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Technical Memorandum No. 1

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To: Devin Smith, Skagit River System Cooperative

From: Paul DeVries, Ph.D., P.E.

Subject: Illabot Creek Alluvial Fan Channels Restoration Project: Basis of Design

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CONTENTS

1. BACKGROUND, ENVIRONMENTAL SETTING

R2 Resource Consultants, Inc. (R2) was contracted by the Skagit River System Cooperative (SRSC) to develop a design to restore a reach of Illabot Creek (Figure 1) and convert it from a channelized single thread planform closer to a semblance of its historic braided state, and set up natural processes facilitating alluvial fan flooding and sedimentation processes, involving constructing one or more new bridges. Based on an alternatives analysis of conceptual alternatives involving between one to three new bridges and reported by TranTech (2011), a two bridge option was selected because it provided the greatest habitat benefits for the cost. The project reach and general concept were identified in a feasibility assessment performed by the SRSC (Smith and Ramsden 2006). The over-riding goal of restoring natural alluvial fan flooding and deposition processes is to create and maintain spawning and rearing habitat for Chinook salmon (*Oncorhynchus tshawytscha*) and other fish species in the project reach.

This technical memorandum summarizes the rationale and technical basis behind the selected design, including relevant design details related to hydrology, geomorphology, channel layout and dimensions, hydraulic modeling, and design of log and rock components of the project.

1.1 Geographic and Geomorphic Setting, and Design Constraints

The project reach extends upstream and downstream of the Rockport-Concrete road, encompassing private land. The project reach is a relatively steep (~1.6 % gradient), plane bed channel that is situated on a large scale fan morphologic feature (Figure 2). The riverbed is composed of coarse boulder-cobble-gravel substrates, is generally clean with low fine sediment embeddedness, and transports cobble and gravel bedload readily (Figure 3). There is little in the way of large woody debris in-channel forming habitat presently. Pools are formed primarily at bends. Illabot creek has experienced considerable historic manipulation of the channel and floodplain. Skagit County channelized the stream ca. 1971 and constructed a single bridge. Aerial photographs taken before that time show a braided channel that moved periodically across an alluvial fan throughout the project reach, above and below the road location (Smith and Ramsden 2006). Hence, the design of channel planform should focus on identifying geomorphic tendencies towards braiding and designing a channel planform that is consistent with dominant channel slope, bankfull discharge, and streambed grain size.

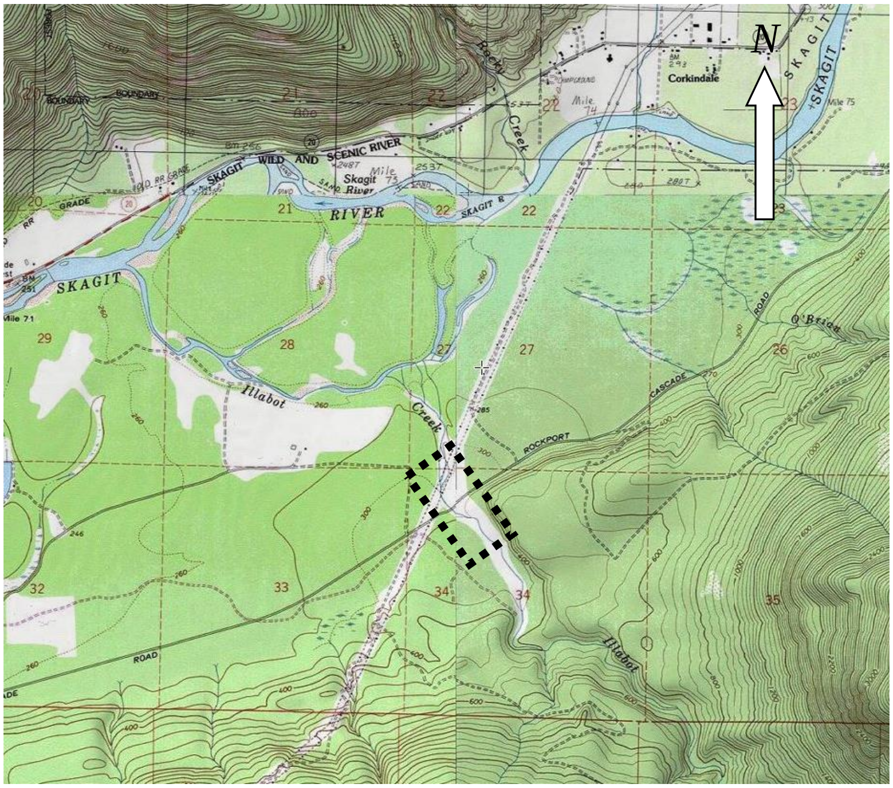


Figure 1. General location of Project Reach on Illabot Creek, indicated by dashed box. Flow is from south to north.

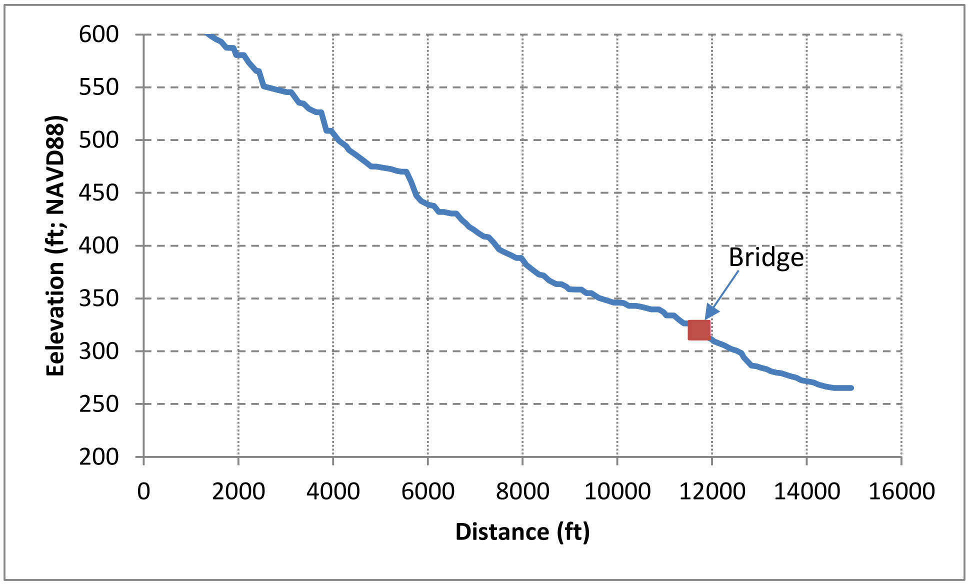


Figure 2. Long profile of Illabot Creek extending above and below the project reach; derived from USGS StreamStats. The reach encompasses a bump in the profile symptomatic of an older fan morphology located around a large scale slope break and reduction in valley confinement. Location of the Rockport-Cascade road bridge is indicated.

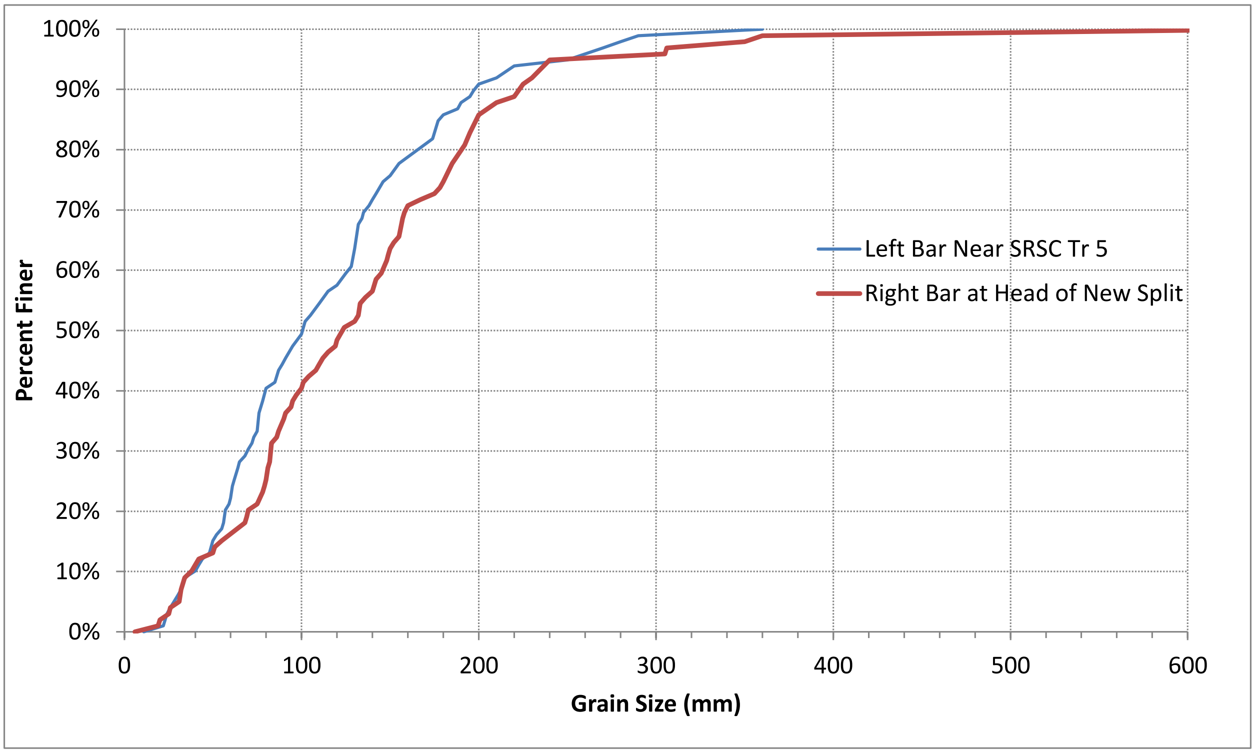


Figure 3. Grain size distributions determined at two locations in the project reach using pebble counts performed over defined deposits. The samples reflect the general grain size of bedload passing through the reach.

1.2 Hydrology

Hydrology is necessary for (1) bridge scour evaluation (2) channel and structure design. The 100-yr flood is the design parameter for both. SRSC had earlier estimated the magnitude to be ~7,080 cfs (Smith and Ramsden 2006). For increased confidence in design, the estimate was revisited using additional available information. Limited gage data exist for Illabot Cr, insufficient for a formal peak flow frequency analysis, thus we resorted to a regional regression approach using the USGS StreamStats website (based on Sumioka et al 1997), and analyzed available gage data and HEC-RAS modeling for evaluating the need to adjust regression estimates (or not). Instantaneous flow measurements were performed by Duke Engineering at a gage for the SRSC over WY 99-02. The USGS gaging station daily flow data were for WY ‘83-’85. Both gages are representative of comparable drainage areas, and there are no significant tributaries between the two gage locations.

As corroborative analysis, the regression mean estimate of the 2 year flood (Q_2) was compared with (1) plots of available annual peak flow estimates vs. plotting position (generally inaccurate, but should be reasonable for defining a likely lower bound to Q_2), and (2) predictions of bankfull flow in a basic single channel HEC-RAS model of the existing channel using SRSC-surveyed cross-section and long profile data combined with LiDAR data (see section 3.3).

The range of estimates of Q_2 at the bridge was 2000-3200 cfs based on the daily flow data (lower end of range) and regression analyses (upper end). The HEC-RAS prediction of bankfull flow ≈ 2800 cfs at SRSC transect 6 (HEC-RAS Sta 21). This result implies the regional regression mean estimate (3170 cfs) is conservative, therefore the 100-year flood regression estimate (9,700 cfs) may also be conservative, which is judged to be a satisfactory design flow for evaluating abutment scour risk at bridge. Consequently, the regression-based mean estimates were taken to define the design hydrology. The resulting estimates of flood magnitudes for specific recurrence intervals are listed in Table 1.

Table 1. Approximate flood magnitudes estimated for various recurrence intervals in Illabot Creek.

Recurrence Interval (years)	**Flow (cfs)**
100	9,710
50	8,600
25	7,240
10	5,830
2	3,160

Specific climate change impacts on Illabot Creek hydrology are uncertain, but some general trends are likely (http://www.skagitclimatescience.org/skagit-impacts/hydrology/). The Skagit basin is predicted to shift to a more rain dominant behavior by the end of the 21st century, with largest losses of snowpack projected for mid-elevation basins such as Illabot Creek. Large scale modeling results predict an increase in winter runoff, resulting from more precipitation falling as rain rather than being stored as snow, which is projected to increase the frequency of the 100-year flood in the lower Skagit River by about 30%. Thus, it behooves the design hydrology to veer on the high side for project element stability, which further supports the use of the estimates in Table 1. At the same time, the uncertainty in hydrologic predictions means that the design should aim towards facilitating natural channel braiding processes.

1.3 Private Land Owner Goals and Constraints

The project spans parcels owned by Seattle City Light (SCL), Skagit County, and a private landowner (Pauline Ryan). All have been consulted at various stages during development of the design. In discussions with the SRSC, the private landowner indicated the following desires and constraints for the project design:

- Restoring salmon habitat
- Not adversely affect timber harvest ability or other potential uses of the property outside of the 100 year floodplain, including protecting plantings
- To minimize damage to standing trees on the property and to use trees that must be taken down as habitat features in the project to the greatest extent possible
- Design work completed by a professional engineer licensed in the State of Washington and all permits secured by SRSC

In general, the private landowner is supportive of the habitat improvements implemented throughout the project reach, and has approved the various elements included in the 90% design drawings.

Skagit County owns the road right of way and is responsible for maintaining the County road and bridge across Illabot Creek, and will also maintain the two new bridges once they are constructed. The County has indicated the following constraints for the project design:

- The potential for debris, aggradation, and flood risk to the Rockport-Cascade Road should not be enhanced over current conditions so that the County will not need to perform increased maintenance.
- The road should meet County road design and safety standards.

In discussions with the SRSC, SCL indicated the following constraints for the project design:

- The portion of the project reach underneath the transmission line right of way cannot involve plantings such as trees that would grow tall enough to threaten the power transmission lines or towers
- The transmission line towers must be protected against channel erosion.
- Construction equipment used in the project must not result in arcing from the high voltage lines to the ground.
- Access to the transmission line right of way and towers must be preserved.

2. DESIGN CONCEPT

Based on the above, the following key observations influenced the selection and design of project elements:

- The overriding goal of the project is to add one or more new bridges to supplement the existing one, thereby allowing Illabot Creek to braid upstream and flow through multiple openings in a manner that is more consistent with an alluvial fan setting.

- Each bridge should be sized to pass 100% of the 100 year flood to allow for channel transition periods or temporary blockages at the other bridge(s).
- Braiding should be facilitated by designing a ‘kick-off’ state that approximates expected final geomorphic planform and cross-section characteristics of a channel with the prevailing slope, bankfull discharge, and grain size distribution of Illabot Creek.
- The streambed should be able to adjust both laterally and vertically in response to erosion-deposition processes; of the two directions, it is most important to not constrain vertical stability of major channels through implementation of hard grade control. Lateral erosion may be controlled in some locations give the presence of the powerline right-of-way.
- Aggradation should be avoided in the vicinity of the road crossings, as it may lead to future flooding problems.
- The potential for debris blocking new bridges should be minimized to avoid flooding impacts.
- Since tree restoration, which would in the long run provide juvenile habitat, is not an option for the subreach under the transmission line right of way, measures should be implemented to create and facilitate processes that maintain spawning habitat for Chinook salmon using means other than relying on future LWD recruitment locally.
- While most of the streambed is composed of coarse gravel and cobble, there appears to be sufficient small gravel being transported through the reach and deposited on bars that could be induced to deposit selectively in response to the addition of roughness and/or reduction in grade locally. Such deposits could be potentially used by Chinook salmon adults for spawning.

After reviewing aerial photographs, the DEM, walking the site, and performing geomorphic analyses (described in next section), the following key elements were identified and brought forward to final design:

- The prevailing geomorphic processes favor establishing two new channels to supplement the existing one. The proposed channels should follow existing floodplain swales that were the location of former channels to mimic natural processes and minimize earthwork.
- Distributing various log structures throughout the reach to provide instream habitat and encourage channel movement, promote substrate sorting, increase backwater effect to increase connectivity with pilot channel braids, trap loose logs during floods to protect new bridges during braided channel evolution, and protect SCL infrastructure; and
- Installing boulder fields to increase roughness locally to either (i) promote formation of spawning riffles, or (ii) increase backwater effect to increase connectivity with pilot channel braids.

Planting native vegetation to increase riparian, floodplain, and older floodplain terrace vegetation diversity and density, and provide a future source of large woody debris to the stream channel was deferred from the design for two reasons:

1. SCL cuts any trees growing under the high voltage powerlines to prevent arcing to the ground, and
2. In the remainder of the project reach, braiding processes tend to be associated with bare ground at unpredictable locations, but at the same time, natural recolonization occurs relatively quickly where it can. The SRSC will develop a planting plan separately from this design.

Collectively, these actions are expected to lead to improved fish habitat and natural flooding and sedimentation processes in this project reach. The next section describes the process and decisions related to selecting, siting, and designing each of the above project elements.

3. DESIGN SUMMARY

Major elements of the design process involved (i) collecting survey data to complement and update a LiDAR topographic base map, which was used in developing the design, for creating a HEC-RAS model of the reach for design analyses and impact assessment, and for estimating earthwork quantities for the engineer’s cost estimate; (ii) analyzing geomorphic characteristics of the project reach and comparing with geomorphic criteria defining braided channels; (iii) developing both an existing conditions and a 3-split channel HEC-RAS model for design; (iv) reviewing the LIDAR DEM and walking the reach to identify the appropriate scale and types of project structures and actions, and identify specific locations for each; (v) evaluating the flood hydrology for the reach in designing channel connectivity, levee excavation elevations, log structure stability and function, and new bridge conveyance and scour assessments; and (vi) designing structures and earthwork. These elements are described in greater detail below.

3.1 Surveying and Adjustment of LiDAR Data

A variety of survey data were collected:

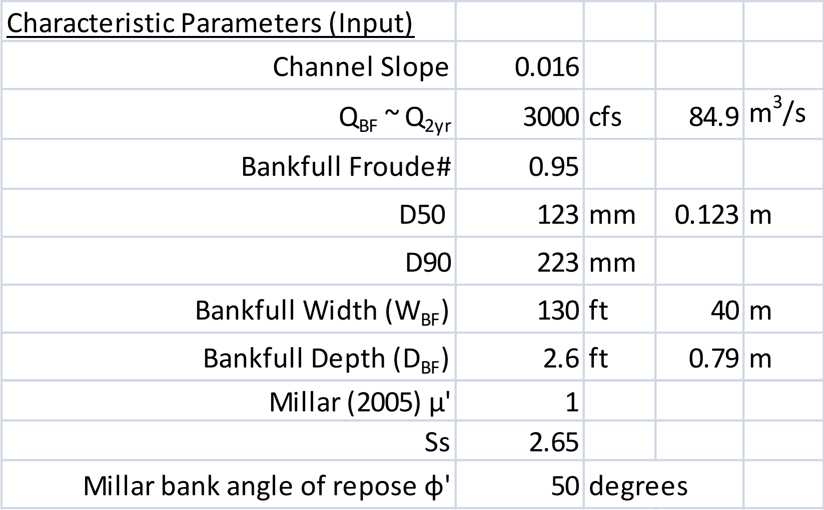
- The SRSC surveyed to local datum:
    - Longitudinal profile of the existing channel and general location of proposed pilot channels;
    - Cross-sections of the existing channel and floodplain for use in HEC-RAS modeling;
    - Significant tree locations for identifying locally available wood material; and
    - Miscellaneous topographic data to define levee morphology, a proposed fill area.

- The SRSC contracted out surveying to Pacific Survey & Engineering (PSE), who established survey controls and collected topographic survey data for use in the bridge design and ground truth data for evaluating the accuracy of a LIDAR DEM developed previously. The map datums were NAD83 State Plane (horizontal) and NAVD88 (vertical).

The PSE data indicated that the LiDAR DEM was biased high and tilting slightly eastwards. The cause of the bias and tilting was determined to be an artifact of not having ground control to the east of the project area. The reason was that the LiDAR survey originally was contracted to occur to the west of the project site, and the SRSC requested the contractor to extend the area eastwards using the ground control established for the original survey. The LiDAR DEM was adjusted -2.7 ft by PSE accordingly based on the ground truth data.

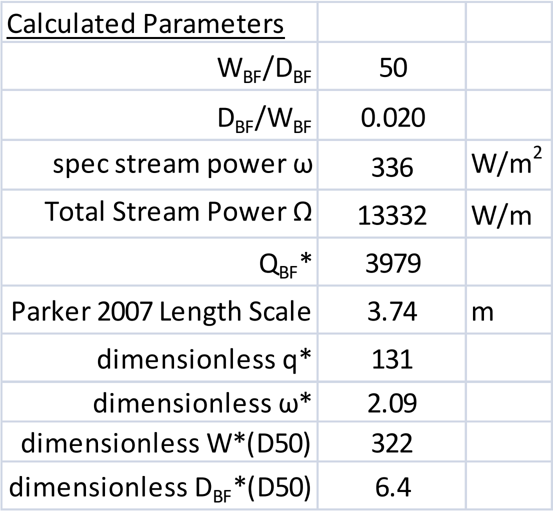
3.2 Geomorphic Assessment and Channel Planform Layout

Channel planform, slope, and cross-section dimensions were designed using published empirical geomorphic criteria for braided streams. Available data defining geomorphic parameters included surveyed reach slope, grain size distribution (pebble counts performed on bars along water's edge at upper end of site), and LiDAR and survey cross-section data. Based on the estimate of bankfull flow (see Section 3.3), hydraulic simulations of the existing channel and from survey and pebble count data, the characteristic parameters for the project reach are estimated to be:



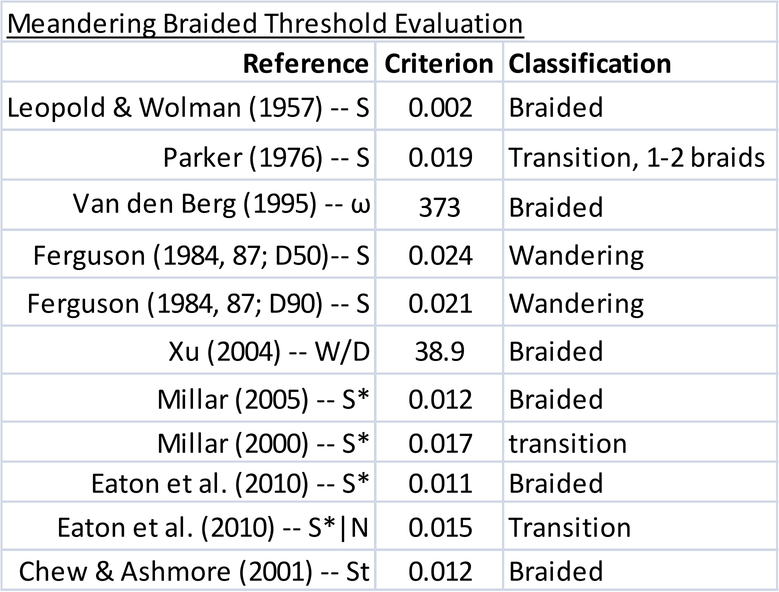
Characteristic Parameters (Input)				
Channel Slope	0.016			
$Q_{BF} \sim Q_{2yr}$	3000	cfs	84.9	m^3/s
Bankfull Froude#	0.95			
D50	123	mm	0.123	m
D90	223	mm		
Bankfull Width (W_{BF})	130	ft	40	m
Bankfull Depth (D_{BF})	2.6	ft	0.79	m
Millar (2005) μ'	1			
Ss	2.65			
Millar bank angle of repose ϕ'	50	degrees		

From these, the following characteristic dimensionless variables were computed for applying geomorphic hydraulic geometry relations for the bankfull/channel forming flow condition:



Calculated Parameters		
W_{BF}/D_{BF}	50	
D_{BF}/W_{BF}	0.020	
spec stream power ω	336	W/m^2
Total Stream Power Ω	13332	W/m
Q_{BF}*	3979	
Parker 2007 Length Scale	3.74	m
dimensionless q*	131	
dimensionless ω*	2.09	
dimensionless W*(D50)	322	
dimensionless D_{BF}*(D50)	6.4	

Based on these values, the nature of the planform tendencies for the reach are predicted to be predominantly braided/wandering channels:



Meandering Braided Threshold Evaluation

Reference	**Criterion**	**Classification**
Leopold & Wolman (1957) -- S	0.002	Braided
Parker (1976) -- S	0.019	Transition, 1-2 braids
Van den Berg (1995) -- ω	373	Braided
Ferguson (1984, 87; D50)-- S	0.024	Wandering
Ferguson (1984, 87; D90) -- S	0.021	Wandering
Xu (2004) -- W/D	38.9	Braided
Millar (2005) -- S*	0.012	Braided
Millar (2000) -- S*	0.017	transition
Eaton et al. (2010) -- S*	0.011	Braided
Eaton et al. (2010) -- S*|N	0.015	Transition
Chew & Ashmore (2001) -- St	0.012	Braided

The following characteristic dimensions for the new channels were then predicted to be within the following ranges:

Channel Design Dimensions			
Reference	**Parameter**	**Value**	
Bertoldi et al. (2009)	Wet Braid Width|Q_{bf}	36	m
Bertoldi et al. (2009)	Active Braid Width|Q_{bf}	13	m
Millar (2005)	W/D|Q_{bf}	63	
Millar (2005)	W|Q_{bf}	42	m
Ashmore (2001)	W|Q_{bf}	50	m
Millar (2005)	D|Q_{bf}	0.70	m
Parkler & Ashmore (1983)	Max Scour Depth @ Confluence	4.8	m
Ashmore (2009)	Bar Wavelength (lo)	198	m
Ashmore (2009)	Bar Wavelength (hi)	475	m
Hundey & Ashmore (2009)	Confluence-Bifurcation L (lo)	143	m
Hundey & Ashmore (2009)	Confluence-Bifurcation L (hi)	179	m
Eaton et al. (2010)	N Stable/Active Channels	1	
Egozi & Ashmore (2009)	N Total Channels	2	
Ashworth (2001)	Braid Wavelength λ	323	m

From these results, and following review of channel traces in Smith and Ramsden (2006), we expect Illabot Creek to form between 2-3 channels at a point in time, with 1-2 of those channels classified as actively transporting significant bedload. This, along with bridge alternative analyses, led to selecting two new bridges and designing two pilot channel braids accordingly. The selected alternative was considered to require the least amount of intervention in ensuring natural fluvial processes would occur.

Channel locations were identified by tracing floodplain swales using the LiDAR. Two independent pilot channels, called A and B, were located west of the existing channel, and joined downstream under the powerlines to form a combined Channel C. The inlet of Channel A is upstream of the inlet of Channel B, and thus Channel A is longer than Channel B. A concave profile was developed for the new channel complex, with breakpoints designed to occur well upstream and downstream of the bridges, so that local aggradation problems would be minimized. The most downstream channel (C) was forced to have a 1 percent slope under the powerlines to facilitate formation of spawning habitat (revegetation with trees under the lines is not an option). The lower section of Channel A was set to be similar in magnitude to the reach slope, which necessitated making the slope of the upper section of Channel A steeper (see CAD design sheet 5 for channel designations). The slope of Channel B was fixed by the elevation at the junctions with the main channel and the confluence with Channels A and C. After several iterations based on achieving a maximum target invert elevation under the bridges = 309 ft NAVD88, the optimal profiles were designed (Figure 4).

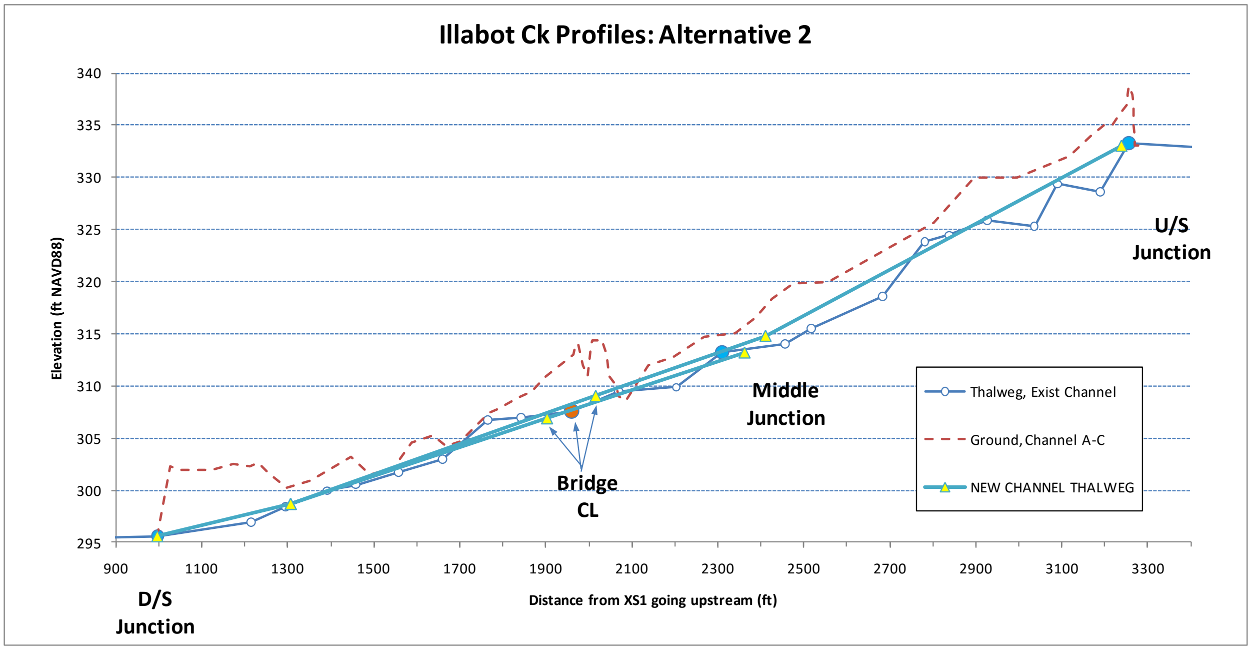
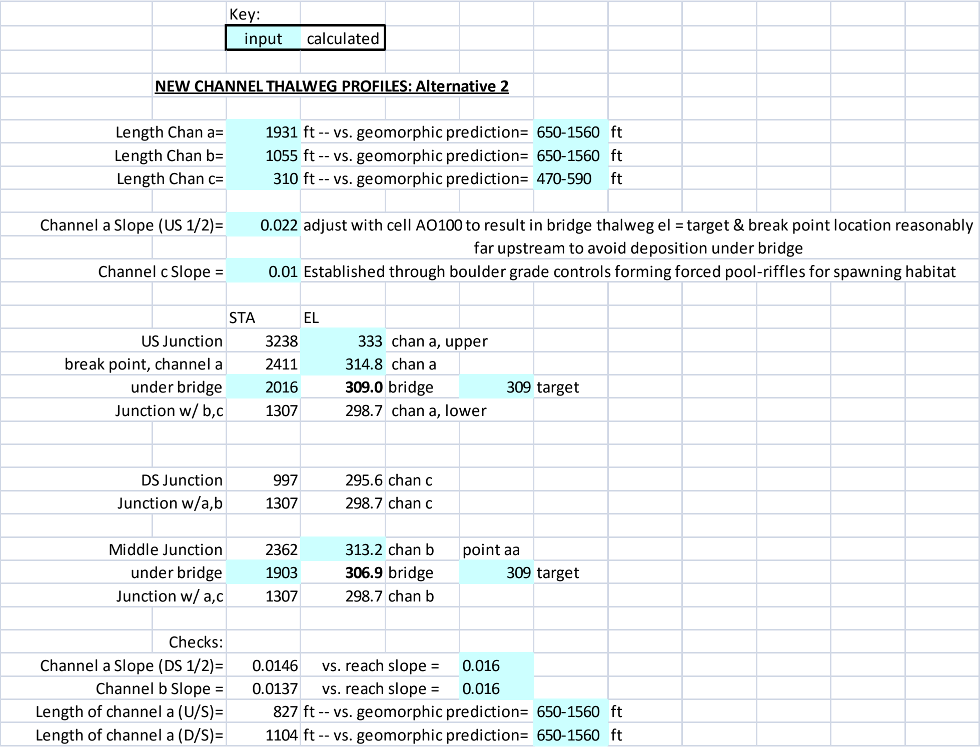


Figure 4. Longitudinal profiles of existing and proposed pilot channels. Channel B inlet is located at the 'Middle Junction'; Channel A inlet is at the 'U/S/ Junction'. The junction of Channels A and B to form Channel C is located at about station 1300 in the graph. The pilot channel slopes approximate the existing channel slope.

The slopes and invert elevations of the new channels generally follow the existing channel, which appears to have reached a graded, concave profile. The slopes and dimensions of the selected channel configuration were also generally consistent with geomorphic criteria:



	Key:					
	input	calculated				
NEW CHANNEL THALWEG PROFILES: Alternative 2						
Length Chan a=	1931	ft -- vs. geomorphic prediction=			650-1560	ft
Length Chan b=	1055	ft -- vs. geomorphic prediction=			650-1560	ft
Length Chan c=	310	ft -- vs. geomorphic prediction=			470-590	ft
Channel a Slope (US 1/2)=	0.022	adjust with cell AO100 to result in bridge thalweg el = target & break point location reasonably far upstream to avoid deposition under bridge				
Channel c Slope =	0.01	Established through boulder grade controls forming forced pool-riffles for spawning habitat				
	STA	EL				
US Junction	3238	333	chan a, upper			
break point, channel a	2411	314.8	chan a			
under bridge	2016	**309.0**	bridge	309	target	
Junction w/ b,c	1307	298.7	chan a, lower			
DS Junction	997	295.6	chan c			
Junction w/a,b	1307	298.7	chan c			
Middle Junction	2362	313.2	chan b	point aa		
under bridge	1903	**306.9**	bridge	309	target	
Junction w/ a,c	1307	298.7	chan b			
Checks:						
Channel a Slope (DS 1/2)=	0.0146	vs. reach slope =		0.016		
Channel b Slope =	0.0137	vs. reach slope =		0.016		
Length of channel a (U/S)=	827	ft -- vs. geomorphic prediction=			650-1560	ft
Length of channel a (D/S)=	1104	ft -- vs. geomorphic prediction=			650-1560	ft

It was decided during design reviews and considering construction costs to construct the channel braids as smaller pilot channels with pre-set floodplain widths meeting geomorphic criteria, and let them adjust their bankfull width and depth naturally, starting with values that are consistent with the empirically predicted parameters. Given the longitudinal profiles depicted above and the general depositional braided setting, it is unlikely that the pilot channels will incise significantly and that most adjustments will occur to bankfull width as the channels evolve. Indeed, given the setting it is more likely the channels will tend to aggrade over the long term. The following design dimensions were estimated accordingly for constructing the pilot channels:

Channel Dimensions For Pilot Channels by Alternative							
	Channel			Active			
Alternative	Segment ID	Type	Slope	W_{BF} (ft)	D_{BF} (ft)	W_b (ft)	W_{FP} (ft)
2	a (U/S)	Braid	0.022	29	1.7	26	103
	a (D/S)	Braid	0.0146	19	2.2	15	81
	b	Braid	0.0137	18	2.3	14	78
	c	Joined	0.01	26	3.7	20	105

Based on empirical relationships, the following dimensions are estimated to represent the evolved (i.e., dynamic equilibrium) state of the new channels after adjustment:

Channel Dimensions For Bankfull Flow-Ready Channels by Alternative

Alternative	Channel Segment ID	Type	Slope	W_{BF} (ft)	D_{BF} (ft)	W_b (ft)	W_{FP} (ft)
2	a (U/S)	Braid	0.022	67	1.7	63	103
	a (D/S)	Braid	0.0146	54	2.2	50	81
	b	Braid	0.0137	52	2.3	48	78
	c	Joined	0.01	55	3.7	49	105

3.3 HEC-RAS Model

An existing conditions HEC-RAS model was developed first to assess bankfull flow geometry and evaluate worst case design conditions if all flow goes through one channel and bridge opening. HEC-RAS cross-section data were created by N. Kammer (SRSC) under direction of P. DeVries (R2) using SRSC survey data and LiDAR data adjusted by Pacific Surveying & Engineering based on recent ground-truthing surveying work. Manning's n was selected to be 0.045 for the channel and 0.1 for the floodplain based on comparison with data in Barnes (1967) and Hicks and Mason (1998). The hydrology in Table 1 was run through the model, and cross-section plots reviewed to evaluate bankfull geometry (Figure 5). This correspondence served as corroboration that the hydrology estimates in section 1.2 were also generally representative. The model was also run to evaluate approximate maximum velocities that might be expected and needed for design of structure stability.

A split channel HEC-RAS model was then developed for the selected alternative. The model configuration is depicted in Figure 6. Two geometries were analyzed: (1) with the pilot channel dimensions, and (2) with estimated evolved channel morphology, assuming that most adjustment of the pilot channel occurs through widening rather than deepening. The model was also provided to GeoEngineers (sub to TranTech) for use in scour depth estimation at the bridge locations. Flow split percentages were determined for the 100 year flood via the optimization feature in HEC-RAS, for both geometries. The adjusted ('established') channel geometry was used for design, with depths and velocities at the 100 year flood estimated for structure design. Hydraulic predictions are summarized in Figure 7.

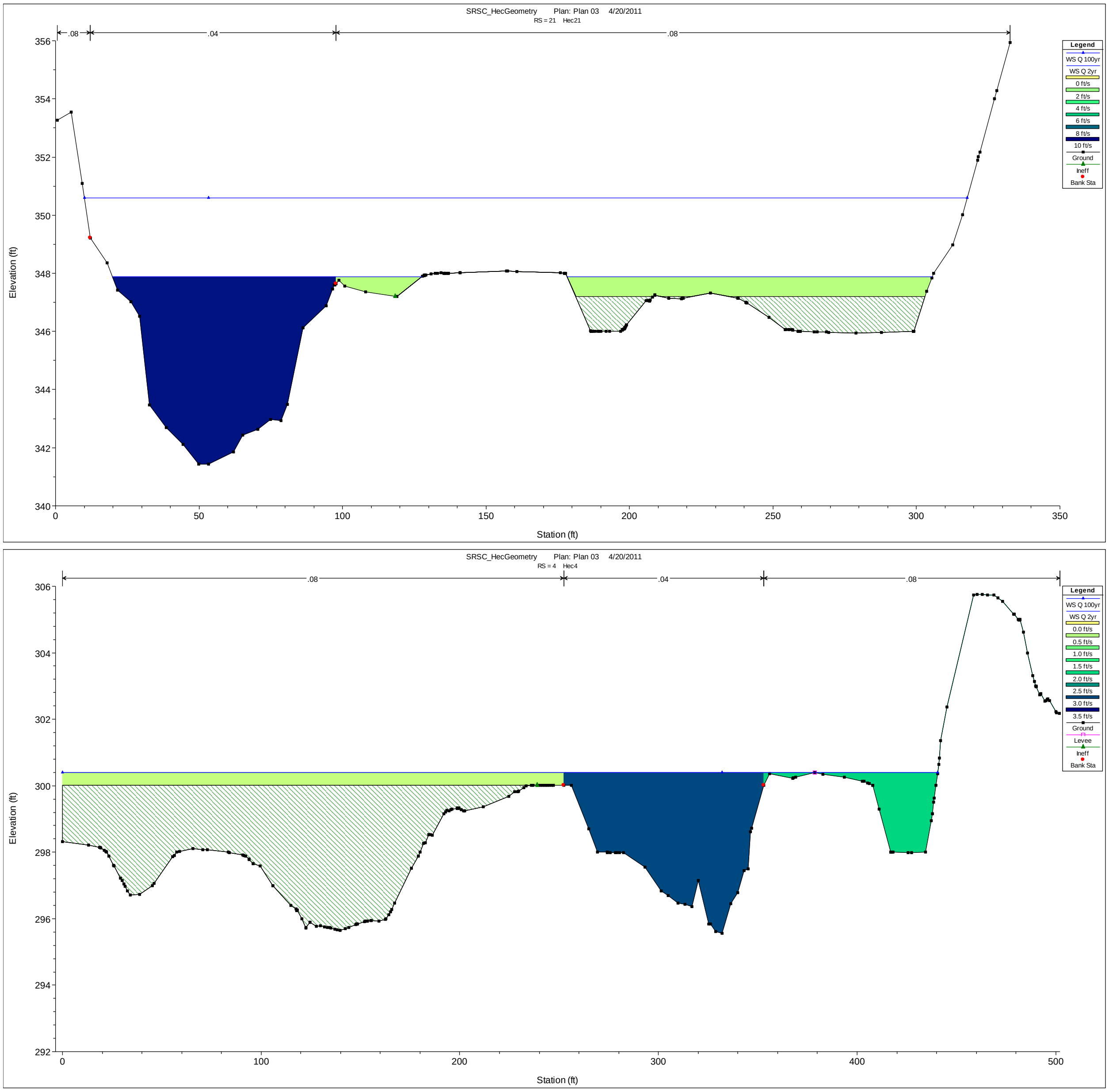


Figure 5. Bankfull flow simulation at cross-sections with a reasonably natural appearing bankfull cross-section morphology, located near the upstream and downstream ends of the project reach where the channel has more freedom to migrate laterally. The 2-year flood approximates the top elevation of bar form surfaces at each location, and appears to be a conservative estimate of the bankfull flow magnitude.

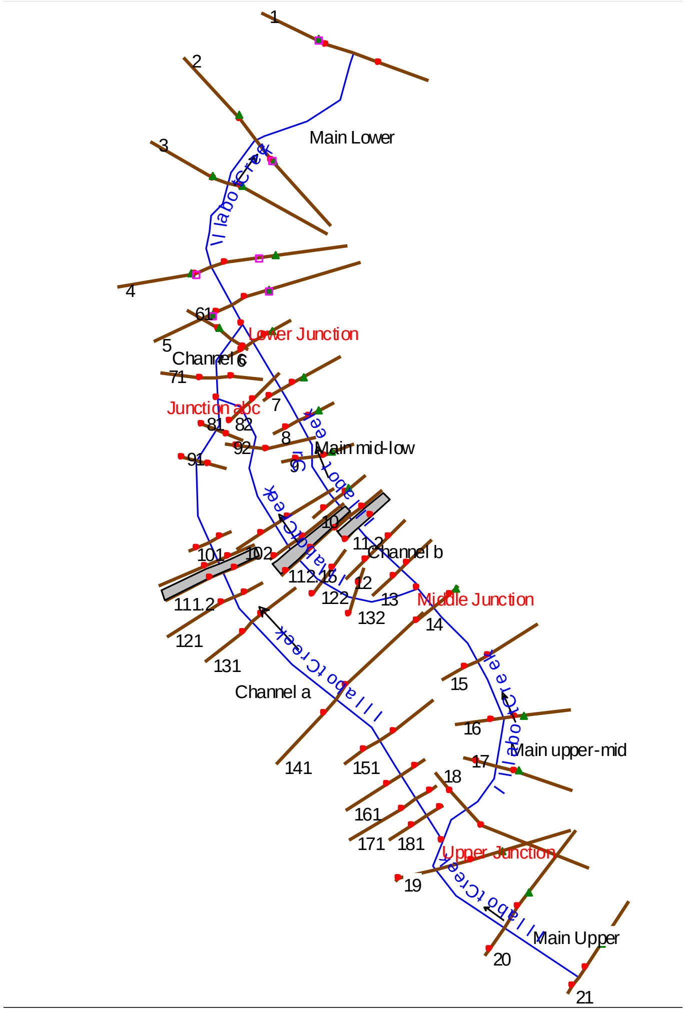


Figure 6. Split channel HEC-RAS model cross-section layout used in developing the design.

Reach	River Sta	Q Total	Min Ch El	W.S. Elev	Crit W.S.	E.G. Elev	E.G. Slope	Vel Chnl	Froude # Chl	Shear Chan
		(cfs)	(ft)	(ft)	(ft)	(ft)	(ft/ft)	(ft/s)		(lb/sq ft)
Main Upper	21	9710	341.44	351.31	350.46	352.54	0.010653	11.03	0.68	5.23
Main Upper	20	9710	337.94	345.7	345.7	348.24	0.025823	12.78	0.99	8.14
Main Upper	19	9710	332	338.35	338.35	340.4	0.019071	11.49	1	4.76
Main upper-r	18	4800	329.1	334.1	334.1	335.7	0.020285	10.17	1	4.03
Main upper-r	17	4800	325.51	332.6		333.46	0.006174	7.43	0.59	1.87
Main upper-r	16	4800	322.6	329.69	329.69	331.9	0.015195	12.05	0.93	4.83
Main upper-r	15	4800	316.31	323.67	323.67	326.06	0.018804	12.41	1	5.33
Main upper-r	14	4800	311.9	319.03	319.03	321.16	0.019308	11.7	1.01	4.91
Channel a	181	4910	328.37	333.69	333.69	335.69	0.02012	11.35	1.01	4.74
Channel a	171	4910	326.88	332.34	332.34	334.18	0.017886	10.92	0.96	4.34
Channel a	161	4910	324.79	330.12	330.12	332.11	0.020075	11.34	1.01	4.73
Channel a	151	4910	321.75	327.07	327.07	328.82	0.018292	10.83	0.96	4.31
Channel a	141	4910	317.2	322.72	322.72	323.93	0.013118	9.43	0.82	3.23
Channel a	131	4910	310.75	317.46	316.98	318.83	0.012414	10.04	0.81	3.5
Channel a	121	4910	309.14	316.27	315.78	317.61	0.010092	9.74	0.75	3.17
Channel a	111.2	4910	307.81	315.92	314.59	316.8	0.005589	7.99	0.57	2.03
Channel a	111.15	Bridge								
Channel a	111.1	4910	307.13	314.1	313.91	315.75	0.012733	10.53	0.83	3.78
Channel a	101	4910	306.11	312.72	312.67	314.72	0.016585	11.52	0.94	4.62
Channel a	91	4910	301.89	308.83	308.54	310.46	0.012793	10.52	0.83	3.78
Channel a	81	4910	300.04	308.42		309.27	0.005052	7.75	0.54	1.89
Channel b	132	2800	309.42	315.06		316.34	0.014496	9.07	0.84	3.12
Channel b	122	2800	307.97	313.63		314.9	0.014357	9.04	0.83	3.1
Channel b	112.2	2800	306.69	312.58	311.9	313.7	0.011759	8.49	0.76	2.68
Channel b	112.15	Bridge								
Channel b	112.1	2800	306.06	311.63	311.27	312.96	0.015473	9.26	0.86	3.27
Channel b	102	2800	305.03	310.37	310.37	311.8	0.018039	9.69	0.93	3.64
Channel b	92	2800	301.65	308.66		309.26	0.004509	6.35	0.5	1.36
Channel b	82	2800	300.01	308.63		308.89	0.001498	4.36	0.3	0.59
Channel c	71	7710	297.81	307.8		308.43	0.003846	7.3	0.48	1.62
Channel c	61	7710	296.28	307.06		307.81	0.003647	7.52	0.48	1.67
Main mid-lov	13	2000	309.77	315.44		316.39	0.008861	7.83	0.67	2.21
Main mid-lov	12	2000	309.5	313.93	313.86	315.07	0.020453	8.55	0.96	3.11
Main mid-lov	11.2	2000	307.58	313.43	311.75	314.06	0.005507	6.37	0.53	1.44
Main mid-lov	11.15	Bridge								
Main mid-lov	11.1	2000	306.89	311.68		312.75	0.012516	8.3	0.77	2.63
Main mid-lov	10	2000	305.97	311.03		311.85	0.010089	7.29	0.71	2.05
Main mid-lov	9	2000	303.56	308.24	308.17	309.54	0.020504	9.16	0.97	3.45
Main mid-lov	8	2000	301.48	307.84		308.31	0.004167	5.5	0.47	1.08
Main mid-lov	7	2000	301.48	306.97		307.66	0.00768	6.65	0.62	1.67
Main mid-lov	6	2000	296.2	307.29		307.36	0.000219	2.13	0.12	0.12
Main Lower	5	9710	296.2	304	304	306.68	0.015183	13.76	0.96	5.89
Main Lower	4	9710	295.55	302.67	302.67	304.2	0.0154	12.1	0.94	4.88
Main Lower	3	9710	289.9	299.02		299.9	0.005176	9.14	0.58	2.44
Main Lower	2	9710	291.83	297.38	297.38	298.59	0.012558	10.01	0.83	3.49
Main Lower	1	9710	285.97	291.32	290.73	292.32	0.01	9.05	0.75	2.83

Figure 7. HEC-RAS model output for the split channel, assuming the channel has had a chance to evolve and establish an equilibrium cross-section (see section 3.2).

3.4 Design of Log Structures

Five types of log structures were conceived and designed that emulate fish habitat formation processes:

1. Exposed roughness element and debris trapping flood fencing in the main channel in the vicinity of the inlet to Channel A to increase local roughness and facilitate flow split into the new channel;
2. Buried flood fencing at key locations in the new channel to guide the channels away from the bridges and western SCL powerline towers;
3. Exposed debris trapping flood fencing in the main channel in front of where the new channels return to the main channel, to protect the eastern SCL powerline towers;
4. A log crib jam along the left bank of where Channel A flows under the powerlines to protect the left bank and provide instream habitat structure; and
5. Small log jams countersunk in the new channels, with rootwads at the edge of the pilot channel to provide local habitat diversity as the channels adjust.

Design details are given below.

3.4.1 Small Modular Engineered Log Jams (ELJs)

A small sized ELJ appears to scale well with the size of Illabot Creek. A modular structure is proposed that is relatively cost effective to construct and works well under a dynamic flood environment. The structure is constructed as an array of four crisscrossed horizontal logs with rootwads protruding out into the channel, and the array is held in place by six vertical anchor logs with buried rootwads and hemp rope lashing (Figure 8). Several structures are located throughout the pilot channels to provide pool habitat at bends, and promote channel splitting in straighter sections.

A small number of horizontal logs was specified to be laid out at the surface of the riverbed to reduce construction cost and conserve logs. Two logs are aligned streamwise; the remaining two logs are oriented perpendicular to the channel. The vertical boles anchor the horizontal logs and block lateral movement. The horizontal logs are free to float with rising water levels, although drag and friction against the vertical logs, in combination with ballast gravel and cobble spoils from the pilot channel excavation placed on top of each structure, will generally act to counter buoyancy forces. The vertical logs serve another function where they can rack up large logs during high water, thereby helping reduce the potential for adverse impacts to private property and infrastructure downstream while the pilot channels evolve.

The jams are designed to be stable in anticipation of future channel changes, and are intended to last roughly 10 years, at which time if the river erodes in such a way that it washes out the logs, the structure will fail safely without being carried downstream as a single large mass of inter-tied logs. Using vertical boles for stability precludes the need for cable or chain, which have been known to presents hazards to infrastructure and public safety downstream when a log structure fails. In addition, tying together the four horizontal logs with hemp rope provides additional resistance to movement by individual logs. In the event of failure, the hemp rope should break under stress in the event the structure stays as one as it is entrained downriver and wraps itself around a bridge pier. The hemp rope is thicker than needed initially, to allow for decay and continued strength until vegetation takes hold within the ballast material on top of the jam; the ballast material also covers the hemp rope to retard decay by insects and photo-degradation. Friction (associated with the wrap around the vertical boles) and tension forces in the rope (for point of breakage) were analyzed in previous designs for larger structures, and determined to be adequate; this was later borne out by persistence after severe flooding in other applications. By extension, the specified rope diameter (1.5”) will be sufficient for this application.

Figure 8. Example of small modular ELJ proposed for Illabot Creek, two years after construction.

The structures were designed for stability in the near term, where vertical boles provide lateral (drag forces) and pull-out (buoyancy forces) support to the structure, and the crisscrossed horizontal logs interlock with the vertical boles. Drag and scour were evaluated conservatively by assuming a debris buildup with a projected obstruction dimension of 6 ft high by 15 ft long. A drag coefficient C_D=2.0 was used to represent a massive obstruction (Alonso 2004).

Scour depth was estimated using the HEC-18 method (Richardson and Davis 2001) to be approximately 9 ft at 7.5 ft water depth and 12 ft/s (~peak depth and velocity predicted in the vicinity of the structures by HEC-RAS during the 100 year flood). This is probably an over-estimate for the size of channel and substrate (it is more likely that the scour depth will scale with the effective obstruction height, or around 6-7 ft with some debris racked up). The vertical boles were designed to be installed complete with rootwads to provide anchoring while reducing the excavation depth required to counter the combined potential for scour and pull-out by buoyancy and drag (logs without rootwads would need to be installed deeper to achieve the same resistance to pull-out). The combined force resisting pullout was taken as the submerged weight of the substrate plus the internal friction force resisting shearing of the substrate upwards. The number of vertical boles was balanced with the excavation depth, where more boles with rootwads result in requiring less excavation depth for anchoring vs. resulting in a more massive structure with potentially greater scour depth and more complicated construction with more materials. It was determined that 6 vertical boles with rootwads would require a minimum ~3 ft thick layer of gravel on top to resist pull-out. Thus the top of the rootwads are designed to be installed at least 10 ft below the pilot channel invert, which as discussed earlier, is not expected to degrade.

3.4.2 Crib Structure

An anchored low profile crib structure was designed to protect a bend in Channel A underneath the powerlines, and prevent the channel from migrating towards the powerline towers. The structure is also intended to provide lateral scour pool habitat as the pilot channel evolves. The height of the structure was designed to extend below the pilot channel invert in anticipation of future bend scour, and above the bankfull terrace elevation to protect the upper slope from overbank flows. Horizontal cross-logs oriented upstream-downstream provide a support base for the logs with rootwads sticking out from the bank and protect against toe erosion.

The log was designed to be held in place by a combination of native soil-gravel-boulder ballast, vertical boles, and earth anchors. The ballast and earth anchors counter buoyancy pull-out forces. The vertical boles and embedding into the bank counter lateral movement caused by drag forces during high flows, following method of Broms (1964; in Murthy 2003) to evaluate lateral resistance of partially embedded logs to movement in the streamwise direction. In addition, the logs are tied together with hemp rope for similar reasoning as the ELJ structures. The structures are intended to last roughly 10-20 years while scrub-shrub revegetation occurs and roots take hold, after which it can either remain in place or rot and break up in individual pieces during flooding. In addition, a buried flood fence is placed behind the structure to prevent an end-run.

3.4.3 Flood Fencing

Flood fences are arrays of vertical boles that come in two basic forms, one with taller, wider spaced arrays of vertical logs or boles to trap debris, and the second with shorter, more closely spaced boles to increase local roughness and facilitate deposition of smaller sediment particles. The arrays can be pre-charged with slash and smaller logs to resemble a more natural appearing accumulation from the onset.

The shorter, denser roughness function arrays are proposed for siting in Illabot Creek only on an expansive gravel and cobble bar located near the upstream Channel A split to promote deposition and create backwater, which will accelerate pilot channel connectivity.

The taller, more widely spaced debris-catching arrays are proposed for selected locations in Illabot Creek to trap loose wood with specific purpose depending on location:

1. One array is sited near the upstream Channel A split to work with roughness arrays in promoting deposition and creating backwater, which will accelerate pilot channel connectivity.
2. Several arrays are sited on a low gravel bar in front of the levee along the right bank downstream of the existing bridge to protect the SCL towers from erosion and encourage planform change from a straight to a more sinuous channel, and accelerate connectivity with the downstream end of Channel C.
3. Several arrays are sited along the pilot channels in anticipation of future channel growth, and are intended to serve a variety of functions. Arrays are placed upstream of the new bridges to trap large logs before they pass underneath while the channel cross-section and long profile evolves. Arrays are placed at other locations below the bridges to initiate channel complexity and development of log jams.

The height of the taller arrays are designed to be around the 100-year flood elevation so that the array would trap wood debris at all overbank flows, thereby forming a hard point to direct water flowing over the floodplain toward channel splits, or causing deposition downstream of the array to promote bar growth.

The design procedure involved selecting a bole spacing and height of installation that minimizes local scour potential while also increasing local roughness. The design process is iterative, reflecting a balance between maximizing flow obstruction, minimizing local scour depth, and resisting buoyancy pullout, breakage, and ploughing. There is no single ideal combination of bole diameter, installation depth, height above the bed, and spacing, thus the design process starts with a template specification and converges on a reasonable set of specifications.

We use an in-house spreadsheet that allows rapid assessment of alternative designs and development of the selected specifications. Douglas fir and western red cedar were specified based on their strength, durability, and being available both onsite and from USFS sources. Diameter was specified based on review of maximum bending moment calculations and material strength properties. The height of installation was specified to resist breakage at full submersion when impacted by a 20 ft long, 2 ft diameter log floating at the maximum channel velocity predicted by the HEC-RAS model. General experience has been that if a larger log impacts, it typically impacts more than one bole. Depth of installation was the sum of design scour depth around bole and minimum depth to prevent buoyancy pull-out. Ploughing was evaluated using piling design principles, but was neglected because the phenomenon has not been observed to occur frequently, and when it has, has not resulted in a significant loss of boles. Scour depth was estimated using, alternatively, standard single pier and bridge piling scour equations from HEC-18 (Richardson and Davis 2001) and from experimental studies of Dey et al. (2008). Pull-out depths were determined by considering substrate-wood friction coefficient, and assuming the upper 5 times diameter depth does not provide substantive resistance, following general piling design guidelines (e.g., Peck et al. 1974; FEMA Prestandard 356). Roughness was estimated using roughness relations for vertical cylinders (Stone and Shen 2002).

3.5 Design of Boulder Fields

Boulders provide suitable instream cover habitat for streams with gradients between about 1-3%, and are best placed in the central portion of the channel in runs and the lower half of riffles (Ward and Slaney 1979; Mooney et al. 2007). Indeed, stable boulders and larger riprap from bridge construction can be found at other locations in the project reach, and thus offer a natural analog. Boulders also can provide a form of grade control where needed. Two types of boulder structures were accordingly designed for installation in the lower reaches of the pilot channels and in the main channel near the existing bridge:

1. Boulder fields that provide roughness to (i) promote formation of gravel and cobble spawning deposits upstream for Chinook salmon under the powerline, and (ii) raise the water level upstream in the current Illabot Creek channel during flooding to increase connectivity with the inlet to Channel B. By providing open streambed lanes between individual boulders, the fields perform as adjustable grade controls that retard incision

(e.g., desired under the powerline corridor in the unlikely event it occurs) and do not create an upstream fish passage barrier. The grade controls can adjust with the riverbed and thus have the advantage over boulder weirs by not requiring a fixed bed profile. In addition, the boulder fields allow fish passage by not creating plunging flow – fish can swim freely upstream and downstream between boulders. The spacing of the grade controls followed criteria in USBOR (2007), and resulted in desired spacing between about 100-230 ft, with specific locations selected to be away from bends and confluences where scour processes are magnified.

2. A continuous boulder weir controlling flow into a former channel located near the junction of Channels A, B, and C to avoid further affecting private property downstream in the near term. Combined with flood fencing, the aim is to prevent the channel from migrating into the left bank floodplain downstream in the near term until the system has readjusted to its braided state. At that point in time, it would be a simple matter to cut through the grade control should future restoration management goals indicate that to be desirable. The same rock sizing as the boulder field is specified.

Design criteria for streamwise spacing in the boulder fields vary, but in general the idea is to space boulders so that their downstream wake zones do not overlap to maximize feeding lane availability for juvenile salmonids and so scouring is not enhanced. Additional spacing criteria for boulder placements in Saldi-Caromile et al. (2004) indicate the submerged area of boulders should not exceed 20% of total flow area during channel forming flows. Mooney et al (2007) present criteria that suggest a minimum spacing of 3 ft between boulders.

Stability was designed and checked in two ways. The first involved a drag force analysis of mobility during extreme flood events. Key design criteria included projected blocking area of boulder, approach velocity which was analyzed for the highest velocity predicted by the HEC-RAS model for the 100-year flood, and the drag and lift coefficients for the boulder which were set respectively as $C_D= 0.2$ and $C_L= 0.85C_D$ following D’Aoust and Millar (2000). Boulder-bed friction angle was set equal to 42° corresponding to general design criteria for a single boulder on a riverbed (D’Aoust and Millar 2000; Fischenisch and Seal 2000). Larger friction angles do not appear warranted from a design safety factor perspective. Also, while during a flood the boulder is sitting in an active, live bed scour hole, the sum of the angle of the downstream face of the scour hole (26°; reflects general pier scour top width criterion of twice the scour hole depth; Richardson and Davis 2001) and the effective friction angle to begin movement within the scour hole (unknown and unspecified in the literature) is unlikely to be substantially different from the design criterion. Further support comes from the empirical results of D’Aoust and Millar’s (2000) review of projects that effectively support the design criterion.

As a backup analysis, design charts presented in USACE (1994) for stone size in turbulent stilling basins indicate that the selected size (3 man boulders, WSDOT specification 9-03.11(3)) can withstand velocities up to about 15 ft/s. The highest velocity predicted by the single channel HEC-RAS model at the 100 year flood is less than 15 ft/s in more confined channel sections. It is likely that with the two additional channels, velocities will be lower, so the designed boulder size is conservative.

To reduce flood conveyance blockage and enhance stability, the boulders are designed to be installed by working them partially into the streambed using the excavator thumb and bucket.

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