HYDROLOGIC AND HYDRAULIC DESIGN OF THE LOWER COAL CREEK FLOOD HAZARD REDUCTION PROJECT

30% DESIGN REPORT

Prepared for:

CITY OF BELLEVUE UTILITIES DEPARTMENT
Bellevue, Washington

Prepared by:

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Seattle, Washington

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1 INTRODUCTION

The City of Bellevue has initiated the Lower Coal Creek Flood Hazard Reduction Project to respond to frequent flooding on Coal Creek. Undersized culverts, debris blockage, and development have all contributed to the flooding issues experienced by nearby Newport Shores residents. This document reports on the hydrologic and hydraulic design of bridges which will replace culverts at Cascade Key, Upper Skagit Key, Glacier Key, Newport Key, and Lower Skagit Key.

2 BASIN HYDROLOGY

2.1 Hydrologic Time Series

The peak annual flood frequency, seasonal frequencies, and other statistics describing the stream flow in Coal Creek were estimated from an HSPF model of the entire Coal Creek basin. The model was calibrated to both gaged flows along the creek within Newport Shores and to water surface elevations observed in the I-405 flow control and sedimentation pond. Development and calibration of the model are described in a report on an earlier phase of this project (NHC 2015). The model was used to simulate 65 years of continuous hourly flows at each Coal Creek culvert crossing. These time series provided the data for analysis of peak annual exceedance probabilities and other statistics.

2.2 Coal Creek Flood Frequency

Flood frequency curves were fitted to peak annual flow data by plotting flow exceedance levels against recurrence intervals corresponding to a median plotting position. It was found that a non-parametric fit based on moving averages and logarithmic interpolation most closely followed peak annual flow data from the HSPF model.

An example of the fit to the data at each crossing is shown in Figure 1. In this figure, RCHRES 1 represents the lower Skagit Key crossing, RCHRES 2 represents the Newport Key crossing, etc., up to RCHRES 5, which represents the Cascade Key crossing. For events up to the 100-year flood, the corresponding flow changes by less than two percent from the upper to lower end of the project area. This is logical because the change in drainage area from Cascade Key to lower Skagit Key is very small in proportion to the overall basin drainage area. Additionally, it was found that widening one or several of the existing culverts would not significantly alter flood frequency at any crossing due to a lack of flood storage along the creek within Newport Shores.

2.3 Construction Season Flood Probability

The probability of Coal Creek flows of different magnitudes occurring during the construction season was investigated using seasonal flood frequency and high-flow-event duration analysis for the 3-month period from July through September and for each individual month in that period.

2.3.1 Flow Exceedance Probabilities

As shown in Table 1, the flow with a one percent probability of being exceeded in the three month July–September period of any given year is 232 cubic feet per second (cfs), 43 percent of the full-year 100-year flow of 535 cfs. This seasonal value is considered to be conservative for two reasons:

- The peaks generated by the HSPF model take place during a period when precipitation data used in the model are based on a single gage record.
- Spatial variability of summer storm events is represented by two multipliers on a single gage record. Thus, rainfall amounts within the basin vary geographically, but the general pattern of rainfall is assumed to be synchronous. This is less of a problem for full-year flood frequency analysis since winter flood-causing storm events tend to involve larger weather systems with more uniform coverage.

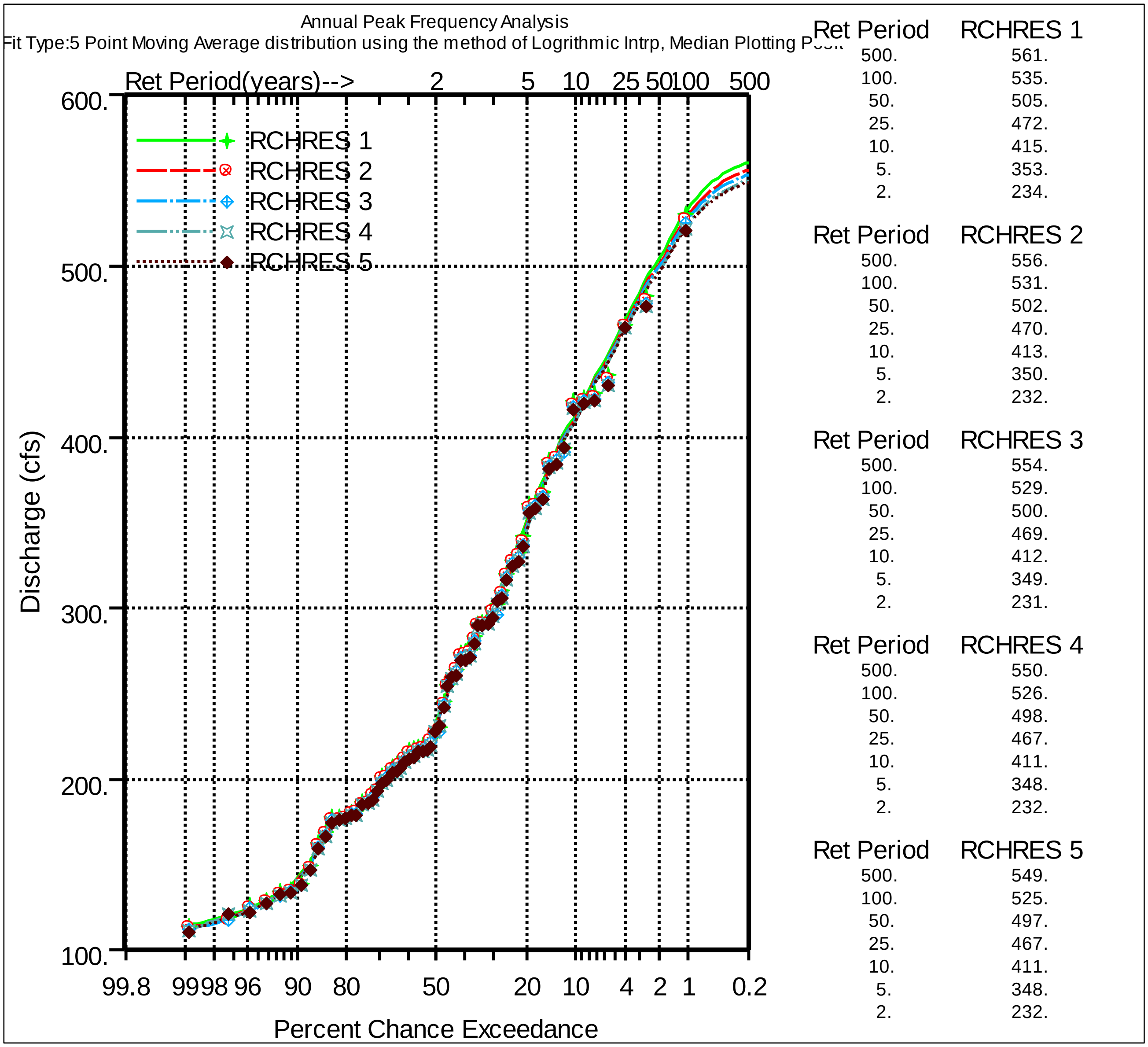


Figure 1. Peak Annual Exceedance Probability

Table 1. Annual Exceedance Probability by Month and Season

Annual Probability of Exceedance	Coal Creek Flow at Corresponding Exceedance Probability (cfs)			
	July	August	September	July–September
50%	19	19	40	62
10%	68	103	113	144
4%	112	157	157	190
1%	162	232	200	232

2.3.2 Flood Event Durations

Eighty percent of 2-year (50-percent exceedance probability) flow events (see 1) last less than five hours in July, and less than ten hours in August, although some of these events can last more than a day. The 10-year (10-percent exceedance probability) flow events are all typically short-lived, ranging from a 15 minutes to 2 hours in July and August.

2.4 Monthly Mean Hydrograph

Table 2 provides average monthly flows in lower Coal Creek throughout the water year for different exceedance probabilities. The 50-percent column represents the typical average monthly flow. In July, August, and September, these values tend to be less than 2.5 cfs. Barring significant summer storms, flows are reasonably steady from hour to hour and day to day during this season.

Table 2. Probability of Mean Monthly Flows

	Average Monthly Flows at Corresponding Exceedance Probabilities (cfs)				
	5%	25%	50%	75%	90%
October	21.7	5.0	2.3	1.7	1.5
November	57.2	19.3	7.7	3.4	2.1
December	67.4	25.2	11.9	5.7	3.6
January	74.4	28.5	12.7	6.2	4.1
February	56.3	22.3	11.1	6.0	3.9
March	48.7	18.2	8.8	5.3	4.0
April	32.4	10.0	5.6	4.0	3.2
May	14.5	5.0	3.7	3.0	2.7
June	11.3	3.9	3.1	2.6	2.3
July	4.3	2.9	2.5	2.1	1.9
August	4.2	2.5	2.1	1.9	1.6
September	7.4	2.5	2.0	1.7	1.5

3 STREAM HYDRAULICS

Culvert design, flood levels, and channel stability were evaluated using a one-dimensional, steady-state HEC-RAS hydraulic model of lower Coal Creek. The model was originally developed and calibrated as part of an earlier phase of this project (NHC 2015), but it was subsequently updated using new channel survey data and updated flood frequency results to improve calibration and model performance at each crossing. From five to 14 cross-sections were added upstream and downstream of each crossing based on channel survey conducted in fall 2015. The following sections describe the methods and assumptions used to recalibrate the model and evaluate existing and proposed conditions.

3.1 Model Calibration

The HEC-RAS model was recalibrated to match high water marks measured by the City during flood events in December 2007 (estimated peak flow between 457 and 480 cfs) and December 2010 (estimated peak flow of 441 cfs) (NHC 2015). Some inconsistencies were found in the observed data. For example, the high water marks from the 2010 event were higher than those observed during the larger 2007 event. This and other apparent discrepancies could be explained by observer bias or geomorphic changes in bed form between 2007 and 2010. The differences were addressed by calibrating the model to the "average observed" high water mark. A single flow value of 455 cfs was computed, based on estimates from 2007 and 2010. The model was calibrated by adjusting parameters such as roughness (Manning's 'n') and contraction/expansion coefficients to improve the match between the simulated and observed high water marks at each crossing. Consistent with previous analysis (NHC 2015), the culvert barrels at Glacier Key, Newport Key and lower Skagit Key were assumed to be fully scoured.

Recalibration of the updated model yielded better agreement between modeled and observed water surfaces (±0.25') than was achieved in the earlier calibration (±0.5) (NHC 2015), except downstream of the upper Skagit Key culvert. There, the new modeled water surface differs from the observed high water mark by 0.5 feet, the same as for the previous modeling. This is likely due to the complexity of channel morphology at this location and resultant complex hydraulics, which are not as well represented with a one-dimensional hydraulic model. **Error! Reference source not found.** 2 compares the calibrated modeled water surface profile to the observed average high water marks.

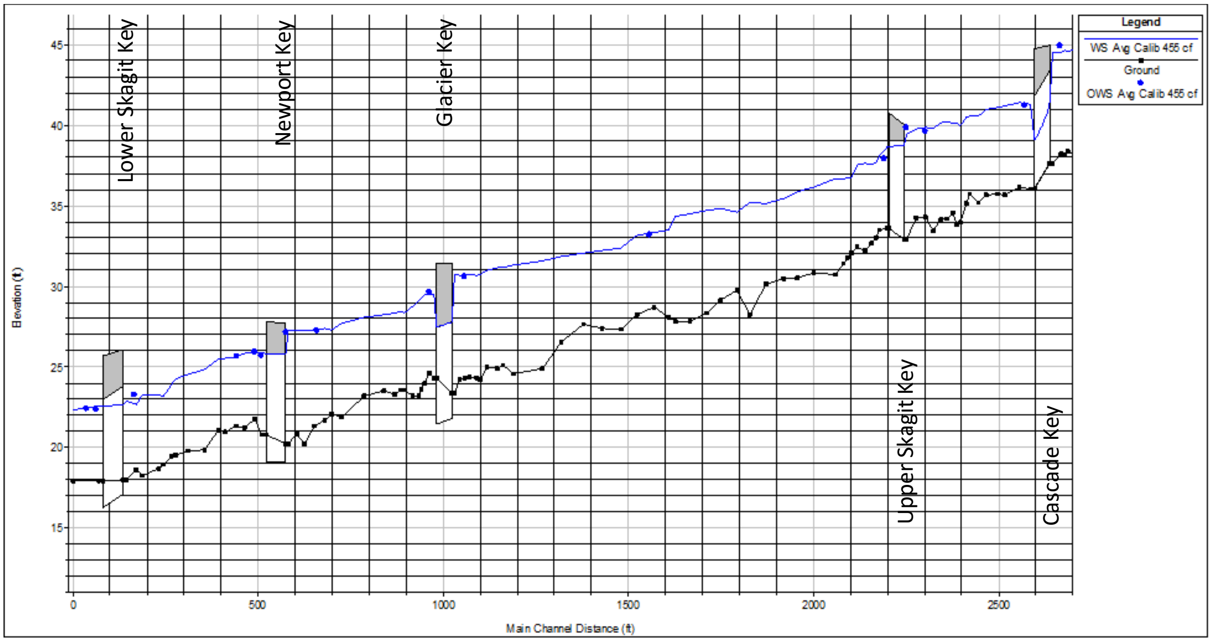


Figure 2. Calibration of Flood Profile for the Calibration Flow of 455 cfs

3.2 Modeled Bridge Configuration for Proposed Conditions

A standard bridge configuration was assumed, to model proposed conditions on Coal Creek after completion of this project. Bridges were sized to meet fish passage requirements according to the stream simulation methodology outlined in the Water Crossing Design Guidelines (Barnard et. al. 2013). This guidance requires that bridge width be determined using the stream simulation method based on the bank-full width of the stream channel. Multiple bank-full width measurements were taken between 75 and 180 feet upstream of each crossing, which is out of the hydraulic influence of the culverts. Measurement locations where neither bank was armored were preferred, but if no such locations were available, then locations where only one bank was armored were selected. At Newport Key, revetments are continuous along both banks for a long distance upstream of the culvert, so unarmored bank conditions were unavailable. Measurements were collected from pool, riffle, and glide geomorphic units. Because the constructed channel is confined and typically isolated from the floodplain, a combination of features, such as vegetation, slope, and sediment size, was used to define the width measurements. A letter report documenting the bank-full width investigation is in a separate memo.

Average bank-full widths above the five culverts ranges from 15 to 17 feet, with a minimum of 12.3 feet and a maximum of 20.3 feet. Washington Department of Fish and Wildlife design guidance suggests that the culvert bed width be 20 percent larger than the bank-full width plus 2 feet (Barnard et al. 2013, Equation 3.2). Based on the observed bank-full width values, the computed minimum width for the culverts would range from 20.0 to 22.4 feet at the various culvert crossings. A single width is proposed for all five crossings in the project, so a width of 24 feet was assumed for the analysis of replacement bridges.

The proposed-condition HEC-RAS modeling assumed regrading of surrounding banks at culvert faces (within the right of way) and bridge structures modeled as 24-foot-wide openings with the low-chord above the 100-year water surface elevation. The Manning's 'n' values, representing friction, was uniformly set to 0.04 through the structures.

3.3 Existing and Proposed Flood Profiles

The recalibrated HEC-RAS model was used to estimate the water surface profiles for the 2-, 10-, 25-, and 100-year events under existing conditions. Proposed-condition water surface profiles were then computed to assess flood reduction benefits of the culvert replacements. Figures 3 – 6, compare computed existing and proposed condition water surface profiles for the 2-, 10-, 25-, and 100-year events.

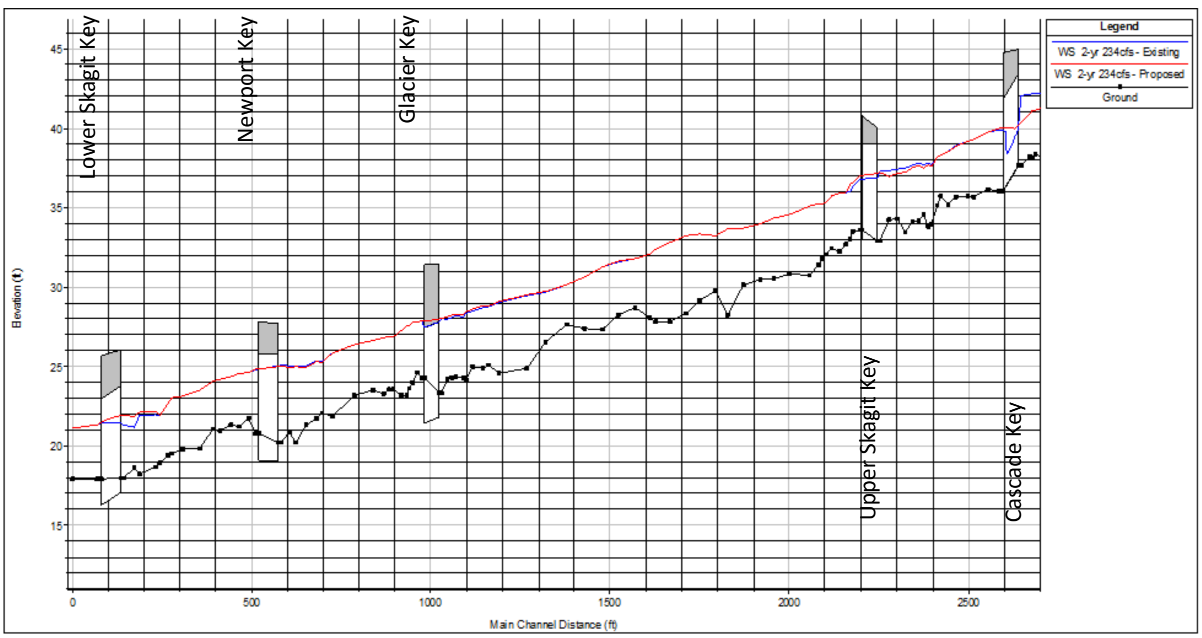


Figure 3. 2-Year Water Surface Profile for Existing and Proposed Conditions

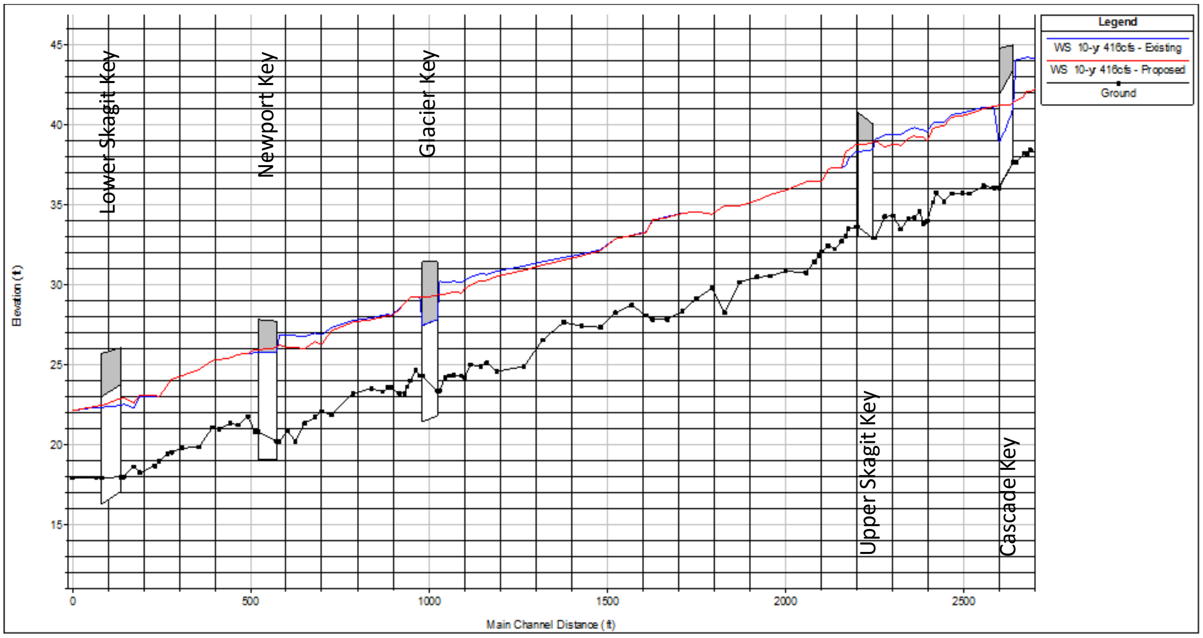


Figure 4. Figure 4. 10-Year Water Surface Profile for Existing and Proposed Conditions

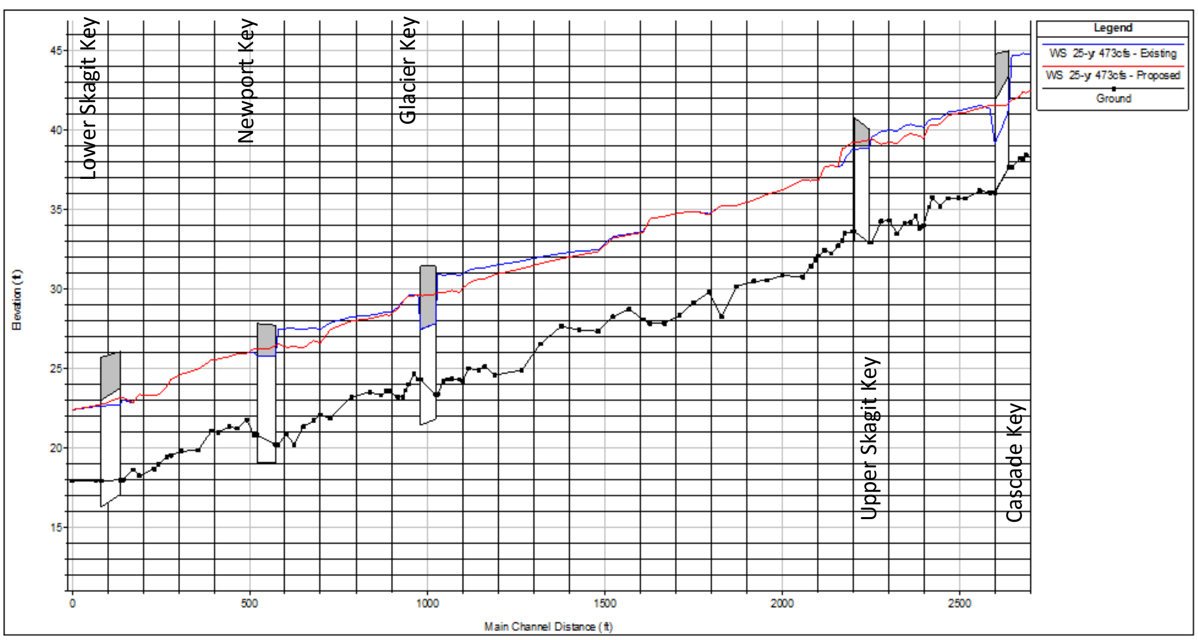


Figure 5. 25-Year Water Surface Profile for Existing and Proposed Conditions

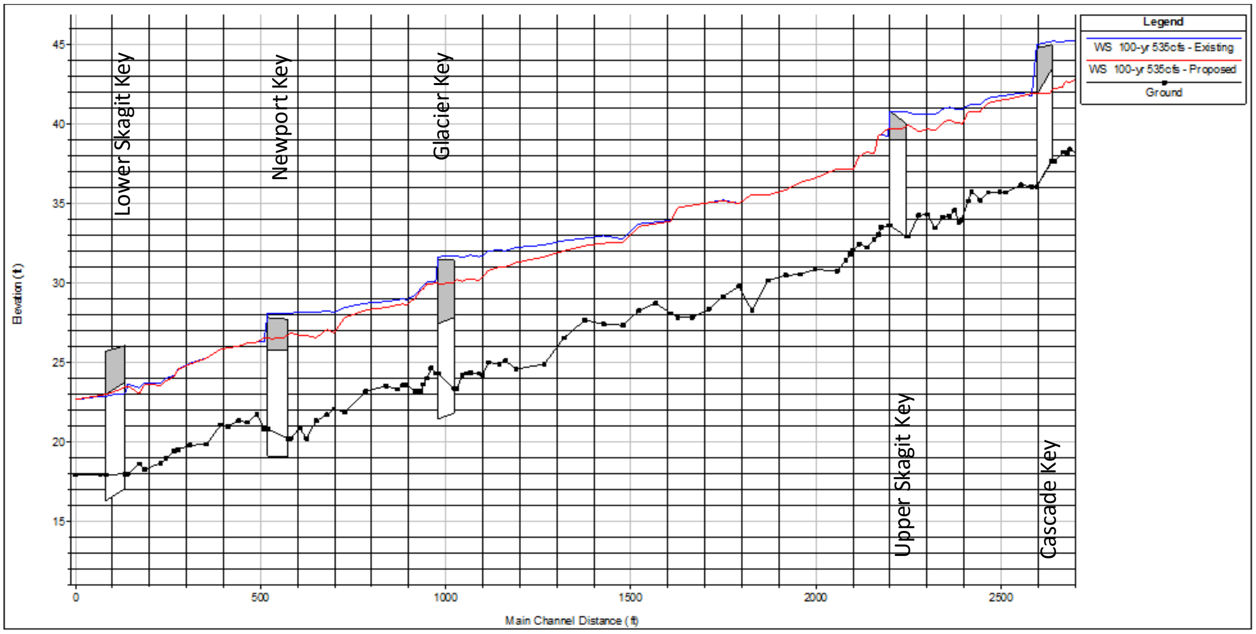


Figure 6. 100-Year Water Surface Profile for Existing and Proposed Conditions

The largest flood event recorded between 1949 and 2013 on lower Coal Creek (2007) had a peak flow of about 460 cfs, slightly less than the 25-year event at all project crossings. During this event, overtopping of the road surface did not occur except at Cascade Key, where a piece of wood blocked the culvert entrance. These observations are consistent with modeling of existing conditions, which does not predict overtopping of the culverts for flows below a 100-year event; at the 100-year event, the existing-conditions modeling predicts overtopping at all but the lower Skagit Key crossing.

Under proposed conditions, with 24-foot wide bridge structures, overtopping during a 100-year event is not predicted at any crossing, and flood level reductions upstream of the crossings are on the order of 1.5 to 3 feet. A slight increase in the water surface elevation at the proposed lower Skagit Key structure is predicted for the 2- and 10-year events. This increase is due to the wider channel constructed with the proposed structure that introduces a small expansion loss for lower flows.

3.4 Ordinary High Water in Coal Creek

The ordinary high water depth in Coal Creek, as estimated from field observations of bank conditions, ranges from 2.0 to 2.5 feet. A calibrated HEC-RAS model of the creek (see Section 3.1) estimated that the stream flows that produce this range of ordinary high water depths range from 100 to 110 cfs. There is greater than a 98-percent probability that the ordinary high water depth will be exceeded for at least an hour in any given year. There is a 74-percent chance that the ordinary high water depth will occur for more than 24 hours in any given year.

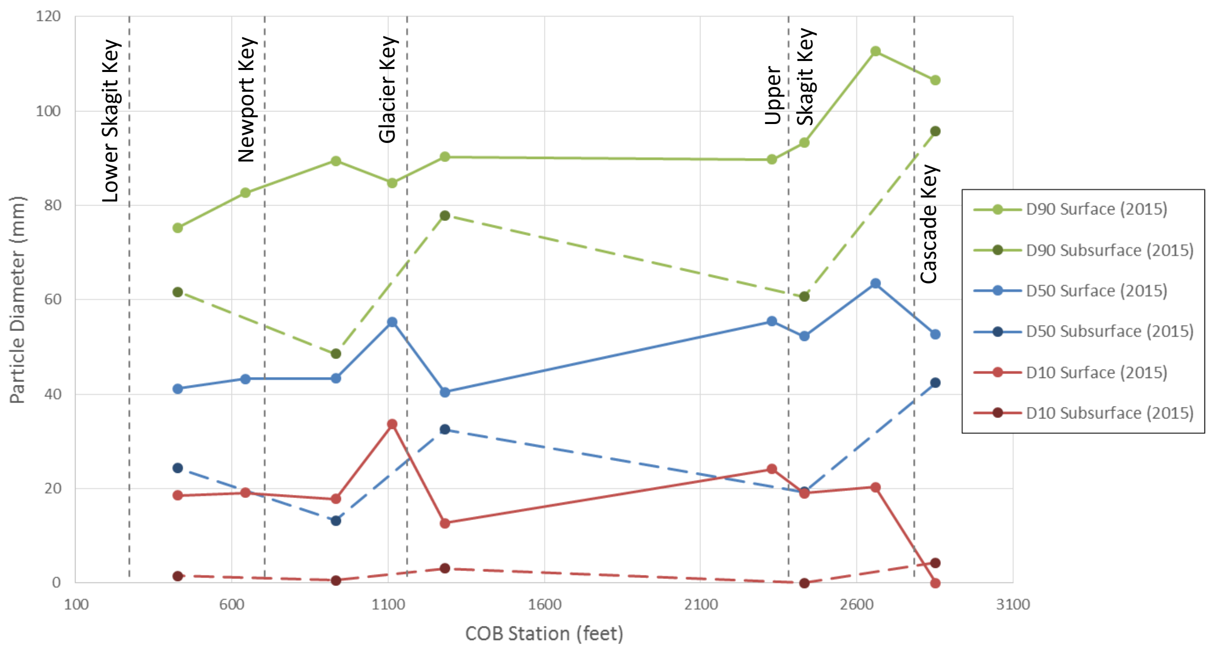
4 STREAMBED DESIGN

4.1 Channel Bed Scour

Channel stability and scour were evaluated using field data, HEC-RAS modeling, and standard bed scour relations. Field data consisted of streambed sampling in fall 2015 to determine grainsize composition at each crossing. Surface samples were collected both upstream and downstream of each crossing using a random walk pebble count method (Wolman, 1954). Subsurface material was sampled upstream of each crossing by scraping away a surface layer and collecting a bulk sample, which was sent to a laboratory for sieving. Samples were collected in similar geomorphic units (e.g., riffle crests) within 200 feet upstream or downstream of each crossing, except at lower Skagit Key where access was not available on the downstream side. Figure 7 shows the profile of the D90, D50, and D10 characteristic particle sizes (D50 is the diameter that 50 percent of particles are less than or equal to; D90 is the diameter that 90 percent of particles are less than or equal to; etc.).

Figure 7. Characteristic Surface and Subsurface Particle Sizes Along Lower Coal Creek

At the Cascade Key, upper Skagit Key, and Glacier Key crossing



s,

median surface particle diameters (D50) are smaller on the upstream sides than the downstream side, indicating that current hydraulic constrictions and backwater induce sediment deposits. These smaller upstream deposits may be vulnerable to erosion once culverts are replaced. Further, armoring is apparent along the entire reach, as indicated by comparison between D90 and D50 surface and subsurface values, but is most pronounced downstream of Glacier Key and upstream of upper Skagit

Key. Here, relatively large deviations between surface and subsurface characteristic particle sizes suggest increased scour potential if the surface armor layer were to be disturbed during a flood event.

General reach stability was evaluated by comparing computed channel shear stress to the incipient motion threshold of typical surface sediment found in lower Coal Creek. Channel shear stress was computed by the HEC-RAS model for the 2- and 100-year flood events. Incipient motion threshold was estimated using Shields criteria for a D50 particle diameter of 64 mm and Shields parameters of 0.03 and 0.06 (USACE 1994). Figure 8 shows the findings for existing and proposed conditions.

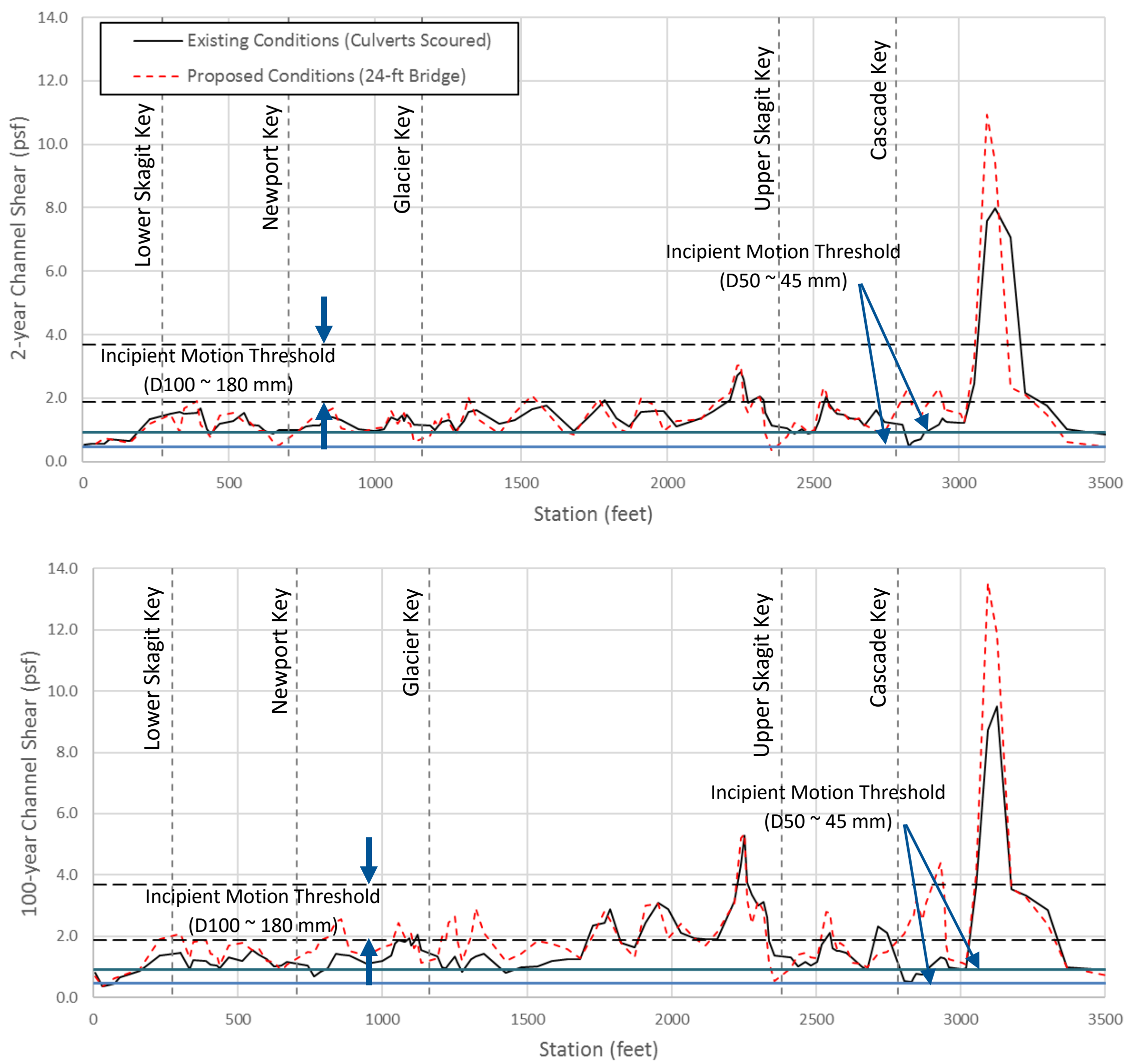


Figure 8. Computed Existing and Proposed Condition Longitudinal Shear Profile and Incipient Motion Thresholds (D50) for the 2-Year (a) and 100-Year (b) Events

For the 2-year flood event (Figure 8a), the most pronounced effect of culvert replacements is upstream of Cascade Key, where reduced backwater conditions result in increased shear stress that can mobilize sediment and cause channel degradation. Downstream of upper Skagit Key, shear stress is reduced, indicating potential sediment deposition. Further downstream, the difference between existing and proposed conditions is minimal. For the 100-year flood event (Figure 8b), proposed conditions show channel shear stresses along the downstream half of lower Coal Creek significantly above those of the existing condition. This suggests that channel scour and degradation are possible during higher flows. However, sediment transport through the reach during lower flows would likely redeposit sediment in reaches degraded during high flow events.

Localized scour at each crossing was estimated using the "competent velocity" method outlined in TAC (2004). This method assumes that scour within a constricted waterway (e.g. bottomless culvert or bridge) will occur until the mean velocity is lower than the competent velocity, defined as the velocity that is able to mobilize bed material. The procedure was implemented iteratively using the HEC-RAS model. Assuming a 100-year flow, the bed level under the bridge was manually lowered until computed velocities within the barrel did not exceed the competent velocity for the existing surface and subsurface D50 particle diameters measured upstream at each crossing. Table 3 summarizes the results.

Table 3. Summary of Competent Velocity Scour Analysis

	Computed 100-Year Bridge Velocity, Existing	Upstream D50 (mm)		Competent Velocity (feet/second)		Potential Scour Depth Below	New Computed 100-Year Bridge Velocity, Existing
Crossing	Bed (feet/second)	Surface	Subsurface	Surface	Subsurface	Existing Bed (feet)	Bed (feet/second)
Cascade Key	5.9	53	42	6.9	5.9	1	5.2
Upper Skagit Key	7.7	52	19	6.9	4.9	3.5	4.7
Glacier Key	6.0	40	32	5.9	4.6	3	4.0
Newport Key	6.4	43	13	4.6	3.9	4.5	3.9
Lower Skagit Key	5.5	41	24	4.6	4.3	3	4.1

Given that subsurface particle diameters are smaller and therefore mobilized at a lower competent velocity, they generally dictate the amount of scour predicted to occur at each culvert. For example, the smaller subsurface D50 of 13 mm at Newport Key results in the most significant scour depth of 4.5 feet below existing bed levels, whereas the coarsest subsurface D50 at Cascade Key results in a scour depth of 1 foot. With site-specific variation, scour depths for a 100-year design flow are expected to range from 3 to 4 feet along lower Coal Creek.

Sheet pile walls on the interior of the bridge abutment are proposed to protect the bridge structure from scour. The embedment depth of the sheet pile should be 1 to 2 times the scour depth.

Due to the potential for both reach-wide and local channel scour following culvert replacement, coarse sediment bands would be constructed within the channel of each bridge structure. In addition to providing grade control, the coarse sediment bands, spaced at minimum of one bank-full width, would prevent channel widening and help maintain definition of a low-flow channel. Following streambed sizing guidelines provided in the *Water Crossing Design Guidelines* (Barnard et. al. 2013), the low flow channel bed material would be sized using the following ratios:

- D84/D100 = 0.4
- D84/D50 = 2.5
- D84/D16 = 8
- with 5 to 10% fines added to mixture

These ratios, and measured D84 particle diameters in lower Coal Creek, yield streambed mixtures with D100 diameters of 160 to 230 mm, D50 diameters of 25 to 40 mm, and D16 diameters of approximately 10 mm. Coarse sediment band material would be sized to two times the D100 of the bed material (Barnard et al. 2013)—from 325 to 465 mm. The material used to construct bands within the culvert will be coarser than the neighboring bed material to protect against erosion and maintain established channel dimensions through the culvert.

4.2 Bank Stabilization

Lower Coal Creek is channelized and generally disconnected from adjacent floodplains, with much of the bank armored. A field investigation was conducted at the onset of this project phase to document the condition of the banks and identify instabilities. Bank conditions 200 feet upstream and downstream of each crossing were inventoried, except downstream of lower Skagit Key where access was not available. Numerous minor instabilities consisting of localized failures were observed along the reaches, but most were considered minor.

The most severe bank instability was observed on the left bank immediately upstream of upper Skagit Key. Here, a 4- to 5-foot high exposed vertical bank is eroding along the outside of a bend. Failure of past armoring is evident, as riprap lines the toe of the bank. Less severe, but still significant, bank instability was observed on the right bank 100 to 120 feet upstream of Cascade Key. Here, a 4- to 5-foot high rockery wall was observed to be undermined on the outside of an abrupt channel bend. The City of Bellevue will notify the property owner of the existing condition revealed during the field investigation of Coal Creek. Replacement of these culverts will increase the channel's conveyance capacity and reduce immediate flood risk, but also is expected to increase velocities. The potential for geomorphic change exists within the creek currently and will continue to exist after the culverts are replaced.

4.3 Large Wood for Bank Protection and Mitigation

Placement of large wood along lower Coal Creek will serve as bank protection as well as habitat mitigation. In total, 41 pieces of wood are being proposed for placement along Coal Creek. Preliminary design calculations have been completed for the log elements, to address buoyant and drag forces acting on the logs. The combined drag and buoyant force acting on an individual log is estimated to be 4.7 tons. To resist this force, non-embedded logs will be held in place with 2 to 4 mechanical anchors and one 2-ton boulder. Mechanical anchors will be secured to both ends of each log to limit movement. The 2-ton boulder (1.2 ton submerged weight) will allow settling and deformation of the structure as the channel adjusts following completion of construction.

The resistance gained by mechanical anchors is a function of their size, driving depth, and soil strength. The manufacturer's strength rating for a Manta Ray MR-1 mechanical anchor ranges from 3,000 to 8,000 pounds in soils with weak strength, similar to conditions found along lower Coal Creek. Because of this uncertainly, anchor pull-out resistance should be tested during construction to determine the number of anchors required. Assuming the lowest pull-out resistance of 3,000 pounds per anchor, four MR-1 mechanical anchors and one 2-ton boulder will provide 7.2 tons of resistance and a 1.5 factor of safety. On the other hand, if pull-out strength for each mechanical anchor is determined to be 6,000 pounds or more, only two anchor and one 2-ton boulder are require to achieve the same resistance safety factor.

4.3.1 Cascade Key

Two groups of wood structures are proposed immediately upstream of the Cascade Key crossing on the left bank and right bank. Three logs will be placed on both banks for flow redirection through the proposed bridge opening as well as for habitat mitigation. Each log will be individually ballasted with a combination of mechanical anchors and a 2-ton boulder. To minimize or eliminate loss of flow conveyance, the root end of these logs will be embedded into the channel and the stem placed in a shallow trench along the slope.

4.3.2 Upper Skagit Key

Severe bank instability on the left bank upstream of the Skagit Key crossing will be addressed with construction of a 35-foot log crib wall and bioengineered bank. The bank will be excavated to allow placement of the crib structure, composed of three layers of logs, with the lowest layer of logs placed below the current thalweg elevation. The logs will be lashed together with chain, and select logs secured with mechanical anchors. After backfilling the crib structure with native materials, the upper bank will be reconstructed with coir-wrapped soil lifts and live plantings. Three additional ballasted logs will be placed on the immediate opposite bank for flow redirection and habitat purposes. To eliminate loss of any significant flood conveyance capacity, the root end of these logs will be dug into the channel and the stem will be placed in a shallow trench along the slope. Each of the logs will be held in place with a combination of two mechanical anchors and a 2-ton boulder.

4.3.3 Newport Key

Although significant bank instability was not observed at Newport Key, large wood features are being proposed upstream and downstream of the crossing to create diversified habitat along the currently uniform, straight reach. Five structures upstream and four downstream, consisting of two ballasted anchored logs each, are proposed. To maintain flood conveyance capacity, the root end of these logs will be dug into the channel and the stems will be placed in a shallow trench along the slope. Each of the logs will be held in place with a combination of two mechanical anchors and a 2-ton boulder.

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NHC Ref. No. 2000044

29 March 2016

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Attention: **Bruce Jensen, P.E., City of Bellevue P.M., BJensen@Bellevuewa.gov**

CC: **Jerry Scheller, P.E., Tetra Tech, Consultant Team P.M.,** Jerry.Scheller@tetratech.com

Re: **Debris Loading and Clearance for Lower Coal Creek Culvert Replacements**

Dear Bruce:

The following letter report summarizes Northwest Hydraulic Consultant's (NHC's) observations and assessment of debris loading along lower Coal Creek including estimates of minimum vertical clearance to pass potential pieces of large through culverts.

1 INTRODUCTION

The City of Bellevue is considering replacement of the five existing culvert crossings along Lower Coal Creek (Figure 2) with larger structures to alleviate localized flooding and improve fish passage. The replacement structures need to meet current requirements for fish passage standards. NHC was retained to provide hydraulic engineering services and design guidance for the proposed culvert replacements.

Lower Coal Creek flows through the Newport Shores residential neighborhood and has been heavily modified by human activity. Located on a former lake delta and alluvial fan deposit, the creek was channelized into its current alignment in the 1960s (Figure 2). Another important human influence on the creek was the lowering of the mean elevation of Lake Washington from approximately 27.5 to 18.5 feet NAVD 88 at the time of the construction of the Lake Washington Ship Canal and Locks. This lowering also accompanied a reduction in seasonal lake elevation variability from approximately 7 feet to 3-4 feet (Chrzastowski, 1983).

Currently, the lower 3,700 feet of the channel is confined and isolated from adjacent floodplains and has an average gradient of 0.6%. Bank revetments of various type are pervasive, encompassing approximately 30% of the total bank length within 200 feet upstream and downstream of five existing culvert crossings. Bank vegetation is variable but dominated by landscaping, brushy material, and trees growing immediately adjacent to the creek.

Figure 1: Vicinity map of lower Coal Creek.

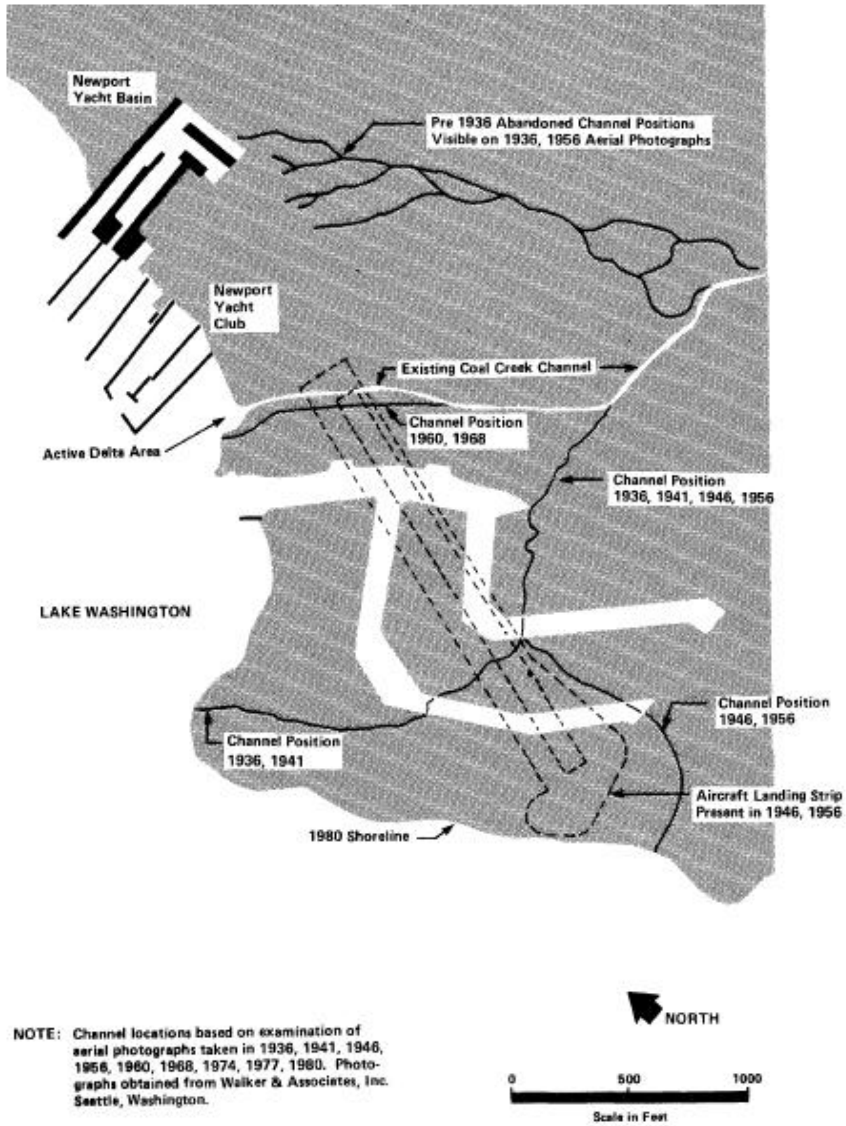

Figure 2: History of channel position in delta. Figure 3 in Coal Creek Basin Plan(King County, 1987).

2 DEBRIS CLEARANCE

2.1 Existing design guidance

Washington Administrative Code (WAC 220-110-070(1)(e) states that "The bridge shall be constructed , according to the approved design, to pass the 100-year peak flow with consideration of debris likely to be encountered."

Guidance for "consideration of debris" is variable. For example, the City of Bellevue Engineering Standard requires 1-foot of freeboard above the 100-year water surface elevation to accommodate debris. WSDOT guidance for bridges over larger streams and rivers is that 3 feet of freeboard be provided (WSDOT, 2010; Barnard et al., 2013; WSDOT, 2015a, 2015b). However, there is flexibility regarding the required debris clearance, as most guidance leaves finalization up to the discretion of the designer, who should consider the flood history, nature of the site, character of drift, risk to infrastructure, cost, and other relevant factors (WSDOT, 2010).

Barnard et al. (2013) suggest the following starting point for debris clearance in smaller culverts:

1. Small streams with bankfull width less than 8 feet: 1 foot above the 100-year water surface.
2. Medium streams with bankfull width from 8-15 feet: 2 feet above the 100-year water surface.
3. Larger stream with bankfull width more than 15 feet: 3 feet above the 100-year water surface. Note that this is a common clearance recommendation for bridges, which would be the recommended structure in streams over 15 feet wide.

If a more detailed analysis of debris clearance is desired, Barnard et al. (2013) suggest following the guidance of Bradley et al. (2006) who rely heavily on the work of Diehl (1997). Guidance developed by Bradley suggests designers consider the existing volume and character of debris stored within a channel, potential future recruitment of debris from the banks (which is a function of the floodplain vegetation and channel migration potential) and size of debris that a channel can transport. The debris clearance analysis for crossings on lower Coal Creek follows these methods as described below.

3 POTENTIAL FOR DEBRIS DELIVERY

3.1 In-Stream Debris Volume

The volume and characteristics of potential floating debris along a creek channel provides the best view of material that may be delivered to a water crossing structure. Potential floating debris (hereafter debris) includes large woody material (LWM) and anthropogenic material, but does not include bed material sediment.

The I-405 Pond control structure includes a trash rack which traps LWM before flow enters the I-405 box culvert. The structure effectively prevents the delivery of LWM from the upstream watershed and limits the reach from which LWM can be recruited to less than 600 feet of channel upstream of Cascade Key and the remainder of the creek within the Newport Shores neighborhood. In other words, debris delivery has been cut off from more than 97% of the upstream channel. Therefore this evaluation focuses on the stream channel between the most downstream culvert (Lower Skagit Key) and I-405. Continuous field observations of conditions along the stream were collected by NHC in October 2013, while additional detailed observations have been collected more recently (October 2015 and January 2016). Although the focus of these field investigations was not observation of debris loading potential, photos taken nearly continuously along the stream provide a suitable inventory of existing debris in the channel.

I-405 to Cascade Key

The catchment zone for debris that may be delivered to Cascade Key extends from the crossing upstream to I-405. The following debris has been observed in the channel in this area:

- Several log grade-control weirs are present immediately downstream of I-405. These are embedded in the banks and are designed to be immobile by the stream.

- Four alder and cottonwood logs ranging in length from approximately 10-30 feet with diameters of 6” to just over 12” are within the bankfull width and span, or partially span, the low-flow channel. These are located along the first 400 feet downstream of the I-405 culvert (Photo 1). As these decompose, high flows may break them down into pieces narrower than the bankfull channel width, which would allow them to float downstream. These wood pieces were broken from standing trees and do not have rootwads.

Photo 1: Example of typical LWM between I-405 and railroad grade (Oct 2013).

Photo 2: Brush and LWM jammed on pilings under old Northern Pacific Railway trestle (Oct 2013). Some of this debris has been transported downstream as of July 2015 (Scheller, personal communication).

- Occasionally branches and debris accumulate 350 feet upstream of the Cascade Key Crossing under the old Northern Pacific Railway trestle (Photo 2). Typically, it is mostly composed of brush, with length <10’ and diameter <4”. There is one large diameter (~36”) but short (<10’) piece and at least one longer piece of smaller LWM similar to those observed upstream. The jam forms on closely spaced piles in the streambed. At low and moderate flows, it probably acts as a sieve, filtering out pieces of smaller brush and LWM transported from upstream. At very high flows, the jam may possibly become buoyant and lift off the piles, delivering a slug of brushy debris to the culverts downstream.

- Several log crib-walls are present along the channel between the old Northern Pacific Railway trestle and Cascade Key Crossing, and are assumed to be immobile.

- An approximately 12” alder fell from the bank during Autumn 2015 storms and spanned the bankfull channel about 25’ upstream of the Cascade Key Crossing. A bar retaining a substantial volume of sediment had accumulated upstream when this condition was observed in December, 2015. As of February 2016, this piece of LWM had been removed from the channel.

Cascade Key to Upper Skagit Key

- A couple of live willows partially block the channel approximately mid-way between Cascade and Upper Skagit Key (Photo 3). A substantial volume of brushy material (3-10' long and <4" diameter) has accumulated on these blockages.

Photo 3: Brush accumulation on live willows between Cascade and Upper Skagit Key crossings (Oct 2015).

Upper Skagit Key to Glacier Key

No significant accumulations of debris were noted between Upper Skagit and Glacier Key crossings. Many rooted trees, typically 12-24" Alders, are present along the banks and often leaning towards the stream A couple of waterlogged, medium length pieces of LWM were noted embedded in the substrate.

Glacier Key to Newport Key

Similar to upstream, no significant accumulations of debris were noted between the Newport and Glacier Key crossings, though some rooted trees are present along the banks (Photo 6). In addition, some broken stems were noted (Photo 6), indicating that LWM has been delivered to this reach in the past, but was either cleared from the channel or transported downstream past the culverts.

Newport Key to Lower Skagit Key

As with Glacier and Newport Keys, numerous rooted trees leaning towards the channel line the banks between Newport and Skagit Key. In addition, a couple of large (12-25" and >20' long) trees span the channel about 175' above the Skagit Key Crossing (Photo 7). A substantial volume of brush has accumulated in the channel upstream between observations made in October 2013 and present.

3.1.1 Debris loading potential

Conditions along the channel banks suggests that there is a low to moderate potential for future LWM loading to the creek. Future lateral channel migration downstream of the I-405 culvert is expected to be negligible because of the limited reach distance between structures, corresponding prevalence of bank revetments, and cohesive bank conditions. However, there are numerous presently live and rooted trees leaning in towards the channel upstream of all five culverts. Wind throw and the prospect of future channel downcutting due to the success of upstream sediment sequestration measures may cause some of these trees to fall into the creek.

Because the creek in the project area flows through residential landscapes, there is also the possibility that people may directly introduce debris to the stream.

Photo 4: Example of trees lining banks between Skagit and Glacier Key (Oct 2013).

Photo 5: Example of leaning trees lining banks and waterlogged LWM embedded in substrate between Upper Skagit Key and Glacier Crossings (Oct 2013).

Photo 6: Rooted trees and broken stems between Glacier and Newport Key crossing (Oct 2013).

Photo 7: Large tree spanning channel approximately 175’ above Lower Skagit Key Crossing (Oct 2013).

3.1.2 Debris transport

Even though existing debris loads are low to extremely low, there is a possibility of future debris generation along lower Coal Creek. As such, it is important to evaluate the size of debris that the creek might be expected to transport. Two factors control this size: the width and depth of flow.

Bradley et al. (2006) state that the minimum depth required to transport LWM is approximately the diameter of the butt plus the distance the root mass extends below the butt, which is typically 3-5% of the height of riparian trees. Other recent research from flume experiments (e.g. Braudrick and Grant, 2000; Haga et al., 2002; Bocchiola et al., 2006, 2008; Curran, 2010); however, suggests that this may not be adequately conservative and that LWM may begin to move by sliding or rolling at a depth approximately one half the diameter of the log.

One large (~36” diameter) log was observed in the creek upstream of Cascade Key, but it was pinned against plies. If this log were to escape the piles, a water depth of approximately 18” could potentially move it based on the half-diameter rule suggested by the flume experiments cited above. As water depths rise to a level sufficient to float a log, the log’s specific gravity will controls what portion is submerged and what portion protrudes above the water surface. Specific gravity can vary from widely from much less than 0.5 to greater 1.0 with values slightly less than 1.0 being most typical.

Although no LWM with attached rootwads was observed in the creek, future downcutting could possibly entrain some trees with rootwads from the banks. For example a 4-ft diameter rootwad with attached 16" butt (1/3 the rootwad diameter) would not be out of the question. Following Bradley et al.'s criteria, the minimum flow depth necessary to transport such a piece of LWM is the butt diameter plus the submerged length of the rootwad or 2.67 ft. This flow depth would just allow the butt and attached wad to be transported. In this situation, the minimum vertical opening from the bed to any low chord would simply be the rootwad diameter plus minimal clearance. For larger flow events in which depths exceed 2.67 feet, 1/3 of the rootwad diameter would be expected to protrude above the water surface (assuming neutral buoyancy of the butt). In this freely floating condition the minimum vertical opening required for free movement through a culvert or bridge opening would equal the water depth plus 1/3 the rootwad diameter.

Diehl (1997) recommended that the maximum log length expected to be mobile be determined by the smaller of the following values:

- The narrowest location in the channel upstream.
- The maximum length of sturdy logs, which is defined by the height and diameter of mature trees on the streambanks.

On lower Coal Creek, the first of these parameters applies, and the longest logs expected to be transported by the creek would be equivalent to the narrowest locations along the channel, which are typically around 12'. Considering that this is much shorter than trees with significant rootwads, this length should prohibit LWM with attached rootwads from being mobile in the creek unless human activity or wind breakage of trees reduce the length of stems or poorly anchored butts and rootwads are introduced to streambanks.

3.2 Summary and Conclusions

Due to the limited stream length for LWM recruitment and the size of observed woody material in the channel within project area, there is a low potential for debris blockage of the replacement culverts within Newport Shores. The minimum vertical clearance between the stream bed and the low chord of road crossing structures required to pass LWM is the greater of the longest vertical dimension of the transported LWM or the sum of the water depth plus the height of the LWM floating above the water surface. Under typical conditions, a log with attached rootwad will float with the log fully submerged, 2/3 of the rootwad submerged, and 1/3 of the rootwad diameter protruding above the water surface. These ratios provide support for design decisions affecting minimum vertical openings of replacement structures for the existing lower Coal Creek culverts.

It should be noted that regardless of the level of conservatism adopted for debris clearance in the design of the proposed lower Coal Creek culvert replacements, all of the proposed structures will be wider, provide higher hydraulic conveyance capacity, and have increased debris passage capability than the existing narrower culverts. Thus, full project implementation will inherently lessen risk of debris blockage at all five crossings.

Please do not hesitate Andrew Nelson, Peter Brooks, or Erik Rowland with any questions about these observations or recommendations at (206) 241-6000.

Sincerely,

Northwest Hydraulic Consultants Inc.

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nhc
northwest hydraulic consultants

NHC Ref. No. 2000044

28 March 2016

City of Bellevue Utilities
450 110th Ave. NE
P.O. Box 90012
Bellevue, WA 98009

Attention: **Bruce Jensen, P.E., City of Bellevue P.M., BJensen@Bellevuewa.gov**

CC: **Jerry Scheller, P.E., Tetra Tech, Consultant Team P.M.,** Jerry.Scheller@tetratech.com

Re: **Bankfull Width Determination for Lower Coal Creek Culvert Design**

Dear Bruce:

The following letter report summarizes Northwest Hydraulic Consultant's (NHC's) observations of bankfull width along lower Coal Creek. Recommendations for design culvert width are given based on these observations.

1 INTRODUCTION

The City of Bellevue is considering replacement of the five existing culvert crossings along Lower Coal Creek (Figure 2) with larger structures to alleviate localized flooding and improve fish passage. The replacement structures need to meet current requirements for fish passage standards. NHC was retained to provide hydraulic engineering services and design guidance for the proposed culvert replacements.

Lower Coal Creek flows through the Newport Shores residential neighborhood and has been heavily modified by human activity. Located on a former lake delta and alluvial fan deposit, the creek was channelized into its current alignment in the 1960s (Figure 2). Another important human influence on the creek was the lowering of the mean elevation of Lake Washington from approximately 27.5 to 18.5 feet NAVD 88 at the time of the construction of the Lake Washington Ship Canal and Locks. This lowering also accompanied a reduction in seasonal lake elevation variability from approximately 7 feet to 3-4 feet (Chrzastowski, 1983).

Currently, the lower 3,700 feet of the channel is confined and isolated from adjacent floodplains and has an average gradient of 0.6%. Bank revetments of various type are pervasive, encompassing approximately 30% of the total bank length within 200 feet upstream and downstream of five existing culvert crossings. Bank vegetation is variable but dominated by landscaping, brushy material, and trees growing immediately adjacent to the creek.

Figure 1: Vicinity map of lower Coal Creek.

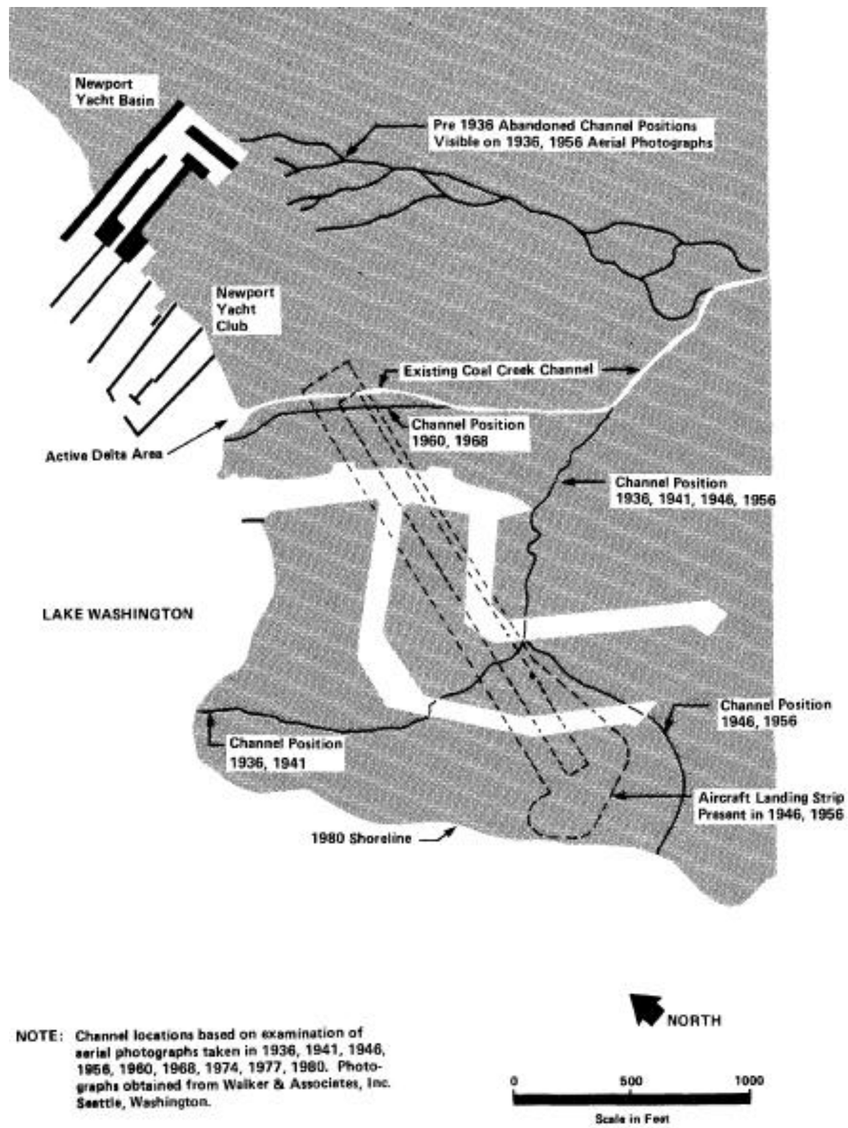

Figure 2: History of channel position in delta. Figure 3 in Coal Creek Basin Plan(King County, 1987).

2 BANKFULL WIDTH

2.1 Width Measurements

WDFW design guidance (Barnard et al., 2013) requires that stream simulation culvert widths be determined based on the bankfull width of the stream channel. On Feb. 2, 2016, an NHC engineer and geologist visited lower Coal Creek in the Newport Shores neighborhood to measure and document bankfull channel width at each culvert crossing.

Multiple bankfull width measurements were taken between 75 and 180 feet upstream of each crossing, which was above the immediate hydraulic influence of the culverts. Measurement locations where neither bank was armored were preferred, but if unavailable, locations where only one bank was armored were selected. At Newport Key revetments were continuous along both banks for a long distance upstream of the culvert, thus unarmored bank conditions were unavailable. Measurements were collected from pool, riffle, and glide geomorphic units. Because the constructed channel is confined and typically isolated from the floodplain, the combination of features suggested by Barnard et al. (2013) Appendix C, were used to define the width measurements.

Results of the measurements are summarized in Table 1. Average bankfull widths above the five culverts ranges from 15 to 17 feet, with minimum and maximum measurements of 12.3 and 20.3 feet, respectively. Figure 4 through Figure 8 show photographs of each bankfull measurement location.

Table 1: Lower Coal Creek Bankfull Width Measurements

Location (ft)[1]	Bankfull Width (ft)
Cascade Key	
85	18.0
105	17.9
130	15.0
average:	17.0
Upper Skagit Key	
75	16.4
100	18.1
125	20.3[2]
155	12.4
average:	16.8
average excluding outlier:	15.6
Glacier Key	
100	17.3
129	17.6
170	15.5
average:	16.8
Newport Key	
92	15.4
130	15.6
160	14.0
average:	15.0
Lower Skagit Key	
115	12.3
150	16.6[3]
180	17.9
average:	15.6

Notes:

1) Measured in feet upstream from upstream culvert face.
2) Outlier caused by local sedimentation and bank erosion upstream of a brush channel blockage downstream (Figure 5).
3) At bankfull elevation the channel is only 14.6 feet wide, but 2 feet of undercut bank included in reported value.

Figure 3: Locations of bankfull width measurements at distances shown above Cascade Key.

Figure 4: Locations of bankfull width measurements at distances shown above Upper Skagit Key.

Figure 5: Location of anomalously wide bankfull width 125 ft above Upper Skagit Key. The channel is anomalously wide at this location due to sedimentation above the downstream obstruction.

Figure 6: Locations of bankfull width measurements at distances shown above Glacier Key.

Figure 7: Locations of bankfull width measurements at distances shown above Newport Key.

Figure 8: Locations of bankfull width measurements at distances shown above Lower Skagit Key.

2.2 Comparison of observed bankfull width to regime equations

The measured bankfull widths are quite narrow compared to undisturbed streams with similar formative discharge values. For example, calculating the expected width using the Castro and Jackson (2001) Pacific Maritime Mountain Stream regime relation, which provides an empirical estimate of BFW using the 1.25 year recurrence interval flow (180 cfs), results in a predicted bankfull width of 32 ft.. The regime equation of Barnard et al (2013 eq. C.1), which empirically predicts bankfull width from basin area (6.8 mi^2) and mean precipitation (45.5 in/yr) also produces results that exceed field measurements. Specifically, it predicts a bankfull width of 23.2 ± 3.7 ft (± 1 standard error). This estimate is not appropriate for Lower Coal Creek because the empirical equation was developed for much steeper streams (slope >2%) and does not account for the creek's actual hydrology (which is muted at channel forming discharges by the I-405 facility and sedimentation ponds). Even though Lower Coal Creek lies outside of the range of streams for which the equation is appropriate, it lies well within the expected range of predicted widths: lying between about 1 and 2 standard errors narrower than the mean predicted by the Barnard et al (2013) equation. In other words, it would lie between about the 2^{nd} and 16^{th} percentile of stream widths for streams with the same basin area and average precipitation.

The relatively narrow character of lower Coal Creek is a remnant of channelization in the late 1960s and persists due to the high bank strength caused by cohesive soils, revetments, and vegetation. The present alignment of lower Coal Creek is below the surface of its paleodelta into Lake Washington and composed of a mixture of sandy alluvial material and cohesive lacustrine silt and clay deposits. These cohesive deposits are the dominant material observable in the creeks banks, and are expected to have high (though unspecified) critical shear stress values (Shields, 1936). As explained below, high bank strength explains the observed relatively narrow width of the creek.

The influence of high bank strength was explored by applying the UBC Regime Model (Eaton et al., 2004; Eaton, 2007, 2015), which predicts channel dimensions using rational regime theory, which is a robust physics based approach to predicting channel dimensions that has been validated against a large empirical dataset. It accounts for many more of the key controlling variables than the local empirical regime equations described above; specifically, it utilizes the controlling variables shown in Table 2, which importantly include specification of a bank strength parameter (μ). This parameter is defined as the ratio of the critical shear stress (τ_c) required to mobilize the bank material to the critical shear stress required to mobilize the bed material. In the case of Lower Coal Creek, all parameters are well known, except the bank strength which would require substantial additional effort to define because it is a result of cohesive soils. Therefore, constant values of discharge, slope, and bed material characteristics were evaluated while bank strength was varied, as shown in Table 2. This is a recommended approach (Eaton, 2015; personal communication) to evaluating conditions for streams with cohesive banks. The results (Figure 9) show three key things:

1) There is a wide range of bankfull widths (12-42 ft) expected to occur given the formative discharge, channel slope, range of reasonable possible bank strength values (Eaton, 2007), and

bed material present along Lower Coal Creek. The observed bankfull widths in the project area (15 to 17') lie well within this range of expected values.

2) The predictions of the Castro and Jackson (2001) and Barnard et al. (2013) regime equations for Lower Coal Creek (30 and 23 ft, respectively) fit well with typical bank strength values for alluvial channels. These widths are consistent with observed channel widths of 20 to 35 ft upstream of the I-405 facility where the creek flows through alluvial material and where there is less attenuation of channel forming flows.
3) It is possible to estimate the bank strength value for lower Coal Creek by comparing the observed widths and rational regime equation results over a range of possible bank strength values. This approach suggests that the typical bank strength along the creek is probably in the range of 3 to 4 times that of the bed (approximately 100 to 160 pa). Because very little empirical data is available to estimate the shear strength of cohesive soils from geotechnical parameters, the only way to confirm this estimate would be to measure the shear strength in place using a submerged jet test device (Clark and Wynn, 2006).

Table 2: Input Values For UBCRM Calculations

	Cascade & Upper Skagit Key	Glacier, Newport, and Lower Skagit Key
Q (cfs)	180	180
S (ft/ft)	0.0087	0.0061
D_{50} (mm)	52	45
D_{84} (mm)	88	76
τ^*	0.02	0.02
μ	variable	variable

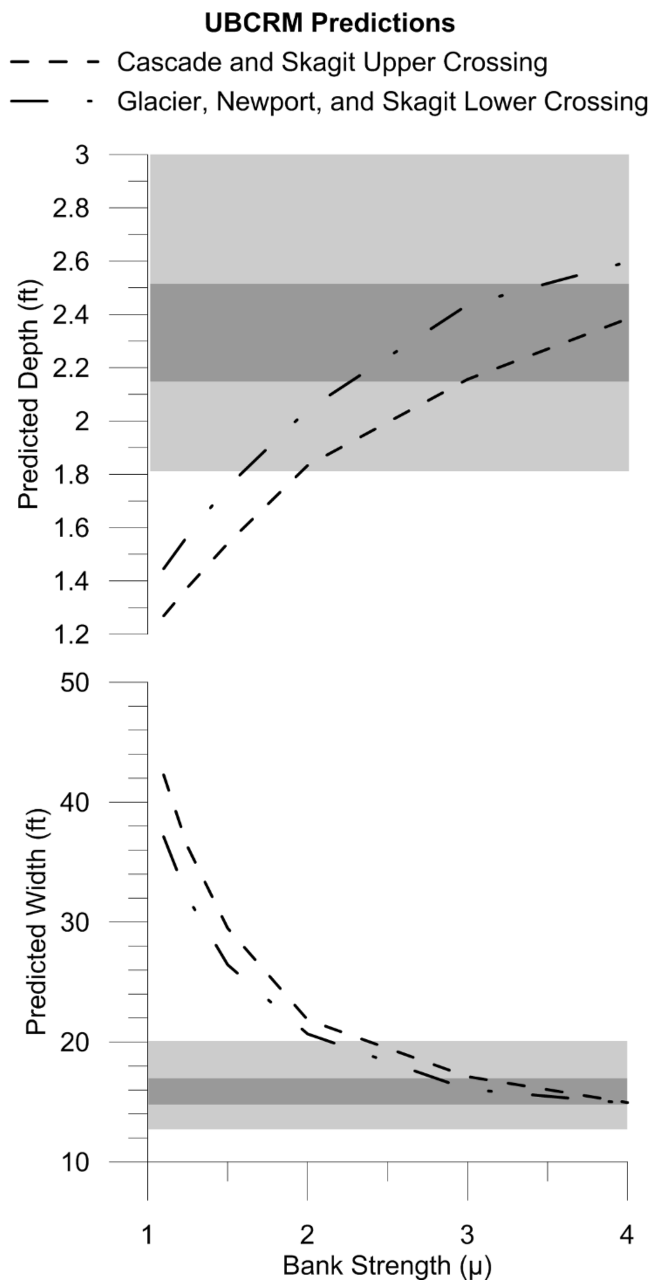

Figure 9: Predicted bankfull width and depth for Lower Coal Creek at two sites based on UBCRM calculations with varying bank strength. The light shaded boxes represents the range of predicted average hydraulic radiuses for the channel forming flow using the HEC-RAS model and observed bankfull widths and the dark shaded boxes represent the range of predicted/observed reach-average hydraulic radius and bankfull width values.

2.3 Recommended culvert widths

WDFW design guidance suggests that the culvert bed width should be 20% larger than the bankfull width plus 2 feet (Barnard et al., 2013, Equation 3.2). Based on the observed bankfull width values, the computed minimum width for the culverts would range from 20.0 to 22.4 ft at the various culvert crossings. If a single width is to be used for all five crossings in the project, it should be no less than 22.4 ft (23 f from a practical design standpoint). Currently, 24-foot wide bottomless culverts are being evaluated as replacement structures.

The UBCRM results (Figure 9) raise an important consideration with respect to design of a low flow channel within the culvert barrel. If material of similar gradation (and therefore cricial shear stress) were to be used to construct both the channel banks and bed within the culvert, the channel would be expected to widen through bank erosion and the result would be an over-widened, poorly defined channel filling the entire culvert width. To address this concern rock bands, spaced at minimum of one bankfull width, are suggested. These bands would help maintain definition of a low flow channel while also providing grade control. It is further suggested that material used to construct banks within the culvert be coarser than the neighboring bed material to protect against erosion and maintain established channel dimensions through the culvert.

Please do not hesitate Andrew Nelson, Peter Brooks, or Erik Rowland with any questions about these observations or recommendations at (206) 241-6000.

Sincerely,

Northwest Hydraulic Consultants Inc.

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REFERENCES

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MEMO

To:	File
Cc:	
From:	Jerry Scheller
Date:	June 20, 2016
Subject:	Lower Coal Creek Flood Risk Reduction – Vertical Clearance for Bridges during Flood Events

This memorandum documents the recommendation for vertical clearance and freeboard for the replacement bridges on Coal Creek in the Newport Shores neighborhood. Vertical clearance is defined as the depth from the channel invert to the low chord of the bridge deck. Freeboard is defined the distance between the low chord of the bridge structure and the 100-year water surface elevation at the upstream face of the bridge. Hydraulic analysis showed that the upper Skagit Key, Glacier Key, and Newport Key bridges would be surcharged during the 100-year peak flood event if the current road profile is maintained.

The following vertical clearance and freeboard guideline were considered:

- The Washington Administrative Code (WAC 220-110-070(1)(e) requires 3 feet of freeboard unless engineering justification shows lower clearance is adequate for passing debris.
- The WSDOT Bridge Design Manual (2016) states freeboard is determined by the hydraulics branch on a case by case basis.
- The WDFW Water Crossing Design Guidelines (2013) provides general guidance for bridge clearance that the bottom of the superstructure should be 3 feet above the 100 year flood water surface. In some instances, the designer may increase the clearance or decrease the clearance as acceptable to the local or state roadway bridge design authority.
- King County Roads Standards (2007) specifies 3 feet of freeboard unless otherwise required by the County Engineer based on other conveyance factors outlined in the Surface Water Design Manual. It doesn't explicitly state it can be less but implies a different value can be used with an analysis of hydraulics, bed aggradation, and debris passage.
- City of Bellevue Surface Water Engineering Standards (2016) specifies 1 foot of freeboard for the 100-year event. Deviating from this standard would likely require a variance.

A vertical clearance of 6 feet from the channel thalweg and 1 foot of freeboard is recommended to pass submerged woody debris during the 100-year peak flood event. The recommendation is based on reach scale hydrology and sedimentation information provided in NHC's Alternatives Analysis Report (2015) and their analysis of debris loading potential (2016, attached) and summarized below.

- Low to moderate debris loading potential in the project reach due to:
    - Limited stream length available for recruitment of large woody debris and the size of observed woody material within the project area.
    - Limited potential for channel migration downstream of I-405 because of prevalence of bank revetments, and cohesive bank material.

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- Relative flashiness of the peak flow hydrograph where high flow depths only occur for a few hours.
- Due to upstream sediment control measures and the current armored condition, the channel bed is stable and expected to remain stable in the future.
- Presence of the I-405 Pond control structure, located on Coal Creek upstream of the project site, includes a trash rack that traps large wood before it enters the I-405 box culvert. This structure limits wood recruitment to the project reach and the 600 foot long reach between I-405 and Cascade Key, cutting off delivery from over 97% of the upstream channel.
- Stream channel conditions would likely prohibit large woody material with attached rootwads from being mobile. The longest logs expected to be transported by the creek would be equivalent to the narrowest locations along the channel, which are typically around 12'. Considering that this is much shorter than height of trees with significant rootwads, this length should prohibit LWM with attached rootwads from being mobile in the creek.
- The largest diameter large woody material was found to be 36". If this log was mobilized with 2/3 submergence would require 1 foot of clearance at the bridge to safely pass the log during high flows.