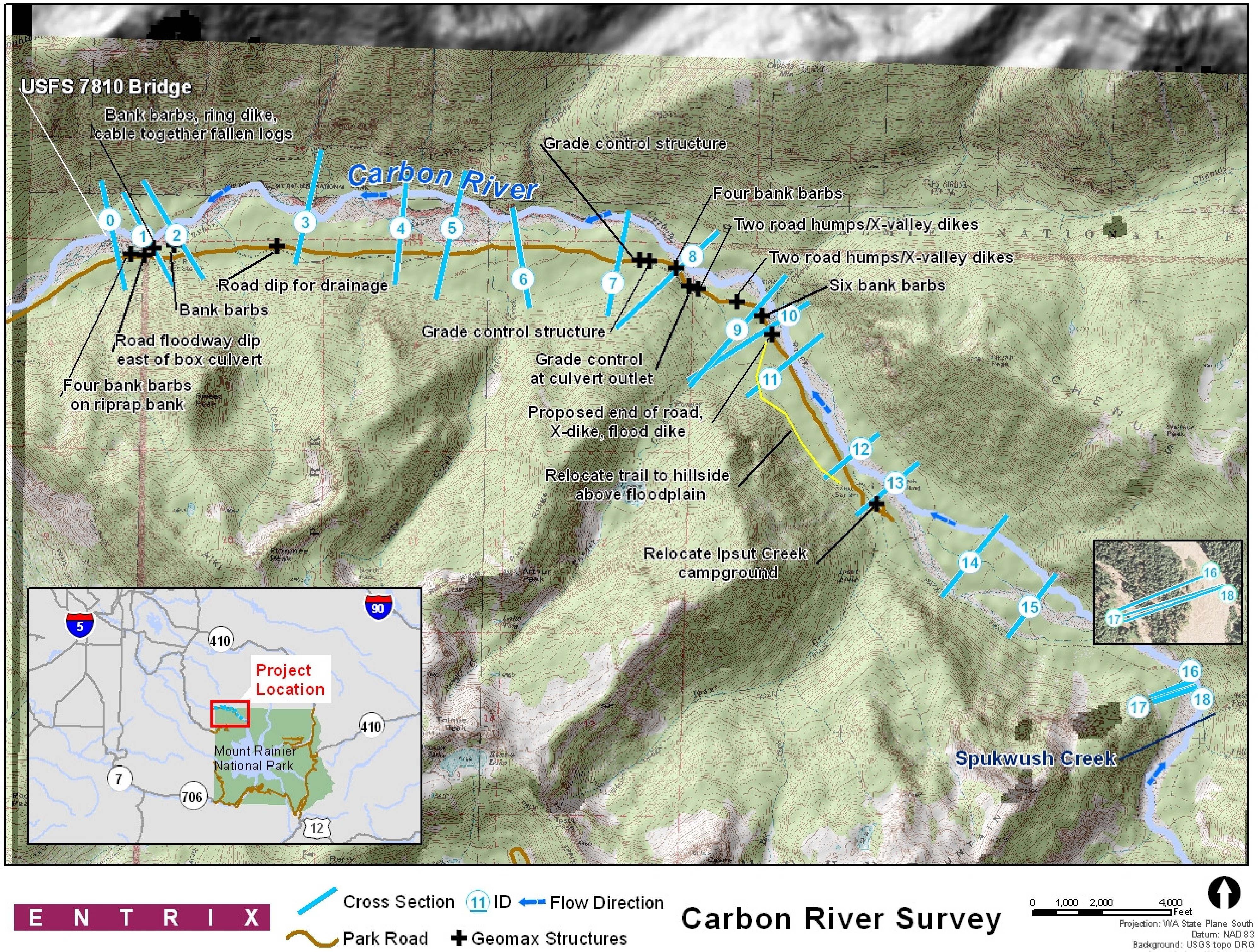

Figure 2. **ENTRIX-surveyed cross-sections, September 2008, with location of GEOMAX-proposed flood protection structure**

4. Topographic Survey

Topographic information is the basis from which hydraulic modeling and sediment transport analysis is built. A topographic survey of nineteen (19) river cross-sections at locations along the Carbon River was conducted. These cross-sections, combined with an additional Carbon River Road profile survey, were used in the development of a hydraulic model for the Carbon River and the adjacent road within Mount Rainier National Park.

The lower sixteen (16) were surveyed to common elevation datum and were used to in the analysis of the GEOMAX structures and Carbon River Road inundation study. The upper three (3) cross sections were used to develop a separate model that looked only at flow conditions in one location. These upper cross sections are located in an area upstream of the Carbon River Road terminus. The hydraulic analysis of the upstream location is presented separately as Appendix E.

4.1. Equipment

The Carbon River topographic survey was conducted using a Nikon Top Gun total station. In conjunction with the total station, a Recon data logger with TDS Survey Pro software was used to process and log each survey point. A GPS was used to record coordinates for selected survey points. Additionally, two to three survey poles and prisms were used to take the survey shots. Other equipment included field radios, waders, binoculars, and personal safety equipment.

4.2. Surveying

Carbon River cross section surveys were conducted on 16 - 18, 23 - 24 September, and 14 - 17 October, 2008. The survey commenced below the Carbon River Road entrance to Mt. Rainier National Park and proceeded upstream through the sequential establishment of control points linked to the initial location.

1) Control points
The initial two control points (CP1 and CP2) were designated through a combination of a GPS point and a geographic location that could be seen on the most recent available (2006) aerial photograph. The initial two locations were created at the center of the Forest Service Road 7810 Bridge (CP1) and the intersection of the Forest Service Road 7810 Bridge and the Carbon River Road (CP2). The total station was set up on CP1 and a bearing was taken to CP2 for proper orientation to begin the survey.

Subsequent control points were primarily created in the center of the river bed at locations where a) visibility was highest across the floodplain and b) the next control point or cross-section location could be seen from the total station. Additional control points were created on the Carbon River Road at cross-sections where it was visible from the river.

2) Cross-sections
For hydraulic modeling purposes total of nineteen cross-sections were surveyed along approximately seven miles of the Carbon River (Figure 2). The lengths of the surveyed cross-sections were dependent on the width of the unvegetated channel and the distance within the forested portions of the river valley that a survey prism could be seen from the total station location. Where a limited line of sight precluded surveying the floodplain all the way from the edge of the unvegetated channel to the valley wall, cross-section geometry was extended to the valley wall with data derived from the USGS 10-meter DEM by matching surveyed floodplain elevations to elevations derived from the DEM for the same spot. A vertical datum shift of + 25 feet was applied to the surveyed data points to compensate for the average difference across all surveyed cross-sections between surveyed and DEM-derived elevations for points located on the forested floodplain outside of the active channel. Forested floodplain was assumed to be ineffective flow area for hydraulic conveyance and therefore not critical information for setting up the HEC RAS model.

The upstream three cross-sections were closely spaced at the Spukwush trail crossing. Due to the high gradient of the river channel and numerous obstacles (debris jams), the survey data for the upper area was not tied to the lower cross sections.

In addition to the hydraulic modeling cross-sections, seven additional cross sections (Figure 3) were surveyed near Ipsut Creek Campground at the locations where cross-sections were previously surveyed in 1994 (Riedel, 1997). These additional cross-sections were relocated using a GPS unit and the unvegetated channel was surveyed along with as much of the forested floodplain as could be seen from the total station location. ENTRIX cross-section 1 (see Figure 2) was also surveyed at the approximate location of Riedel cross-section 9.

Profile charts, photographs, and survey station and elevation data for surveyed cross-sections can be found in Appendix A.

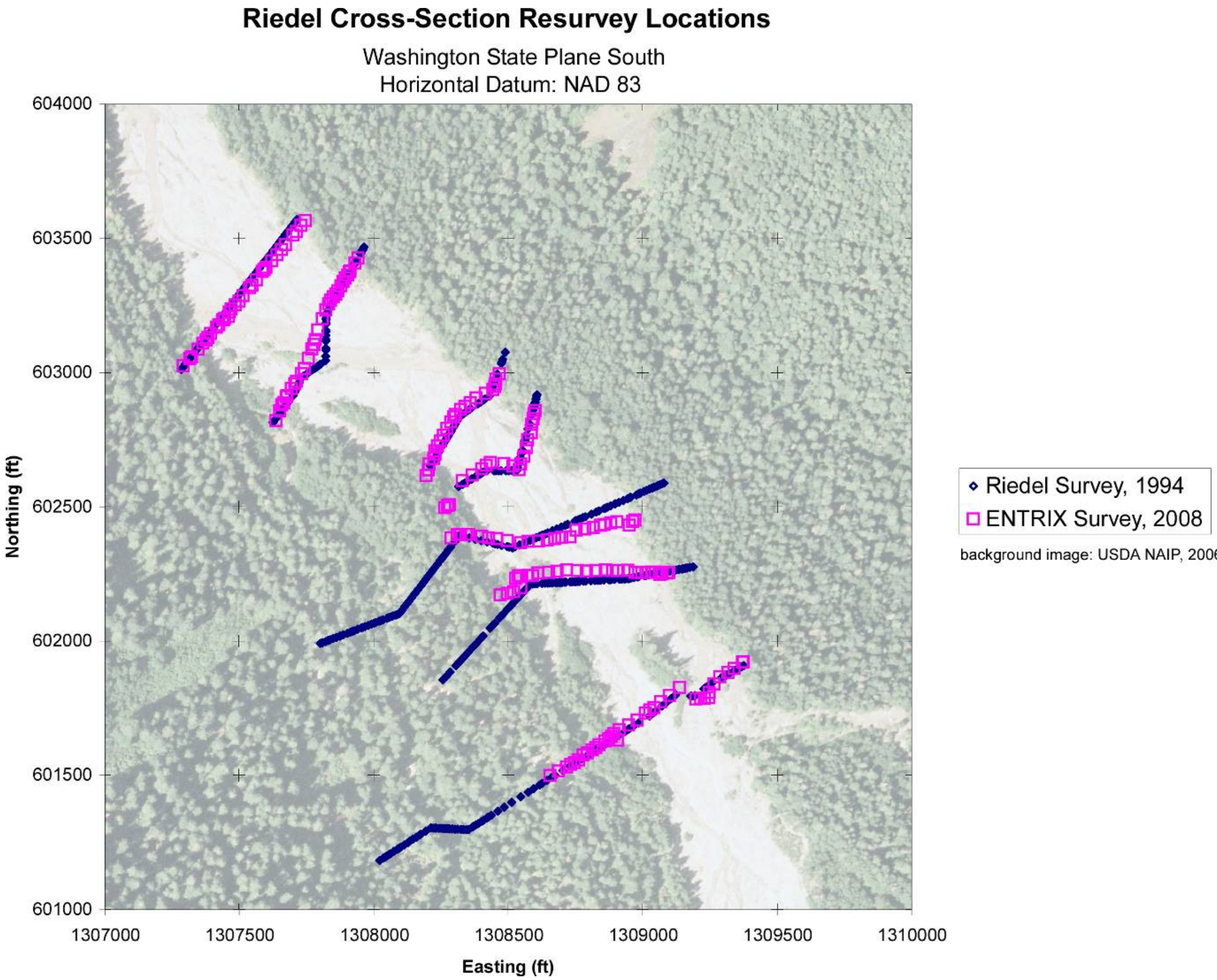

Figure 3. Location of 1994 (Riedel) and October 2008 (ENTRIX) cross-sections at Ipsut Creek Campground

5. Hydraulic Modeling Methods

5.1. Purpose

The nineteen cross-sections surveyed at locations along the Carbon River were used to develop the hydraulic model for this project. The hydraulic analysis conducted for the Carbon River was based on an uncalibrated Hydrologic Engineering Center-River Analysis System (HEC-RAS) model (USACE, 2006) developed for the project reach extending from the entrance to the park up to Ipsut Campground. Model results were compared to visual observations of flooding to evaluate general accuracy of results. The HEC-RAS was used for two purposes: the analysis of hydraulic impacts on proposed GEOMAX structures along the project reach and determination of flooding impacts on the Carbon River Road.

5.2. Model Overview

The Carbon River model was developed using the surveyed unvegetated channel cross sections along with the 10m DEM-derived floodplain data. As described in Section 3, nineteen river channel cross-sections and the road were surveyed along 7.2 mile long reach of the Carbon River was surveyed, from immediately upstream of the FR 7810 Bridge to the trail crossing below Spukwush Creek (Figure 2).

The HEC-RAS model was used to estimate the water surface elevations, velocities, shear stresses and other hydraulic variables of selected return-period flood events along the project reach of the Carbon River. The basic required data inputs for the hydraulic model include river channel geometric data, surveyed cross sections, estimated parameters incorporating the hydraulic character of the river, and stream discharges (hydrology).

5.3. Hydrology

The USGS web-based program StreamStats (http://water.usgs.gov/osw/streamstats) was used to estimate the peak flow values for the 2-year through 500-year return interval peak flows. StreamStats is designed to allow users to obtain streamflow statistics, drainage-basin characteristics, and other hydrologic information for selected sites within Washington and other states. If an area of hydrologic concern is selected that corresponds to a known USGS flow gage, previously published statistical analysis of the recorded flow gage is presented. If an ungaged site is selected, StreamStats estimates information for the site using the program's GIS database and uses the appropriate regional regression equations to determine the flow rates.

The initial StreamStats estimates are shown in Table 1. Included for comparison purposes are the estimated peak flows for the Nisqually River at Longmire on the southwestern slope of Mt. Rainier.

Table 1. StreamStats estimated flow for Selected Locations on the Carbon River

	Location			
	Upper Carbon (XS 18)	Ipsut Campground (XS 15)	Lower Carbon (XS 2)	Longmire (Nisqually River)
Drainage Area	20.5 mi^2	25.7 mi^2	60 mi^2	21 mi^2
Return Period	**Flow (cfs)**			
2-Year	1,580	1,870	3,240	1,380
10-Year	2,920	3,450	5,890	2,540
25-Year	3,640	4,290	7,290	3,160
50-Year	4,330	5,090	8,610	3,750
100-Year	4,890	5,750	9,700	4,230
500-Year	6,520	7,650	12,800	5,620

The regional regression equations used to estimate flow rates at ungaged locations can have a high degree of uncertainty, on the order of 50% of the estimated values. To improve the accuracy of the various flows used in the hydraulic analysis, a scaling factor was developed that incorporated recorded flow rates from the Carbon River near Fairfax, Washington. To achieve this, a log Pearson III statistical analysis was used on the historic recorded annual peak at the Fairfax gage. StreamStat was then used to determine the flow rates at the Fairfax location using the regional regression equations. These values are presented in Table 2. The final scaling factor was determined by dividing log Pearson III flow results by the StreamStat flow value.

Table 2. Log Pearson III and StreamStats Estimated Peak Flows at USGS gage 12094000

Return Period (yrs)	log Pearson III flow (cfs)	Streamstats flow (cfs)	Scaling factor
2	4,448	3,730	1.19
10	8,804	6,730	1.31
25	11,170	8,300	1.35
50	12,983	9,790	1.33
100	14,830	11,000	1.35
500	19,289	14,500	1.33

The final flow rates used in the HEC-RAS model are shown in Table 3. These flow rates were calculated using the scaling factor in Table 2 along with the flow rates presented in Table 1. The 5-Year flow rate, which is not estimated by StreamStat was interpolated from the other flow rates. It should also be noted that these peak flow estimates are based on historical gauging and peak flows may be increasing as a result of climate warming at Mt. Rainier (e.g., Abbe et al. 2008). A conservative estimate of future peak flows could be estimated from the trend in peak flows

Table 3. Best-Estimate Peak Flows for Selected Locations on the Carbon River

	Location		
	Upper Carbon (XS 18)	Ipsut Campground (XS 15)	Lower Carbon (XS 2)
Drainage Area	20.5 mi^2	25.7 mi^2	60 mi^2
Return Period	Flow (cfs)		
2-Year	1,884	2,230	3,864
5-Year	2,850	3,500	5,760
10-Year	3,820	4,513	7,705
25-Year	4,899	5,774	9,811
50-Year	5,742	6,750	11,418
100-Year	6,593	7,752	13,078
500-Year	8,674	10,177	17,028

Climate change appears to be impacting the magnitude and frequency of peak flows in Western Washington. The incidence of large magnitude events appears to be increasing, as see in plots of annual peaks from the Upper Nisqually and Upper Carbon Rivers (Figures 4 and 5). The increase in the magnitude of a 100 yr flow is directly influenced by the gauging record. With increasing magnitudes of flows, the discharge of any recurrence event will increase. This is illustrated in flood frequency plots for the Sauk River in the North Cascades where the 100 yr flood discharge in 1986 is less than the 50 yr flood discharge as of 2007 (Figure 6). The Nisqually and Carbon Rivers show the same trends (Figure 7 and 8). This trend clearly indicates that flood flows are likely to get worse, further confounding problems in the Carbon River.

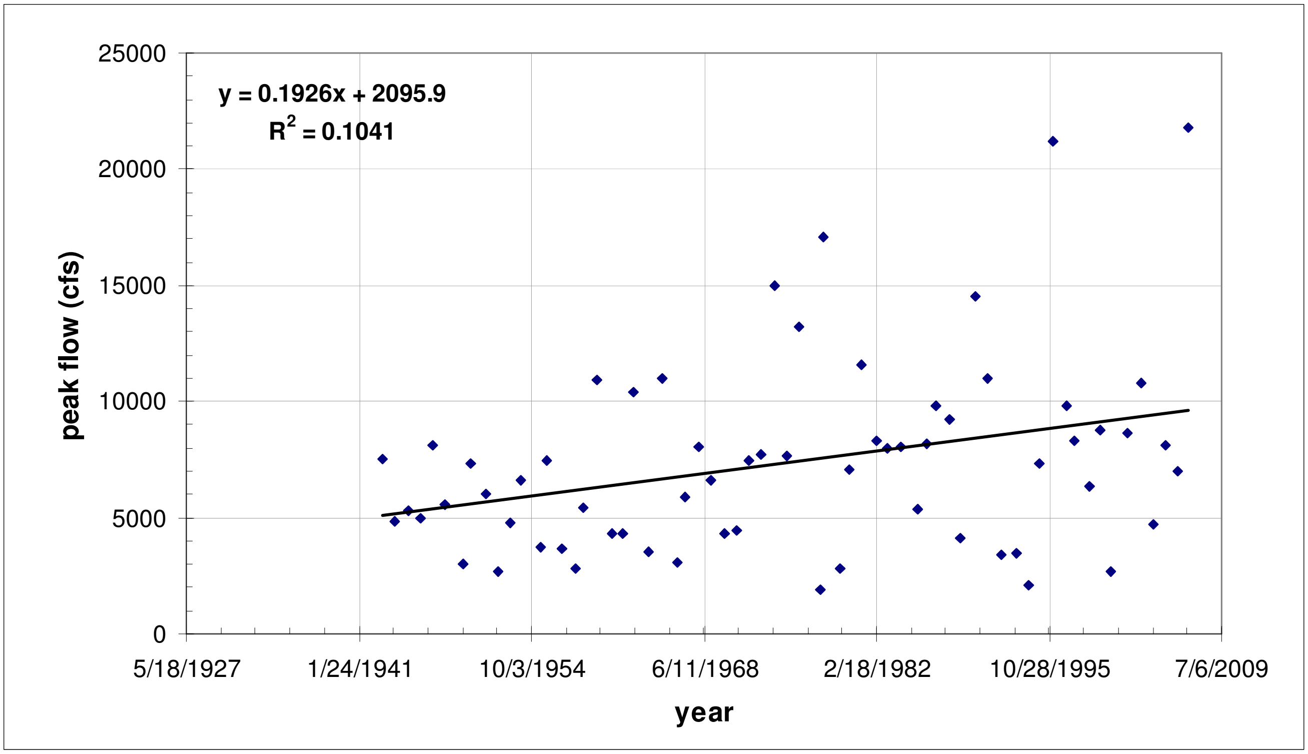

Figure 4. Annual peak flows in Upper Nisqually River near National, WA. Gage 12082500

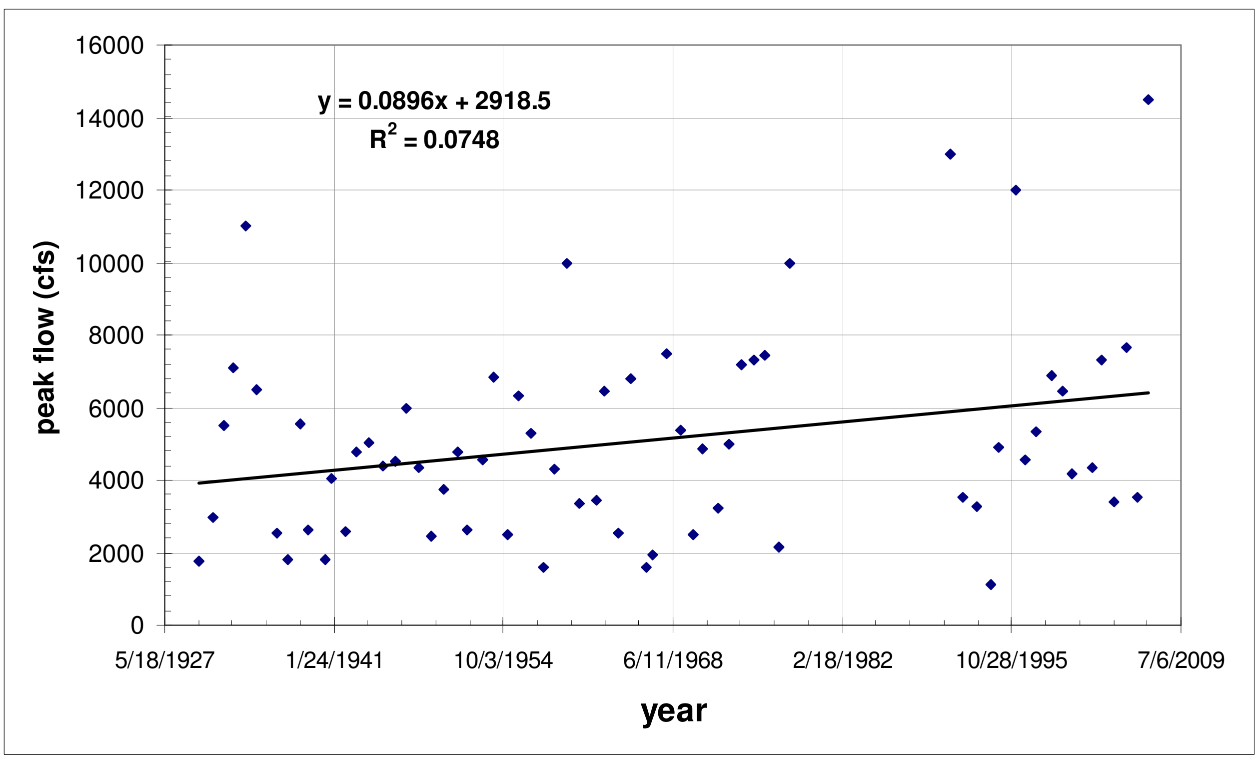

Figure 5. Annual peak flows in Upper Carbon River near Fairfax, WA. Gage 12094000

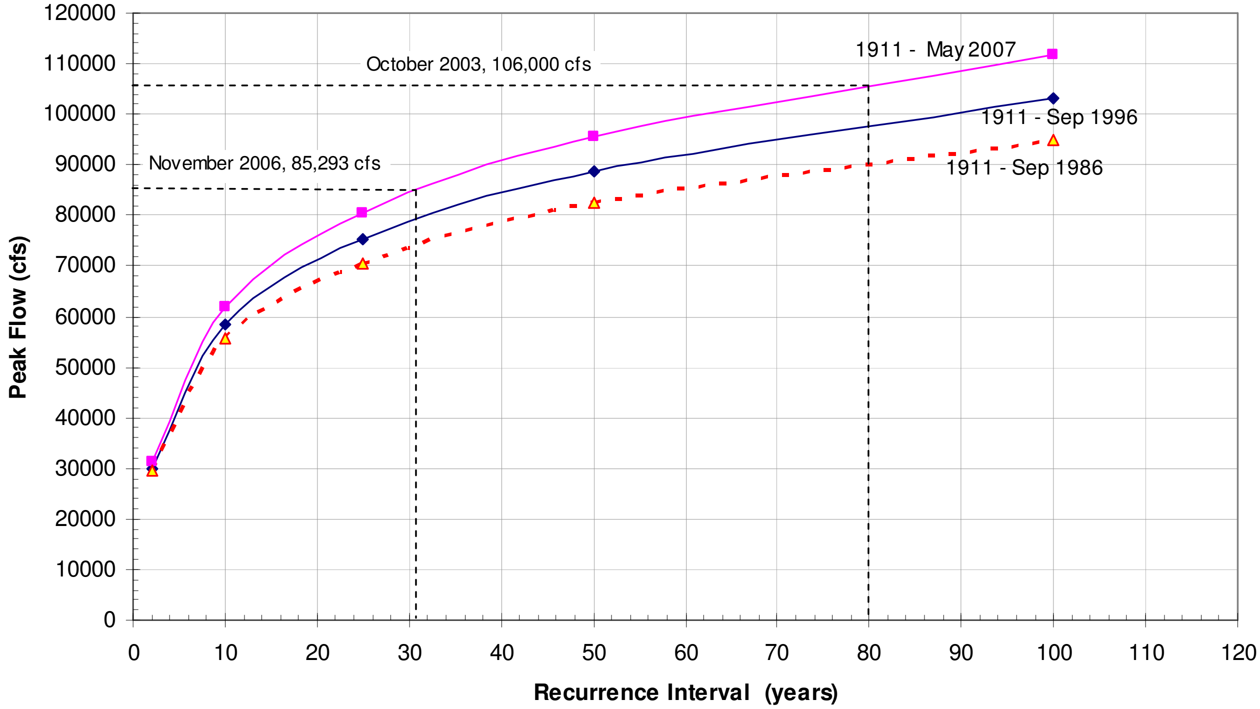

Figure 6. Flood frequency plot for Sauk River (North Cascades, WA) showing influence of increasing magnitude of peak flows on estimated flood recurrence discharges (LP III analysis)

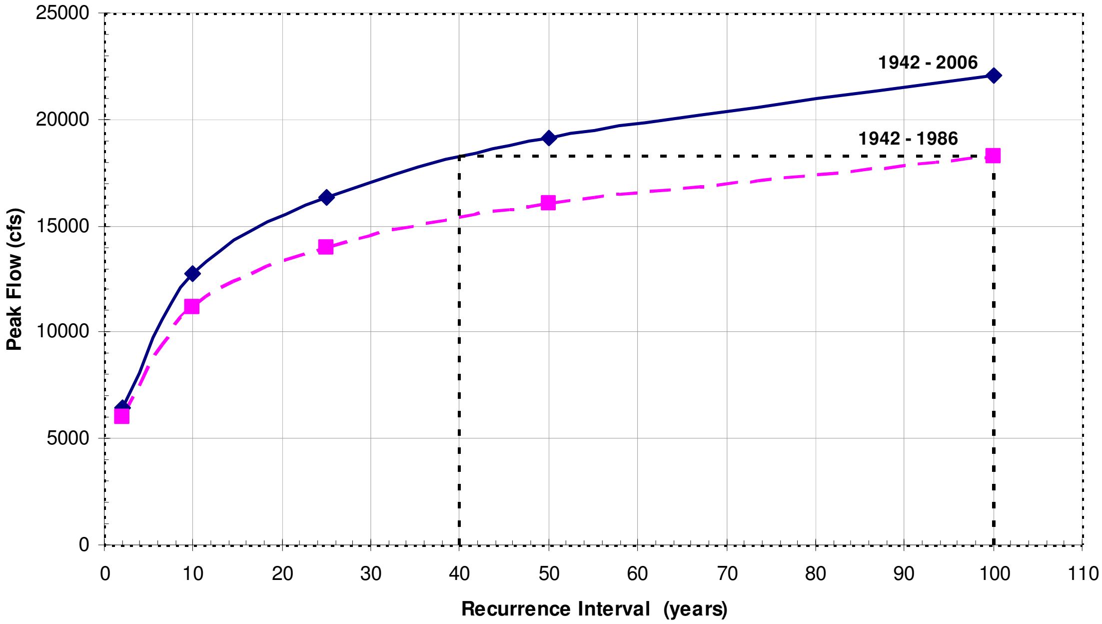

Figure 7. LPIII flood frequency analysis for Nisqually River at National (12082500) done for 1942-1986 and 1942-2006. The 100 year flood in 1986 would only the 40 year flood event based on the frequency of high magnitude events over the intervening 20 years.

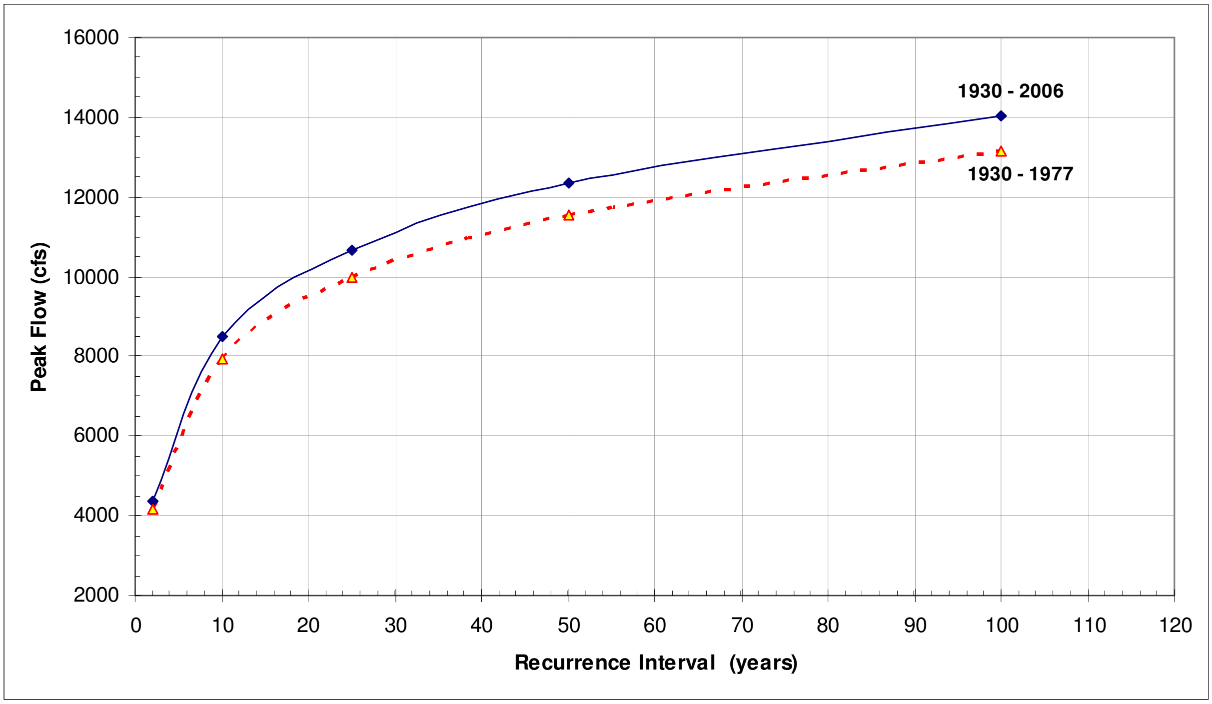

Figure 8. Flood frequency plot for Upper Carbon River showing influence of increasing magnitude of peak flows on estimated flood recurrence discharges (LP III analysis)

5.4. Hydraulic Model Construction

5.4.1. Cross Sections

Sixteen surveyed cross-sections, representing 6.2 river miles of the unvegetated river channel, were used to build a hydraulic model of the river from the FR 7810 Bridge (just downstream of the Carbon River Ranger Station) to approximately 4000 feet upstream of Ipsut Creek campground. To incorporate the floodplain beyond the surveyed data, the 10 meter Digital Elevation Model (DEM) developed by the USGS was used. The two sources of elevation data were meshed together to create a continuous topographic surface of the river valley. Using the combined elevation sources allowed for the development of sixteen (16) valley-spanning cross sections.

Additional cross sections were interpolated using HEC-RAS at approximately 200 foot intervals. The interpolation process conducted within the RAS modeling program uses the 16 surveyed cross sections upstream and downstream and creates cross sections that incrementally change from one cross section geometry to the next. The interpolated cross sections not only provide for greater model stability, they also provide additional analysis locations in case the surveyed cross sections do not coincide with areas of concern.

5.4.2. Manning's Roughness Coefficient

The Manning's roughness parameter, "n" is used to mathematically represent the resistance to flow due to channel characteristics and vegetation. The selection of a representative "n" value for any river section is very subjective. Typically, hydraulic engineers rely on professional judgment or past experience to select a value that may vary from one person to another. To counter this 'opinion' driven selection, the Carbon River model "n" values were calculated for each cross-section using the modified Cowan methods described in USGS Water Supply Paper 2339 (USGS 1989). The Cowan method estimates total roughness (Manning's n) for a channel by computing the scaled sum of five contributing components:

$$n = (n_b + n_1 + n_2 + n_3 + n_4)m$$

Where

n	=	total roughness
n_b	=	base value for straight, uniform, smooth channel in a given material
n_1	=	component incorporating the effects of surface irregularity effects
n_2	=	component incorporating the effects of cross-section variation
n_3	=	component incorporating the effects of obstructions
n_4	=	component incorporating the effects of vegetation
m	=	correction factor the effects of channel meandering

Tables 4 and 5 list the values of each of the roughness factors at each surveyed cross-section, for channel and floodplains respectively.

Table 4. Channel Roughness Components

Channel Roughness							
	Base Value	Surface Irregularity	Cross-section Variation	Obstruction	Vegetation	Meandering	Total Roughness
XS	n_b	n_1	n_2	n_3	n_4	m	n
0	0.04	0.005	0.001	0.01	0	1	**0.056**
1	0.04	0.01	0.003	0.004	0.001	1	**0.058**
2	0.04	0.01	0.003	0.004	0.001	1	**0.058**
3	0.04	0.01	0.005	0.015	0.002	1	**0.072**
4	0.04	0.011	0.005	0.01	0	1	**0.066**
5	0.04	0.01	0.005	0.02	0.005	1	**0.08**
6	0.04	0.01	0.005	0.01	0	1	**0.065**
7	0.04	0.01	0.005	0.005	0	1	**0.06**
8	0.04	0.011	0.005	0.005	0	1	**0.061**
9	0.05	0.008	0.005	0.015	0.005	1	**0.083**
10	0.05	0.008	0.005	0.015	0.002	1	**0.08**
11	0.05	0.005	0.005	0.02	0.002	1	**0.082**
12	0.05	0.005	0.005	0.02	0	1	**0.08**
13	0.04	0.005	0.005	0.015	0	1	**0.065**
14	0.05	0.005	0.005	0.02	0	1	**0.08**
15	0.05	0.005	0.005	0.02	0	1	**0.08**

Table 5. Floodplain Roughness Components

Floodplain Roughness					Left Overbank	Right Overbank		Left Overbank	Right Overbank
		Surface Irregularity	Cross-section Variation	Obstruction	Vegetation	Vegetation	Meander	Total	Total
XS	n_b	n_1	n_2	n_3	n_4	n_4	m	n	n
0	0.025	0.02	0	0.03	0.1	0.2	1	**0.175**	**0.275**
1	0.025	0.02	0	0.03	0.15	0.15	1	**0.225**	**0.225**
2	0.025	0.02	0	0.03	0.15	0.15	1	**0.225**	**0.225**
3	0.025	0.02	0	0.03	0.15	0.2	1	**0.225**	**0.275**
4	0.025	0.02	0	0.03	0.15	0.15	1	**0.225**	**0.225**
5	0.025	0.02	0	0.03	0.15	0.15	1	**0.225**	**0.225**
6	0.025	0.02	0	0.03	0.1	0.15	1	**0.175**	**0.225**
7	0.025	0.02	0	0.03	0.02	0.15	1	**0.095**	**0.225**
8	0.025	0.02	0	0.03	0.15	0.15	1	**0.225**	**0.225**
9	0.025	0.02	0	0.03	0.15	0.15	1	**0.225**	**0.225**
10	0.025	0.02	0	0.03	0.15	0.15	1	**0.225**	**0.225**
11	0.025	0.02	0	0.03	0.15	0.15	1	**0.225**	**0.225**
12	0.025	0.02	0	0.03	0.1	0.15	1	**0.175**	**0.225**
13	0.025	0.02	0	0.03	0.15	0.15	1	**0.225**	**0.225**
14	0.025	0.02	0	0.03	0.15	0.15	1	**0.225**	**0.225**
15	0.025	0.02	0	0.03	0.15	0.15	1	**0.225**	**0.225**

5.5 Hydraulic Model Validation

The ENTRIX HEC-RAS model was validated for low flow conditions only. As part of the ENTRIX survey effort, the water surface elevation at each of the 16 cross sections was surveyed. The representative flow rate for use in the low flow validation model was estimated using the USGS real-time flow data for the Carbon River near Fairfax gage. The data provides recorded flow rates every 15 minutes. Using the 15-minute flow data, the average flow rate for the September 23, 2008 was computed to be 45.2 cfs with the actual flow ranging from 31.8 to 60.8 cfs. The 45.2 cfs average flow rate was then scaled down by 1.2 (see Table 2) for an estimated modeled value of 38 cfs. Table 6 contains the estimated HEC-RAS water surface elevations compared with the surveyed water surface elevations.

Table 6. Carbon River HEC-RAS Validation Results for Low Flow Conditions

River Station	ENTRIX XS	Q Total (cfs)	W.S. Elevation (ft)	Surveyed WSE
33126.17	15	38	2558.12	2558.23
30984.01	14	38	2478.18	2478.69
27547.13	13	38	2338.27	2338.42
26000.7	12	38	2288.2	
22800.95	11	38	2193.22	2193.45
21532.71	10	38	2159.63	
20694.41	9	38	2137.81	
18133.85	8	38	2078.86	
15953.11	7	38	2030.76	2031.31
12691.06	6	38	1967.75	1967.91
10966.94	5	38	1930.2	1931.43
9336.056	4	38	1893.84	
6586.8	3	38	1845.12	1845.00
2340.415	2	38	1772.15	
1577.288	1	38	1759.4	1760.80
581.5512	0	38	1741	

Cross sections in the table with no listed surveyed water surface elevation had multiple channels with variable water surface elevations. Accordingly, direct comparison could not be completed at these sites.

6. Hydraulic Modeling Results for GEOMAX Structure Evaluation

Using the flow rates presented in Table 3 and the surveyed/DEM cross sections described earlier, the HEC-RAS model was used to calculate the flow velocities, stress, and flow depth along the Carbon River project reach. The results of the modeling reveal relatively high flow velocities and subsequent shear stresses throughout the Carbon River model reach.

The magnitude of erosive forces acting upon the channel boundary is often expressed as shear stress. Shear stress is also known as the depth-slope product because it is approximated by the product of flow depth, slope, and the unit weight of water.

$$\tau = \gamma d S$$

Where

τ	=	shear stress, psf or Pa
γ	=	unit weight of water, 62.4 lb/ft^3 or 9.81 kN/m^3
d	=	flow depth, ft. or m.
S	=	slope

Channel shear stress within the project reach is shown in Figure 9. At the locations of the proposed structures, shear stress ranges from 3-4 psf at the upper location and 2-3 psf at the lower site. To illustrate what this means, at a shear stress of 3.5 psf in the Shield's equation below, a grain size of approximately 335 mm is entrained. The exposed bar surfaces of the Carbon River project reach are roughly 10-20% sand. This fraction of sand has the effect of substantively decreasing the dimensionless shear stress, facilitating the movement of larger grains at lower shear stress values (Wilcock and Kenworthy, 2002).

$$d = \frac{\tau}{\tau^{*}(s-1)\gamma}$$

Where

d	=	mobile grain size, ft. or m.
τ	=	shear stress, psf or Pa
τ^*	=	dimensionless shear stress, psf or Pa
s	=	relative grain density = 2.65
γ	=	unit weight of water, 62.4 lb/ft^3 or 9.81 kN/m^3

Although channel shear stress is useful for estimating incipient motion, unit stream power is a better estimate of the ability of the river to do geomorphic work, such as dismantling bank protection structures.

$$\omega = \tau\ v$$

Where

ω	=	unit stream power
τ	=	shear stress, psf or Pa
v	=	stream velocity, fps or m/s

Unit stream power is work done per unit time, and is calculated as the product of shear stress and stream velocity. Unit stream power in the project reach is given in Figure 10. The upper location for proposed structures has consistently high power values, indicating higher relative risk to any instream structure. This risk can be manifested as drag, scour, or sedimentation impacts to the structure.

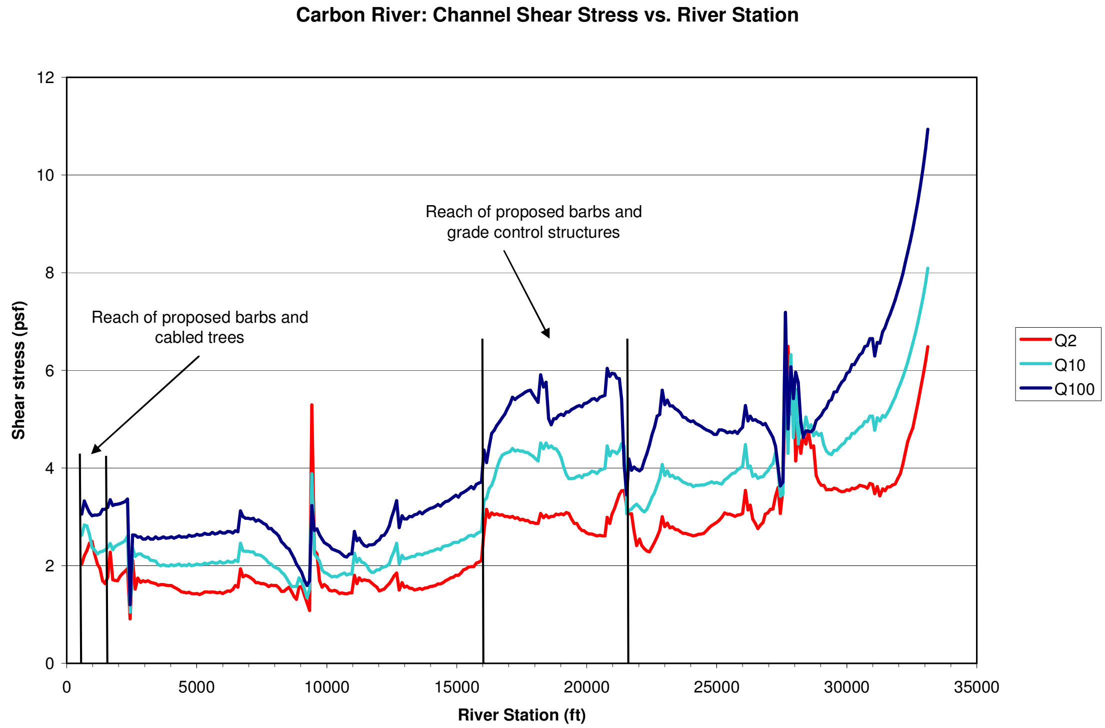

Figure 9. Carbon River: channel shear stress vs. river station

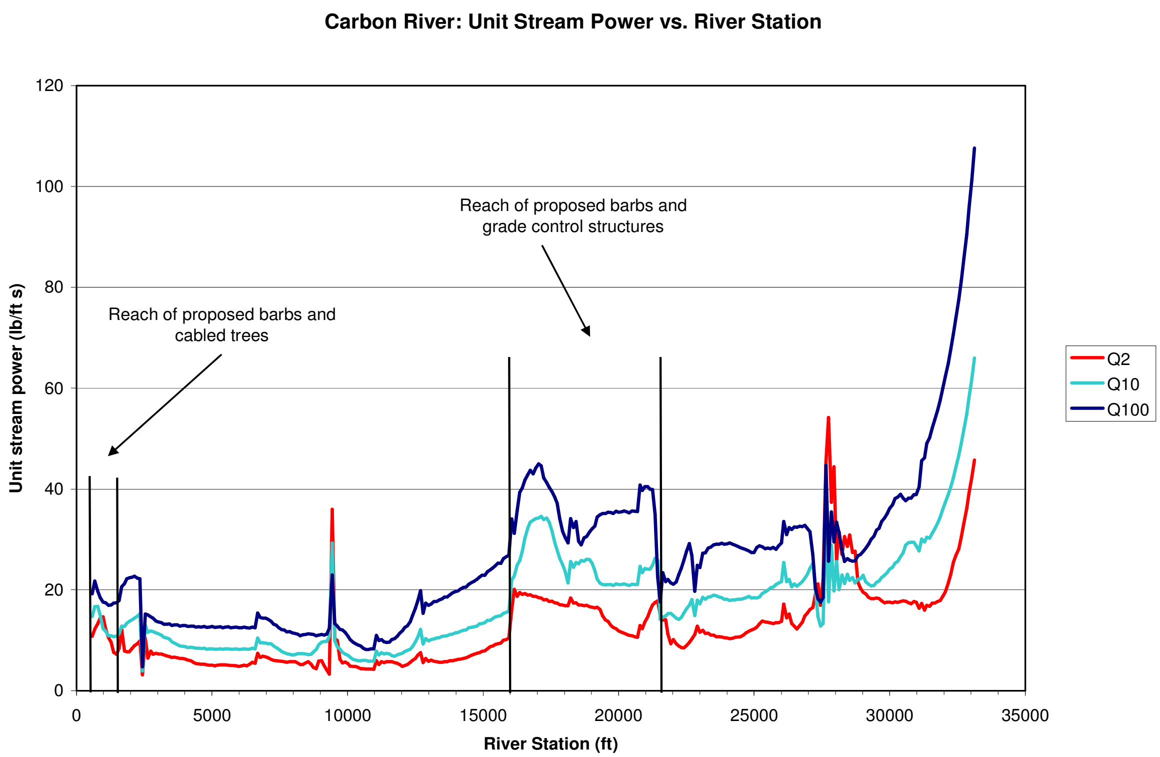

Figure 10. Carbon River: Unit stream power vs. river station

7. Design Assessment Methods

The structures proposed by GEOMAX (2008) consist of in-channel and off-channel (floodplain) structures. Proposed in-channel structures include barbs, various grade control structures, and cabled trees. In-channel structures were assessed by analysis of the likely hydraulic and sedimentation conditions of the river. Off-channel structures were assessed primarily by field observations of the proposed locations of the structures and the surrounding area. The detailed field observations are given in Appendix C.

Tables 7 and 8 list the in-channel and off-channel structures, respectively. Each table gives their station, corresponding RAS model cross-section, channel or floodplain shear stress, likely mode of failure, and alternative recommendations, where feasible. The overall preferred alternative is to find a long-term stable route for the Upper Carbon Road outside the 500 yr floodway and outside the erosion hazard area. Tables 7 and 8 largely assume that road re-location can't be done at the individual site. Given the results of this analysis, protecting and maintaining the Upper Carbon River Road will take major efforts that will include road relocations and structures that can tolerate channel aggradation and high energy flows.

Construction of any dike features obstructing flows such as "X-dikes" will have a significant impact on floodplain flows and could have unanticipated impacts associated with flotsam accumulation and scour where flow is concentrated around the structure. The best alternative is relocating road to high ground in area of low erosion hazard potential.

Table 7. Location and evaluation of GEOMAX In-channel structures.

Structure Location-Road Station	Structure Type	Purpose	Approx. HEC-RAS River Station	Est. Q2 Channel Shear Stress (psf)	Est. Mobile Grain Size at Q2 (mm)	Likely Mode of Failure	Alternative Recommendation
Carbon Entrance	Bank Barb	Redirect Flow from riprap bank	1557.3	1.76	208	Inconclusive*	Flow deflection logjam
Carbon Entrance	Bank Barb	Redirect Flow from riprap bank	1557.3	1.76	208	Inconclusive*	Flow deflection logjam
Carbon Entrance	Bank Barb	Redirect Flow from riprap bank	1557.3	1.76	208	Inconclusive*	Flow deflection logjam
Carbon Entrance	Bank Barb	Redirect Flow from riprap bank	1557.3	1.76	208	Inconclusive*	Flow deflection logjam

Structure Location-Road Station	Structure Type	Purpose	Approx. HEC-RAS River Station	Est. Q2 Channel Shear Stress (psf)	Est. Mobile Grain Size at Q2 (mm)	Likely Mode of Failure	Alternative Recommendation
Carbon Entrance	Culvert Trash Rack	Protect culvert inlet	1557.3	1.76	208	Inconclusive*	Upstream logjams or timber pilings
Carbon Entrance	Bank Barb	Redirect flow from bank near buildings	1557.3	1.76	208	Inconclusive*	Flow deflection logjam
Carbon Entrance	Cabled Trees	Protect bank	1557.3	1.76	208	Scour, cable motion	Flow deflection logjam or floodplain roughness
152+00	Rock Grade Control	Limit flow to side channel	16944.3	3.01	356	Scour	Rock filled log crib weir
154+00	Rock Grade Control	Limit flow to side channel	17241.7	2.97	351	Scour	Rock filled log crib weir
157+50	Bank Barb	Redirect Flow from riprap bank	17638.2	2.92	346	Aggradation	Flow deflection logjam
159+50	Bank Barb	Redirect Flow from riprap bank	17935.6	2.88	341	Aggradation	Flow deflection logjam
161+50	Bank Barb	Redirect Flow from riprap bank	18133.8	2.86	338	Aggradation	Flow deflection logjam
163+50	Bank Barb	Redirect Flow from riprap bank	18330.8	2.98	353	Aggradation	Flow deflection logjam
166+00	Grade Control	Stabilize culvert outlet	18626.2	3.01	356	Scour	Rock filled log crib weir
166+00	Culvert Trash Rack		18626.2	3.01	356	Aggradation	Upstream logjams or timber pilings
166+50	Grade Control (2 small structures)	Check head cut east of culvert outlet	18626.2	3.01	356	Scour	Rock filled log crib weirs

Structure Location-Road Station	Structure Type	Purpose	Approx. HEC-RAS River Station	Est. Q2 Channel Shear Stress (psf)	Est. Mobile Grain Size at Q2 (mm)	Likely Mode of Failure	Alternative Recommendation
186+00	Bank Barb	Redirect flow from riprap bank	20398.9	2.61	309	Aggradation	Flow deflection logjam
188+00	Bank Barb	Redirect flow from riprap bank	20497.4	2.62	310	Aggradation	Flow deflection logjam
190+00	Bank Barb	Redirect flow from riprap bank	20694.0	2.61	309	Aggradation	Flow deflection logjam
192+00	Bank Barb	Redirect flow from riprap bank	20973.8	3.05	361	Aggradation	Flow deflection logjam
194+00	Bank Barb	Redirect flow from riprap bank	21346.4	3.53	418	Aggradation	Flow deflection logjam
196+00	Bank Barb	Redirect flow from riprap bank	21532.7	3.2	379	Aggradation	Flow deflection logjam
192+50	Grade Control Culvert Outlet	Protect outlet from being undercut	20973.8	3.05	361	Scour	Rock filled log crib weir
192+50	Culvert Trash Rack		20973.8	3.05	361	Aggradation	Upstream logjams or timber pilings

*The mode of failure for the Carbon river Entrance area is inconclusive for barbs as a result of the mixed conditions of both localized aggradation and degradation across the active channel.

Proposed in-channel structures are capable of withstanding estimated stream power and sheer stresses if designed correctly. However, they require specific design details related to scour to determine the depth at which the structure should be set within the riverbed. These details are not in the GEOMAX plans. Because assessing the local stream power and shear stress effects to structures requires details on depth of structure placement and the materials to be used for construction, and this information was not provided, the exact robustness of each structure can not be fully evaluated. Modeling results, together with field observation, show the Carbon River is clearly susceptible to variations in hydraulic conditions as well as sedimentation, scour, and aggradation throughout this dynamic channel. Therefore, the proposed structures are not generally suitable for this environment. Finally, with regard to the off-channel areas, structures in these areas are not accurately evaluated with the modeling results due to their position outside the main channel or on tributaries. However, exposed to flow conditions found in the main channel (due to channel migration or an avulsion) they are unlikely to withstand the estimated sheer stress and stream power of the Carbon River.

Table 8. Location and evaluation of GEOMAX off-channel structures

Location-Road Station	Structure Type	Purpose	HEC-RAS River Station	Est. Mobile Grain Size at Q2 (mm)	Floodplain Q100 Shear Stress (psf)	Floodplain Q2 Shear Stress (psf)	Likely Mode of Failure	Alternative Recommendation
Carbon Entrance	Road Flood Dip	Flood overflow for June Creek culvert	1557.3	205	L: 3.14 R: 1.88	L: 1.73 R: 0.49	End-cut around, scour	Road re-location or
Carbon Entrance	Ring Dike Section	Protect entrance buildings	1557.3	205	L: 3.14 R: 1.88	L: 1.73 R: 0.49	Scour of footing	Relocation
Station 42+00	Road Flood Dip	Allow flood waters to cross road	6290.5	259	L: 3.07	L: 2.19	Continued erosion, scour	Improve capacity of existing culverts or relocate
166+50 to 167+00	Road Flood Dip	Flood overflow for June Creek culvert	18626.2	21	R: 2.19	R: 0.18	Continued erosion and acceleration of migrating head cut	Improved culvert capacity or relocate
168+00	Road Hump/X-Valley Dike	Block water flow along road	18823.2	10	R: 1.95	R: 0.08	Erosion/scour	Relocation to higher ground
170+00	Road Hump/X-Valley Dike	Block water flow along road	19020.2		R: 1.79		Erosion/scour	Relocation to higher ground
182+00	Road Hump/X-Valley Dike	Block water flow along road	20005.0	65	R: 2.31	R: 0.55	Erosion/scour	Relocation to higher ground
184+00	Road Hump/X-Valley Dike	Block water flow along road	20201.9	77	R: 2.30	R: 0.65	Scour	Relocation to higher ground
198+00	X-Valley Dike	Protect proposed end of road	21727.8				Scour	Relocation to higher ground
199+00	Flood Dip	Return flow south of channel	21922.9				Scour	Prevent side channel flood overflow

7.1. Assessment of In-Channel Structures

Barbs are designed to protect riverbanks by redirecting flow at the channel forming discharge. This effect requires precise placement of the barb surface at an elevation approximate to the water surface elevation at the channel forming discharge. This feature makes barbs well suited to gravel and cobble bedded rivers with low sediment loads and stable channel geometry. These conditions are not reflected in the morphology of the Carbon River.

Rivers with high sediment loads typically have braided channels with multiple unstable threads. Bed elevations may change rapidly as the active channel migrates. Due to the unstable nature of the channel planform, bank stability is often a challenge, and limits the selection of bank protection techniques. The WDFW Integrated Streambank Protection Guidelines Manual does not recommend the use of barbs in aggrading rivers with slopes >2%, which describes most of the Carbon River project reach (Figure 11, Table 7).

Grade control structures are designed to prevent channel avulsion and incision and are applied to the Carbon River road grade and crossings in the GEOMAX proposal. Grade control structures work in confined sections where they span the width of potential channel migration.

Cabled trees are proposed to armor river banks. Loosely-cabled trees are not an acceptable approach since cable motion can cause more harm than would occur without the structure. Instead, trees should be stabilized using tight cable bindings, not dead-man anchors. For the best results, trees should be used in engineered logjam structures.

The efficacy of the proposed structures was evaluated using results of the hydraulic modeling, as well as estimates of the sediment supply and transport conditions of the project reach. The structure analysis used the following methods to assess efficacy of the structures:

- *Estimation of critical discharge*
  A Monte Carlo analysis was performed using normal distributions of grain size, dimensionless shear stress, and Manning's n values to estimate a mean and standard deviation of the critical discharge to entrain bed material. The recurrence interval of the estimated critical discharge is used to predict how frequently bed material may be in motion

- *Estimation of sediment rating curve*
  The sediment rating curve (water discharge versus sediment discharge) was estimated over a range of discharge values using a representative grain size distribution, channel width, slope, and the Wilcock and Crowe (2003) transport relation. This rating curve was used in the remaining two analyses to determine the sensitivity of the system to aggradation. Details of the Wilcock and Crowe (2003) transport relation are given in Appendix D.

- *Estimation of equilibrium slope to maintain sediment continuity*
  The energy grade slope needed to transport an incoming sediment load is invariant with load up to a point. For example, sediment load may be 1,000 kg/hr or 10,000 kg/hr and the slope to transport that load remains the same. However, at a threshold value, a given slope must be maintained to transport the incoming load. If the slope is less than the equilibrium slope, aggradation of the channel occurs. This analysis sought to determine the sensitivity of equilibrium slope in the project reach.

- *Estimation of bed aggradation*
  The depth of aggradation in the channel was estimated using the Parker morphodynamic model. This simplified model uses the Meyer-Peter Muller transport relation and Exner sediment continuity relation to give gross estimates of the rate and amount of bed profile evolution (either aggradation or degradation) for given discharge in an idealized rectangular-section channel with the same slope, top-width, and grain-size distribution as the real channel. Details of the Parker morphodynamic model are given in Appendix D.

  Bed aggradation was also evaluated by comparing the elevations of the resurveyed Riedel (1997) cross-sections with the elevations recorded in the original 1994 survey (Figure 11, see also Appendix A). For each cross-section the average elevation of the unvegetated channel bed was calculated for each date, and the difference between those elevations plotted against river station (see Figure 15). Because the earlier surveys were registered to a different arbitrary vertical datum than the ENTRIX 2008 surveys, the ENTRIX data was adjusted to the earlier datum by matching the elevation of the road at two cross-sections on which it was surveyed at both times. The two road elevation differences did not match exactly; the uncertainty in elevation due to the uncertainty in relocating the match points is +/- 2.1 feet. Overall, aggradation was confirmed within the Carbon River system using the cross-section comparisons (Figure 11).

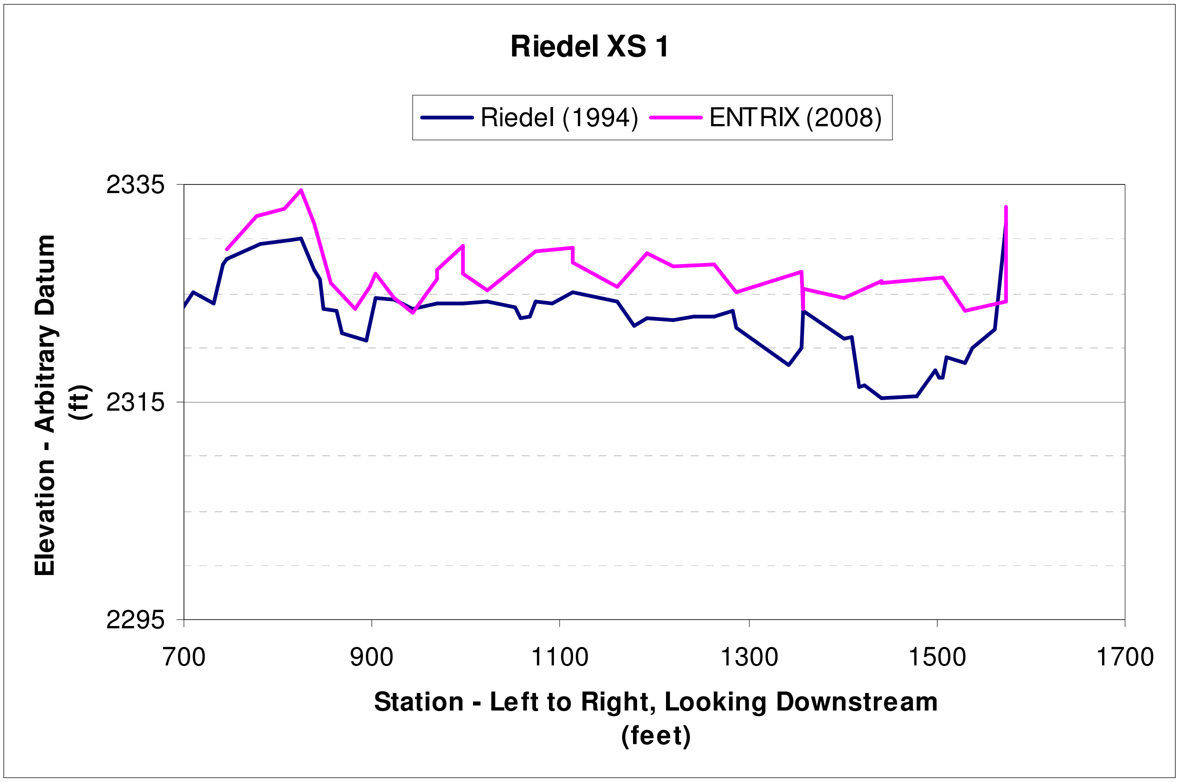

Figure 11. Representative resurveyed cross-section comparison

7.2. Assessment of Off-Channel Structures

Proposed off-channel structures include road dips and rock-cored road humps or cross-valley dikes. Road dips are designed to route flood water off and across the road and back to the main stem channel. Road humps or cross-valley dikes are designed to prevent incision of the road surface and avulsion of the channel on to the roadway.

A field assessment of off-channel structures was performed. This assessment was made to evaluate the site-specific conditions at each proposed location. The condition of the road was also observed, with particular attention given to evidence of erosion or deposition, and pathways of flood flows, and the source of those flood flows (tributary or side channel). Each proposed structure may have beneficial effects, in the appropriate setting. The field assessment evaluated the setting as well as the structure.

The results of the field assessment are summarized in Table 8. The detailed field observations are given in Appendix C.

The analytical assessment of the off-channel grade control structures focused on the magnitude of the shear stress on the floodplain at the Q2 and Q100. Due to the low banks of the Carbon River at some sub-reaches, floodplain shears are high, up to 3 psf, even at the Q2. This indicates that because of the steep nature and high sediment supply, any areas within the

Carbon River flood zone are susceptible to high sheer stresses and stream power even at low magnitude high frequency events (Q2). This means that any facilities within or adjacent to the flood hazard area are likely to require frequent maintenance and repair.

The mobile grain size on the floodplain at the Q2 is also given in Table 8. The large grain sizes entrained are confirmed by the armored nature of the road surface, identified in field observations. The road surface is dominated by cobbles, finer materials are entrained and transported. The vertical and horizontal connectivity of the roadway and the river facilitates flow conditions that are similar to in-channel flow conditions on the roadway.

8. Design Assessment Results

The net result of the four analyses is that the channel is likely to aggrade in many locations, and so is a poor candidate for successful use of either barbs or grade control structures. The structures are likely to become buried or circumvented by the river. This is most critical with regards to barbs. The proposed cabled logs are a poor choice for reasons previously explained, in that they may do more damage then would occur if they were left alone. The best option is to stabilize wood in engineered structures that extend from scour depth to above the 100-year flood elevation. Specific results of the design analysis are presented below, segregated by analytical method.

8.1. Estimation of critical discharge

This analysis creates normal distributions of dimensionless shear stress, grain size, and Manning's n values. Fixed values of channel width and slope are also used. The Monte Carlo solves for the grain stress and the conservation relations (mass and momentum) 1000 times, picking values of roughness, dimensionless shear, and grain from the distributions to create a population of critical discharge values. This analysis produced a mean critical discharge of 3070 cfs, and a standard deviation of 2333 cfs. The mean critical discharge is approximate to the Q5, however the standard deviation is high owing to the wide variation in grain sizes. This critical discharge value and its standard deviation indicate that the bed is frequently mobile.

8.2. Estimation of sediment rating curve

The Wilcock and Crowe transport relation was used to estimate the sediment rating curve (Figure 12). This transport relation utilizes surface grain size distributions and accounts for the presence of sand on the bed surface. In this case, the exposed bar surfaces of the Carbon River are 10-20% sand. Sand has a profound effect on incipient motion and transport. As little as 10-15% sand decreases the dimensionless shear stress value from a nominal value of 0.04 to 0.02. The net effect is to increase motion and transport rates. This rating curve was used to estimate supply rates at different recurrence interval floods. At the Q2, transport capacity is ~8000 kg/min, increasing to ~15,000 kg/min at the Q100. Note that uncalibrated estimates of transport may have order of magnitude errors. Hence, this analysis is a gross estimate to give an idea of the magnitude of sediment moving through the project reach.

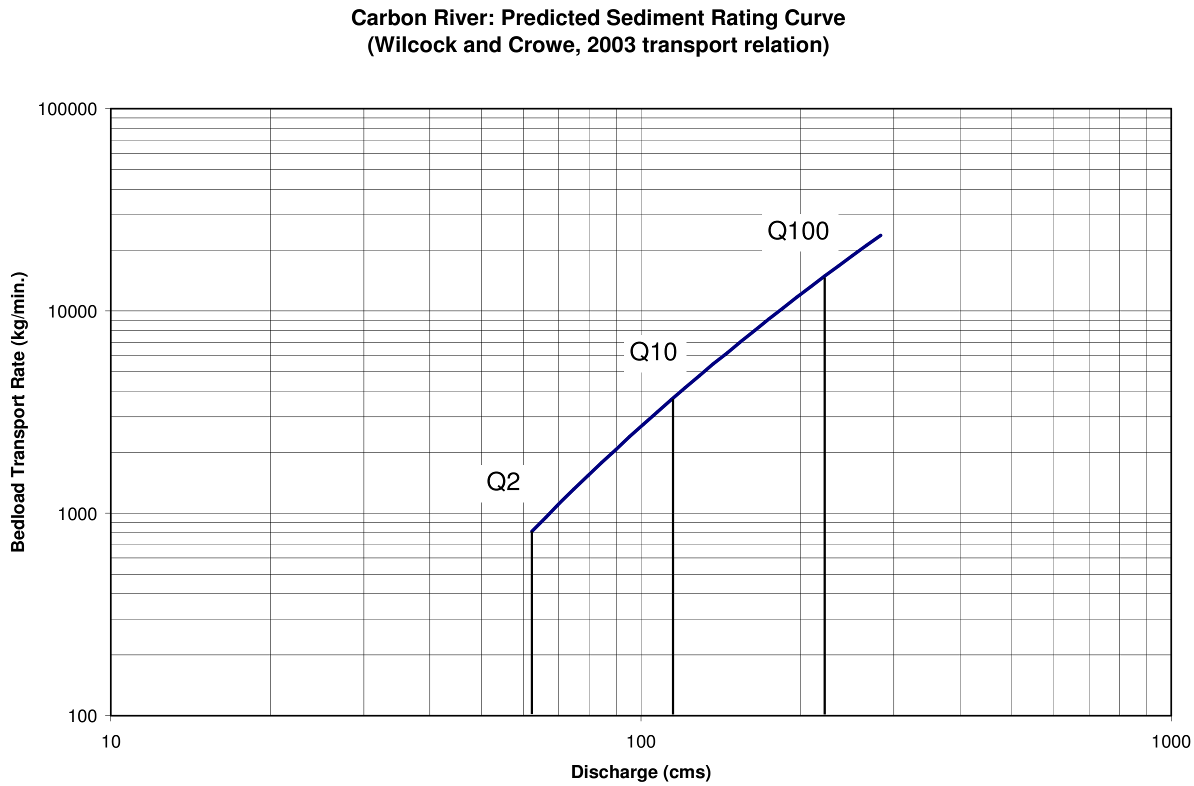

Figure 12. Carbon River: Uncalibrated estimated sediment rating curve

8.3. Estimation of equilibrium slope to maintain sediment continuity

This analysis solves for the slope required to maintain sediment continuity. Sediment continuity is the condition of a channel which neither aggrades nor degrades. The same volume of sediment supplied to a reach is transported out of the reach. In this analysis, it is assumed that the estimated transport capacity (from the sediment rating curve) is approximately equivalent to the sediment supply. Figure 13 is a plot of the equilibrium channel slope required to transport the sediment supplied. If the slope required to transport the incoming sediment is constant (flat line on plot), the channel maintains sediment continuity regardless of channel slope. This analysis shows that the slope required to maintain sediment continuity varies with the sediment supply, thus slight changes in sediment supply will result in slope adjustments. The greater the sediment supply, the greater the slope necessary to move the sediment and not result in bed aggradation. If the existing slope is insufficient, the channel will aggrade until it has attained the necessary slope. Decreases in sediment supply will result in excess stream power that will degrade the channel until a lower slope is attained that reduces the stream power. Assuming sediment supply is proportional to flow magnitudes, slight variations in frequent floods can lead to either aggradation or degradation (Figure 13). This means that in-stream structures will be at risk of both scour and burial. Channel instability within the project reach is also reflected in a large variation in channel widths which are all sensitive to sediment supply.

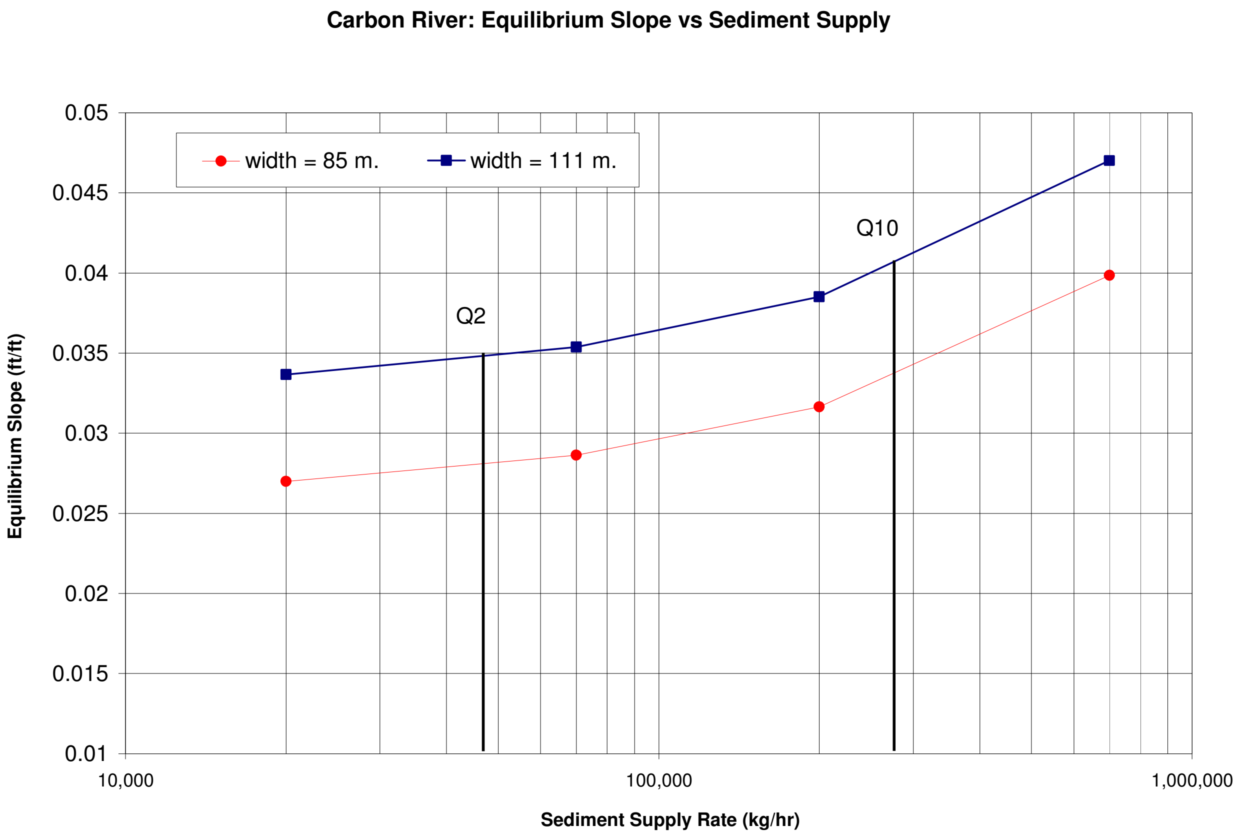

Figure 13. Carbon River: Estimated equilibrium slope as function of sediment supply

8.4. Estimation of bed aggradation

This analysis assumes that the transport capacity estimated from the sediment rating curve is approximate to the incoming sediment supply. Using incoming sediment supply, simplified channel geometry, slope, and grain size, the change in bed elevation is calculated over time and distance. The bed elevation at time zero is the initial elevation. The difference between the initial elevation and the bed elevation at subsequent time steps is the depth of either aggradation or degradation. At the Q2, this analysis shows that the channel aggrades over a period of two years (Figure 14). The deterministic amount or depth of aggradation is not well known, but the channel clearly has a tendency to aggrade at even low magnitude, high frequency floods such as the Q2.

The model of bed aggradation to increase channel slope is supported by the comparison between original and resurveyed cross-sections at Ipsut Creek campground (Figure 15). The seven cross-sections show aggradation between 0.6 and 4.8 ft in the 14-year interval between surveys, with the amount of aggradation increasing in the upstream direction. The upstream-biased aggradation has resulted in the channel slope increasing 0.2%, from 3.4 % to 3.6% – through the Ipsut Creek Campground reach. The resurvey of Riedel cross-section 9 (near the Carbon River Entrance Station – see Appendix A) shows no significant change (elevation change -0.6 ft, +1.7/-2.1 ft). The observations of increasing aggradation upstream are consistent with a diffusion model of bed aggradation associated with an increase of sediment supply at the terminus of the Carbon Glacier. The Carbon River is aggrading at about 0.34 ft/yr, an observation that is consistent with aggradation of 0.10 ft/yr documented in the Nisqually River at Longmire where the river gradient is similar to the Carbon study reach (Beason 2007). This is based on re-survey of the Reidel cross-sections in 2008 around the Ipsut Campground.

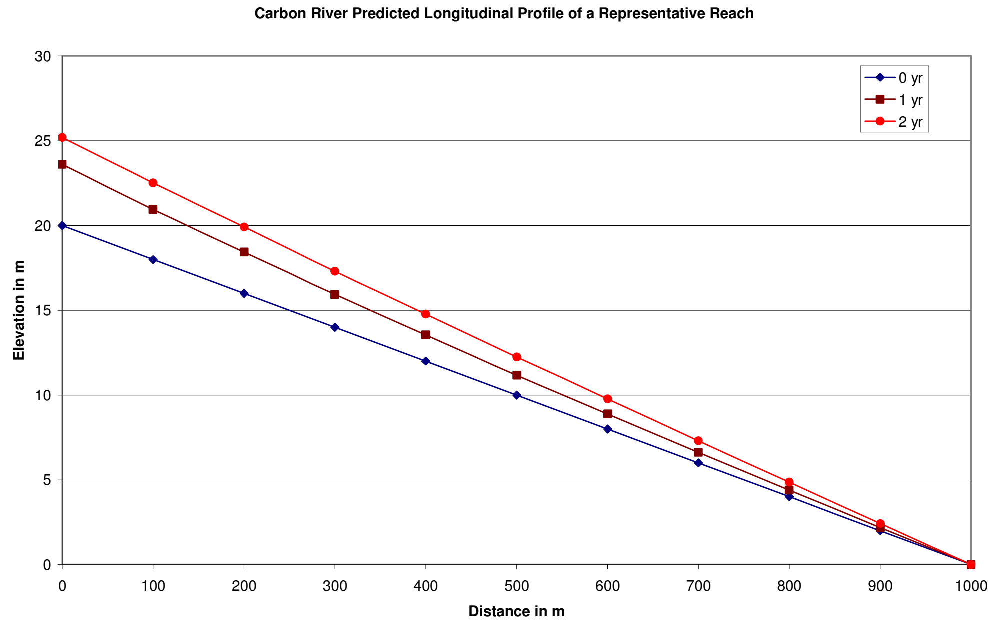

Figure 14. Carbon River: Predicted Aggradation of a Simplified Representative Reach

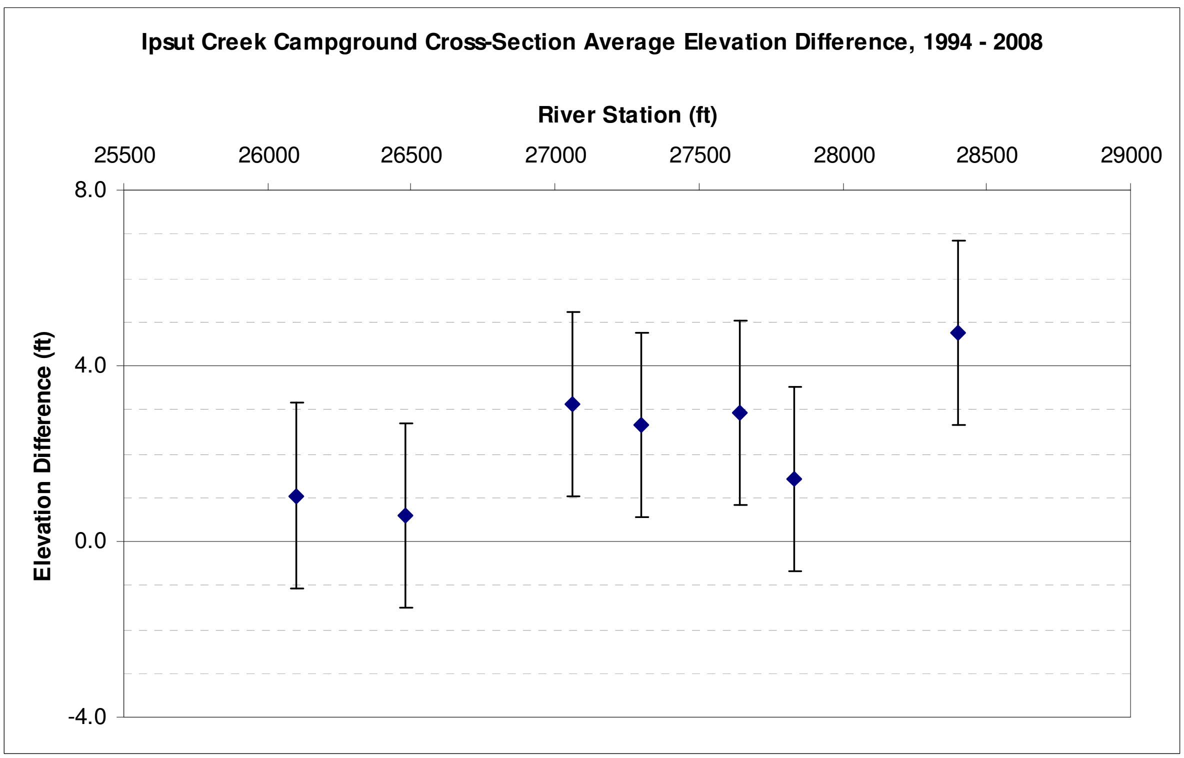

Figure 15. Estimated elevation difference, 1994 – 2008, at Ipsut Creek Campground cross-sections. Figure left is downstream, figure right is upstream.

8.5. Field Assessment of Proposed Off-channel Structures

Results of the field assessment indicate that multiple factors are contributing to flooding and damage to the roadway. A major factor appears to be the lack of capacity in the existing culverts crossing the road. Many of the culverts were observed to be partially filled with sediment or debris. Flood flows in excess of the culvert capacity damage the roadway as flows overtop and flow down the road. An alternative structure, which performs the same function as the road humps and valley dikes is a log crib grade control structure (Figure 16). This structure utilizes above-ground wood, increasing the roughness of the roadway and attracting flood debris to increase roughness.

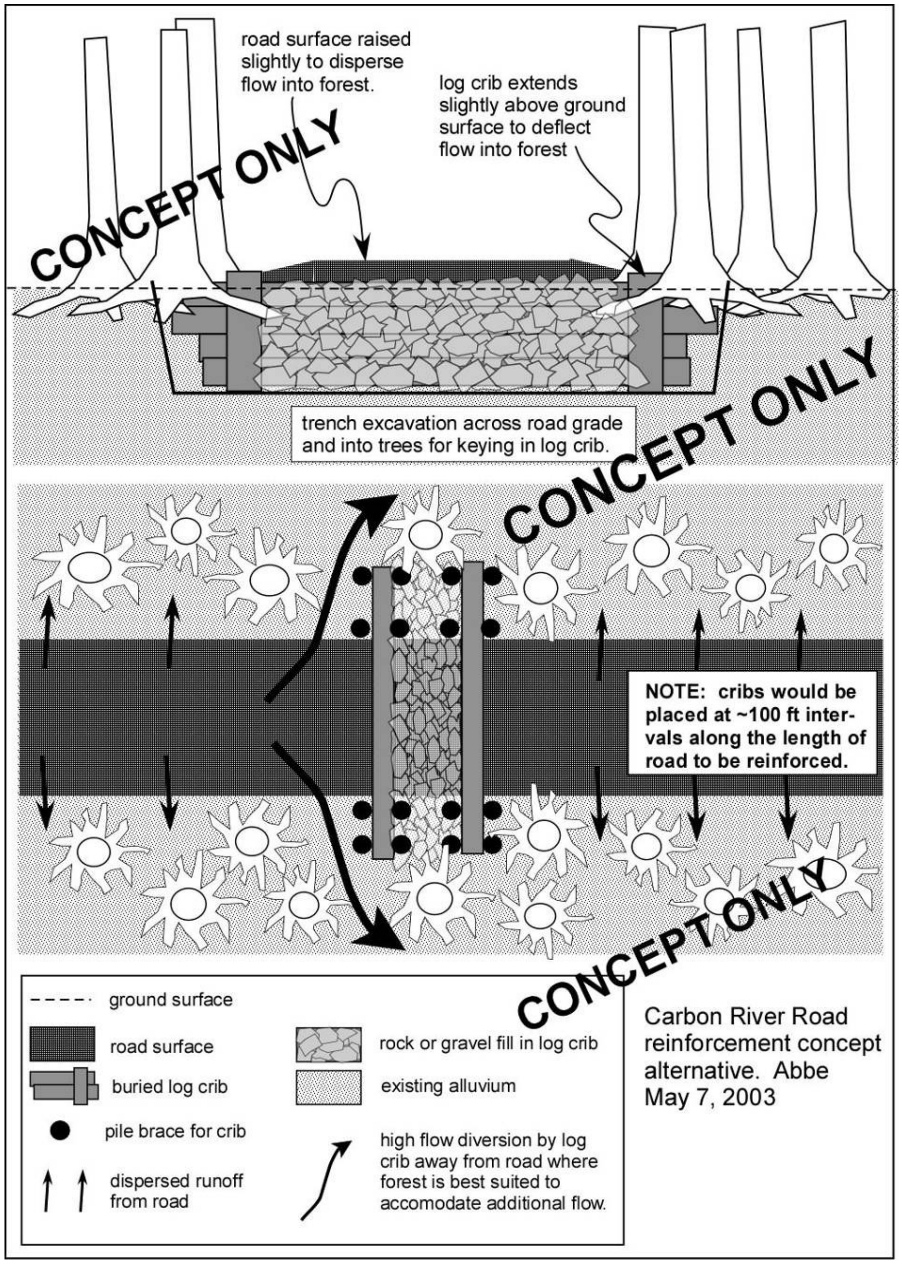

Figure 16. Rock-filled log crib grade control structure as alternative for protecting road segments subjected to overland flow from river or tributaries

9. Carbon Road Inundation Assessment

The second part of the hydraulic assessment conducted for the Carbon River project included the estimation of the Carbon River Road inundation extent and associated general recurrence interval for flooding. Flooding impacts along the Carbon River occur during high flow events typically related to rain on snow events where periods of intense rainfall are combined with rapidly melting snow. Due to the flow energy associated with large flow events, the river may also transport large concentrations of material, including rock, sediment and woody debris. This material adds to the dynamic nature of the river by creating depositional areas and debris jams.

The November 2006 flooding event on the Carbon River heavily damaged many segments of the Carbon River Road. Park staff provided locations where evidence of surface water flow damaged the road. Site evaluation of these locations suggested that some of the damaged locations were directly attributed to the water surface elevation in the Carbon River, while other damage locations may be attributed to local drainage and tributary streams. Many of the local drainage issues were associated with plugged culverts. The site assessment notes based on the GEOMAX Carbon Road alignment and stationing are included as Appendix C.

To adequately compare the model results to the field evidence it is important to know what the recurrence interval of the November 2006 flood event was. Using the peak flow record for the Carbon River USGS river gage near Fairfax, a flood frequency analysis (FFA) was conducted. The November 2006 event had a recorded peak flow of 14,500 cfs, the largest recorded flow ever at the gage. The FFA was carried out with and without the inclusion of the November 2006 event. FFA is a statistical methodology that uses all the recorded annual peak flows to determine the peak flow rate associated with various recurrence intervals. The results are shown in Table 9. Based on the values provided in the table, the November 2006 storm event was approximately equal to the 100-year event when it occurred and afterward would be adjusted to the 85-year event. For this analysis, we will assume the November 2006 event was equal to the 100-year event.

Table 9. Flood Frequency Analysis for the Carbon River at Fairfax USGS Gage

Recurrence Interval	Estimated Peak Flow (cfs)			
	With Nov 06	W/O Nov 06	2100*	2100**
2-Year	4433	4377	5117	6605
5-Year	7041	6824	8357	10491
10-Year	8933	8546	11169	13310
25-Year	11490	10820	14036	17120
50-year	13520	12570	16378	20145
100-year	15640	14370	18460	23304
500-Year	21040	18810	23860	31350
Nov 06 Recurrence Interval	~85 Year	~100 Year		

* Estimated flows in 2100 based on trend since 1977 at Carbon River Fairfax Gage
** Estimated flows in 2100 based on trend at Nisqually River National Gage

As part of the Carbon River Road inundation analysis, along with the surveyed Carbon River cross sections, ENTRIX also surveyed the Carbon River Road from the park entrance up to Ipsut Campground. The surveyed road elevations were used to compare the HEC-RAS modeling results to determine possible road inundation locations along the project reach. Figure 17 provides a graphical presentation of the surveyed data for the road and the river. The HEC-RAS interpolated cross sections were used to create the continuous Carbon River invert.

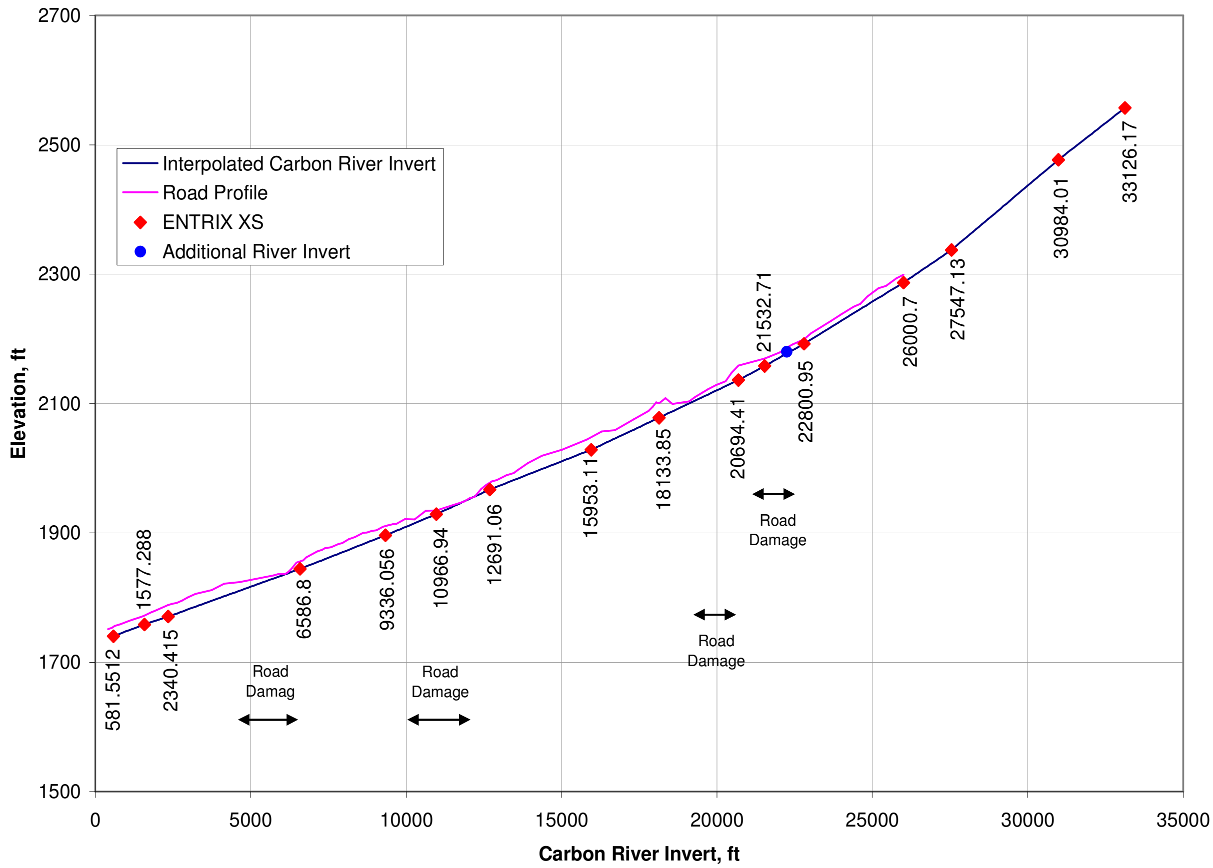

Figure 17. Carbon River road and river invert profile

Figure 18 illustrates how close the Carbon River Road alignment elevation is to the river itself. It is important to remember, the figure shows the surveyed river invert (lowest channel elevation). The river itself has multiple braided channels and gravel bars. The unvegetated gravels bars are indicator of continually migrating channel locations which also means changing channel invert locations. Due to the energy of the river, the channel inverts may move, but they will generally have the same invert within the reach. Figure 12 also contains a single survey location (Additional River Invert), where evidence on the road being inundated was found. During the road survey, ENTRIX staff recorded the road elevation and also surveyed points related to the gravel bar elevation and channel invert.

The "Road Damage" designations in Figure 18 depict the approximate locations of the more severe damage to the Carbon River Road that may be attributed to inundation from the Carbon River during the November 2006 flood event. Due to the scale used on Figure 18, it is hard to determine exactly what the elevation difference is between the road and river.

To better illustrate the elevation relationship between the road and the river Figure 13 was developed. The point data shown is the difference in elevation between the road and river invert in feet. The 0-feet line represents where the river invert and road are at the same elevation. Each point is a location of a surveyed or interpolated cross section. Also shown in the figure is the estimated water surface elevation for the 2 through 500-year high flow events. Based on the modeling results, the road is susceptible to inundation flooding near river stations 6000, 12000, 18000, and 22000. The modeling results also show that the flood stage (water surface elevation) for the modeled high flow events has a range of about 3-feet. This is due to the relatively small watershed resulting in smaller peak flows, and the wide active channel associated with the Carbon River. Once the water surface in the river reaches the elevation of the gravel bars, the active flow width of the channel expands to between 200-400 feet. This results in minor increases in water surface elevations relative to magnitude of flows the Carbon River project reach experiences (Table 3).

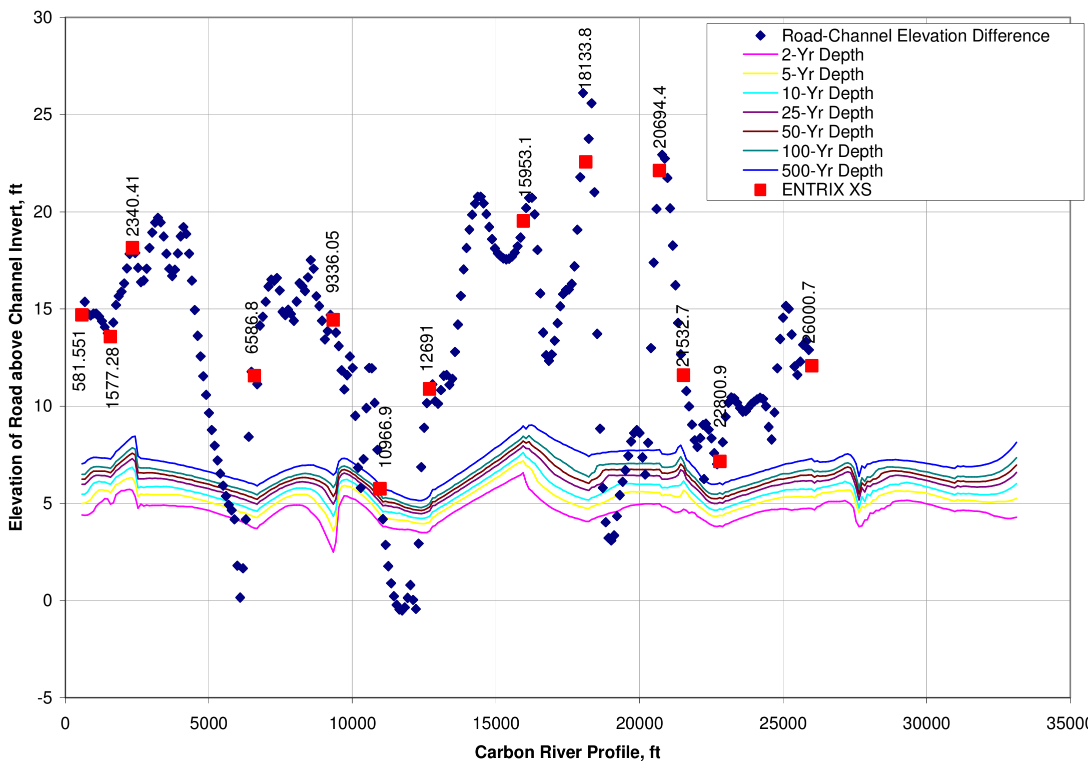

Figure 18. Elevation difference between the Carbon River road and the river

As illustrated in Figures 18 and 19, there are multiple locations along the Carbon River Road where inundation from the river is possible. Whether or not the road actually becomes impacted by the river depends on the floodplain buffer between the river and road. Typically in the likely inundation locations, the floodplain is approximately the same elevation as the road, with multiple side channels, large and small, conveying higher flows from the river. At times flow reaches the road, however, it may also be diverted naturally in another direction. Figure 19 depicts locations with probable inundation impacts and estimated return intervals.

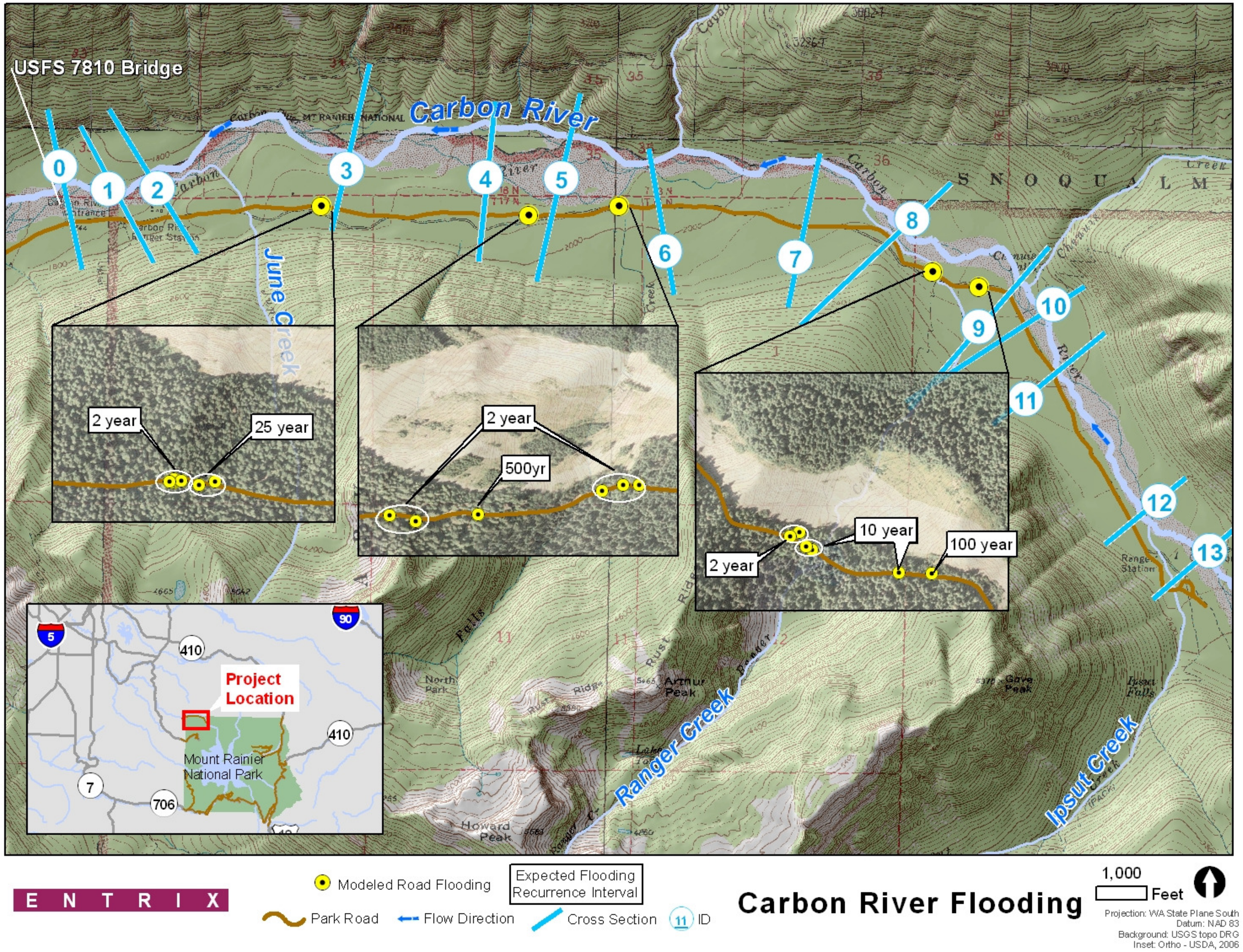

Figure 19. **Modeled Flood Inundation Recurrence Intervals for locations along Carbon River Road in Mt. Rainier National Park**

The complete HEC-RAS modeling results used to create Figure 18 are provided in Appendix B. A tabular summary of the modeling results showing the HEC-RAS modeled WSE along with the road elevation corresponding to the ENTRIX cross section is shown in Table 10.

Table 10. Carbon Road HEC-RAS Summary Results

HEC-RAS XS	ENTRIX XS	Carbon Road Elevation (ft)	Min Ch El (ft)	Road Height Above River Invert	Water Surface Elevation, ft						
					2 Year	5 Year	10 Year	25 Year	50 Year	100 Year	500 Year
33126	15	No road	2557.1	N/A	2561.4	2562.4	2563.1	2563.7	2564.1	2564.5	2565.3
30984	14	No road	2476.8	N/A	2481.4	2481.9	2482.3	2482.6	2482.9	2483.1	2483.6
27547	13	No road	2337.4	N/A	2341.5	2342.3	2342.7	2343.2	2343.5	2343.8	2344.4
26000	12	2298.98	2286.9	12.08	2291.6	2292.3	2292.6	2293.1	2293.4	2293.7	2294.2
22800	11	2199.46	2192.3	7.16	2196.1	2196.7	2197	2197.4	2197.6	2197.8	2198.4
21532	10	2169.59	2158	11.59	2162.7	2163.7	2164.2	2164.6	2164.9	2165.2	2165.7
206941	9	2158.43	2136.3	22.13	2141.3	2141.9	2142.3	2142.7	2143	2143.4	2144.1
18133	8	2100.46	2077.9	22.56	2082	2082.7	2083.1	2083.6	2084	2084.3	2085.4
15953	7	2048.03	2028.5	19.53	2035.1	2035.7	2036.1	2036.5	2036.7	2037	2037.5
12691	6	1977.89	1967	10.89	1970.6	1971	1971.3	1971.6	1971.8	1972	1972.4
10966	5	1934.45	1928.7	5.75	1932.7	1933.1	1933.5	1933.8	1934	1934.2	1934.6
9336	4	1910.64	1896.2	14.44	1898.7	1899.8	1900.5	1901.2	1901.6	1902	1902.7
6586	3	1855.87	1844.3	11.57	1848	1848.6	1848.9	1849.3	1849.6	1849.8	1850.3
2340	2	1788.64	1770.5	18.14	1776.2	1776.8	1777.4	1777.8	1778.1	1778.4	1778.9
1577	1	1771.88	1758.3	13.58	1763.3	1763.9	1764.3	1764.6	1764.9	1765.1	1765.6
581	0	1754.80	1740.1	14.70	1744.5	1745.1	1745.6	1746.1	1746.3	1746.6	1747.1

As the table shows, the ENTRIX survey cross sections did not happen to correspond exactly with the inundation locations. Cross section 5 (10966.94) does show a 5.75 elevation difference which is within the expected flow depths shown in Figure 18 above.

Based on our hydraulic model simulation, the total length of the Upper Carbon River Road potentially impacted by flooding is up to 30% (based on a conservative assumption that flood elevation was within 3ft of the road) 100 yr flood, Table 11, Figure 20. This means that if the Based on observed trends in river aggradation, over the next 50 years, the river bed will rise above the existing road grade and increase flood elevations. Assuming the channel hydraulics remain similar over time with most of the conveyance concentrated in unvegetated channel and the floodplain dominated by ineffective flow, in 50 years, 7% of the road will be lower than the average river bed elevation (Table 11, Figure 21) and 32% of the road will be at risk of inundation during the 5 yr flood (assuming current discharge (Q) estimate, not projected Q in 50 years). Furthermore, inundation will occur during the current 5 yr flood event by the year 2058, and result in a three-fold increase in the length of road at risk (10%). Similarly, the percentage of road at risk of inundation during the 500 yr flood will more than double from 14% to 37% (Table 11).

Table 11. Impacted length of road

Flow Event	Road length (ft)	Road length (miles)	% of total
Total road length	26,000	4.92	
2 yr flood	1,840	0.35	7
5 yr flood	2,524	0.48	10
500 yr flood	3,610	0.68	14
100 yr flood + 3 ft of freeboard	7,725	1.46	30
Projections for year 2058 (50 yrs)			
Riverbed	1839	.035	7
5 yr flood (in 2058)	8444	1.6	32
500 yr flood (in 2058	9620	1.82	37

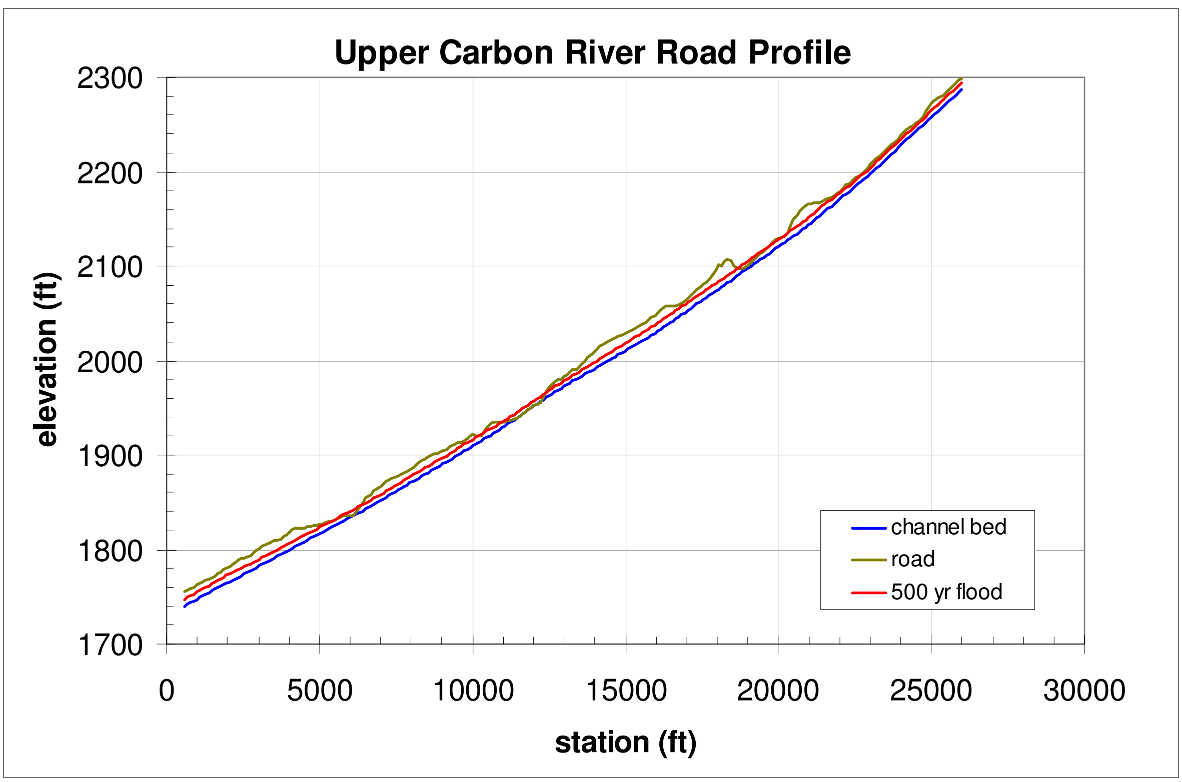

Figure 20. Upper Carbon River profile with road and 500 yr flood

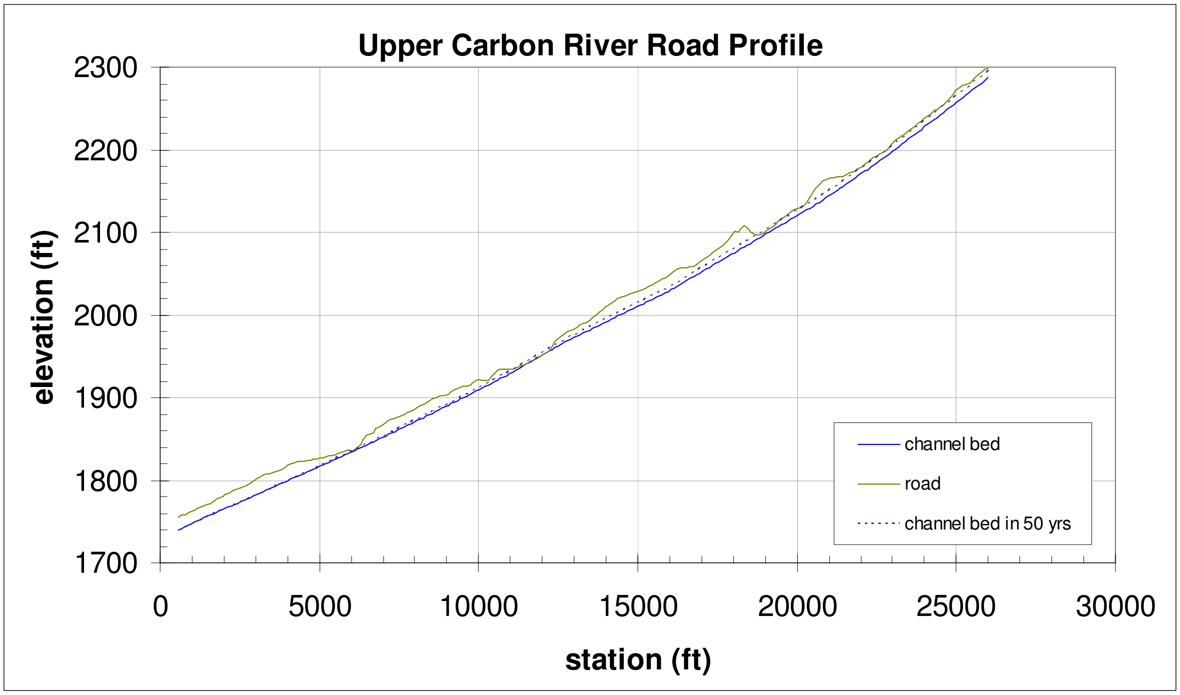

Figure 21. Upper Carbon River bed profile presently (2008) and estimated in 50 yrs (2058) based on observed trends of aggradation.

10. Conclusion and Recommendations

The HEC-RAS hydraulic model of the Carbon River developed for this project is a single channel representation of the project reach of the river. It is also only a 'snapshot' in time for the project reach. Due to the dynamic nature of the river, main channel locations and geometry are likely to change from high flow event to high flow event.

As a single channel model, the Carbon River hydraulic model developed for this analysis assumes a constant water surface elevation across the entire river valley. As field evidence suggests, there are multiple side channels that become active during high flow events. The side channels will likely have a different water surface profile and flow velocity from the main channel that can not be simulated with the current HEC-RAS model. The limited (16 locations) river cross sections do not provide the detail of the multiple channel geometry that would be required to develop a hydraulic model that would be able to simulate the relationship between the main channel and the multiple side channels. The current model does provide a conservative approximation of expected water surface elevations across the valley floor, allowing for the identification of potential locations of adverse flooding impacts to the road as desired for this project.

The combined result of analyses shows that the Carbon River project reach is very dynamic. Bed material is frequently entrained and transported, and the bed elevation is likely to be aggrading over time. Barbs require a precise elevation at the channel forming flow to deflect flow. This requirement renders barbs very sensitive to changes in bed elevation. The aggradational character of the Carbon River predicted by the hydraulic and sediment transport analyses is generally confirmed by the comparison of the Reidel cross-sections with the existing topography. Re-survey of the Reidel cross-sections shows significant aggradation of the channel. In addition to the Reidel re-survey, a study of aggradation rates of rivers in Mount Rainier National Park indicated that the Carbon River has the highest aggradation rate (based upon analysis of historical topographic maps) of the rivers analyzed by this method (Beason, 2007). Using georeferenced historical maps, this analysis shows an average increase in the elevation of the Carbon River of 0.6 ft/ year. This pattern of persistent aggradation, as well as the steepness of the project reach, makes barbs a poor candidate for successful bank protection.

In-channel grade control structures were also proposed to prevent head cutting at culvert outlets and limit flow to side channels. Grade control structures may be effective, if the footings are placed to below the depth of scour. An evaluation of rock weirs for habitat and grade control (BOR, 2007) shows that common mechanisms of failure include undermining due to scour and filling or burial due to sedimentation. Many of the failure mechanisms such as scour and end-cutting can be improved using timber in combination with rock. Since logs have much greater length scale then individual rocks they can better address localized scour or end-cutting that can severely compromise structures only composed of rock. Failure from scour of in-channel grade control structures is probable in the Carbon River project reach since shear stress within the channel is high and the entrained grain size is also large (Table 7). Preventing failure by scour will require placing rock to below the depth of scour. The proposed designs give a rock volume for the structures, but do not specify either stone size or depth of placement.

Off-channel grade control structures were also proposed to limit erosion and prevent avulsion. Table 8 summarizes the grain size entrained at the Q2 on the floodplain. Similar to the in-channel grade control structures, the proposed designs will require large stone sizes placed to below the depth of scour to be effective. Neither grain size nor depth of placement is specified. Specific grade control structures, such as rock-filled log cribs within the road grade (Figure 16), could offer potential for protecting the road from incision, but not from lateral erosion.

Engineered logjams (ELJs) or log crib structures provide the best potential for lateral-erosion protection because their success is neither elevation-dependent nor limited to particular river plan-form, as is the case with barbs. ELJs can be constructed to heights that allow them to be effective even in an aggrading river. Log jams are also naturally occurring in the Carbon River, unlike barbs, so they are more consistent with the National Park Service mission. However, ELJs alone cannot protect the Carbon River Road.

The hydraulic and sediment transport analysis conducted for the Upper Carbon River clearly demonstrates that the Carbon River Road is at serious risk of chronic failure. GEOMAX (2008; sheet 18 of 84) clearly recognized that their Problem Areas 2 and 3 (Falls Creek Washout) lie within an aggrading river channel that cannot be stabilized. GEOMAX state that their original perception that it would "be possible to permanently stabilize this reach" was ill-founded and they changed their opinion because of channel instability. The only location where the proposed barbs offer possible benefit is along the existing rock revetment just up stream of the FR 7810 bridge (station 500-1000, Figures 4 & 5).

When LiDAR topography is obtained for the Upper Carbon River a detailed hydraulic analysis should be done that accurately incorporates all of the floodplain, and a complete road assessment should be conducted to determine if there are locations outside of chronic hazard areas to which the road can be relocated for long-term stability. Using the LiDAR data, the hydraulic model could be developed to include the multiple side channels that convey large volumes of flow. This will allow for a better understanding of how and where high flows are impacting the road right of way. This will allow for identification of where to best position and protect the road or relocate major road segments.

The Upper Carbon Road is currently in an unsustainable location that will continue to be subjected to chronic hazards that are not addressed by the proposed GEOMAX structures. No actions are recommended until a complete topographic and channel-migration assessment is done to determine if a stable road route can be identified.

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