

Assessment, Design, and Some Lessons Learned From Application of Natural Channel Design Principles in Conversion of a Multiple Thread to Single Thread Channel on an Alluvial Fan

Christopher H. Roach P.E.¹, MacNamara C. Shoulders², and Robert F. Carlson Ph.D.³

Abstract

McCallum Creek crosses the Trans Alaska Pipeline in the Central Alaska Range near Paxson, Alaska. It was converted from a braided channel on an alluvial fan to a stable single thread channel at the pipeline crossing. Objectives included controlling the position of the channel at the pipeline crossing and minimizing aufeis accumulations through the converted reach. A natural channel design methodology was used, which involves determining the dimension, pattern, and profile of a stable reference reach for the associated valley type and stream type and emulating those characteristics in the design reach. A failure mode analysis was conducted. Mitigative measures were incorporated into the design for each potential failure mode. The channel was lowered to reduce surface energy loss and associated winter aufeis accumulations. The site has been subjected to at least one bankfull flow event since construction was completed in May 2000. Performance has been good during the 2000 and 2001 summer seasons. Aufeis accumulations have not recurred since the channel conversion. Lessons learned are presented from this and several similar projects constructed along TAPS in 2000 and 2001.

Introduction

This paper describes the assessment, design, and some lessons learned from converting a braided channel on an alluvial fan to a stable single thread channel. The work was a unique application of natural channel design, which has found increasing favor in recent years for stream restoration.

Natural channel design (NCD) involves determining the dimension, pattern, and profile of a stable reference reach for the associated stream type, valley type and hydro-physiographic region and emulating those characteristics in the design reach. *Stability* has been defined as the ability of a stream, over time, to transport the flows and sediments of the watershed while neither aggrading nor degrading and while maintaining a consistent dimension, pattern, and profile (Rosgen, 1996). The active channel is designed for the bankfull discharge while flood flows are accommodated in the floodplain. Sediment transport calculations are performed to verify that the hydraulic conditions of the design channel are adequate to maintain sediment throughput.

Channel controls include a combination of structures and re-vegetation for bank protection and grade control. Bank protection is provided by vane structures that can be constructed from rocks, logs, or a combination thereof. Grade control structures typically include cross-vane weirs for small to moderate size streams and w-weirs for

1 Senior Civil Engineer, M. ASCE, Alyeska Pipeline Service Company, Fairbanks, Alaska 99706

2 Environmental Coordinator, Alyeska Pipeline Service Company, Fairbanks, Alaska 99706

3 Professor, Department of Civil and Environmental Engineering, University of Alaska, Fairbanks, Fairbanks, Alaska 99775

larger channel widths. Vanes project upstream, are angled at 20 to 30 degrees away from the bank, slope down at 2% to 7% from the bankfull stage to the invert at the bed, and typically project out into the channel up to one-third the bankfull width, Figure 1. Vane structures, including cross vane weirs and w-weirs, provide bank protection by altering the hydraulic characteristics of the flow near the banks. Velocity head is reduced while elevation head is increased, resulting in a reduction of velocity, shear stress, and stream power adjacent to the bank and a re-direction of near-bank flows out toward the center of the channel. The characteristics, history, design, and placement of these structures are discussed by Johnson *et al.* (2001) and Rosgen (2001). Re-vegetation of the banks and floodplain decreases the time necessary for re-colonization by riparian plant species, minimizing bank erosion and floodplain degradation should a flood occur shortly following construction.

The Rosgen stream classification system was used in the data collection and assessment process (Rosgen, 1996). This system classifies morphologically similar streams into eight major *stream types*. Each of the eight stream types is further divided by up to six sub-categories depending on the 50th percentile bed pavement size, from bedrock to silt/clay. An alphanumeric designation is used to describe each resulting stream type. Distinguishing morphological criterion includes *entrenchment ratio*, *width to depth ratio*, *sinuosity*, *slope*, and channel bed *pavement size* (D_{50}). The classification system is based on the assumption that valley characteristics will directly influence the resulting stream morphology. *Valley types* are distinguished by down-valley gradient in percent slope and a qualitative description of vertical containment (entrenchment), side slope, and predominant morphological character.

Site Assessment

McCallum Creek flows westward across the Richardson Highway and Trans Alaska Pipeline (TAPS) about 30 km (18 mi) north of Paxson in the Central Alaska Range. The Richardson Highway Bridge is approximately 220 m (725 ft) upstream from the pipeline crossing. McCallum Creek joins Phelan Creek about 0.8 km (0.5 mi) downstream from the pipeline crossing. The reach between the Highway Bridge and Phelan Creek crosses a broad alluvial fan with a down valley gradient of approximately 1.5 percent. This reach has historically been a braided channel relatively free of riparian vegetation, Figure 2.

Upstream from the Richardson Highway Bridge, McCallum Creek flows through a relatively narrow valley with moderately sloping sides and valley floor gradients of about 3 percent for the first several kilometers. Further upstream, the valley width reduces and the gradient increases to about 8 percent as the stream approaches its headwaters. An access road runs up the McCallum Creek valley, crossing the creek by a single lane bridge about 2.4 km (1.5 mi) upstream from the Richardson Highway.

Phelan Creek valley in the vicinity of McCallum Creek has a broad valley floor with moderately sloping sides and extensive glacial outwash deposits. The down valley gradient ranges between 0.6 percent and 1.9 percent, with an average of about 1.2 percent. The predominant channel characteristic is a wide braided pattern with minimal vegetative influence and the active channel limits corresponding to the floodplain boundaries. Two reaches of Phelan Creek have a stable single channel

morphology: one through the Highway Bridge at Richardson Highway Mile Post (RHMP) 201.4 where the stream flows through glacial terrace deposits, and another adjacent to an alluvial terrace deposit near RHMP 206, Figure 3.

Extensive annual afeis accumulations have recurred in the Phelan Creek valley, including McCallum Creek in the vicinity of the pipeline and Highway Bridge where it flows across the alluvial fan. Afeis accumulations appear to be related to channel morphology in this region. Throughout the braided channels, afeis accumulations are extensive and re-occur annually. Afeis has been non-existent at both the stable single channel reaches of Phelan Creek.

Phelan Creek provides year round habitat for several species of resident fish including Burbot, Sculpin, Dolly Varden and Round Whitefish. McCallum Creek provides seasonal habitat for grayling and round whitefish. Grayling spawn from May through June, and round whitefish spawn in the fall. Both species utilize the clear water tributaries of larger systems for spawning habitat. The fry usually remain close to the spawning area during their first summer. The juveniles and sub-adults prefer backwaters and sloughs for summer feeding. After spawning, the adults migrate to summer feeding areas and generally take up residence in pool habitats. Grayling and whitefish feed almost exclusively on aquatic or terrestrial insects. Prior to the stream conversion the reach in the vicinity of the pipeline crossing had no pool habitat and no riparian habitat.

Glacial melt, snowmelt, and rainfall runoff influence the flow regime at McCallum Creek. Spring snowmelt runoff and summer glacial melt provide sustained but low to moderate flows. Large flood events are associated with rainfall runoff or a combination of rainfall runoff and snowmelt. The Richardson Highway Bridge at McCallum Creek was the site of a US Geological Survey (USGS) crest-stage gage from 1967 to 1991. An initial approximation of the bankfull discharge was estimated from the 1.5-year flood (Log Pearson III), at 11.3 cubic meters per second (cms) (400 cubic feet per second (cfs)), Figure 4. The maximum known flood was on August 13, 1967 at a discharge of 28.6 cms (1010 cfs) (Jones and Fahl, 1994). The 1967 flood was a regional event that caused major flooding throughout the Tanana River basin. The USGS maintains a long-term daily gage near the terminus of the Gulkana glacier on Phelan Creek, about 9 km (5 mi) from the study site.

Prior to the channel conversion, riprap protected dikes ran approximately 228 m (750 ft) downstream from the Highway Bridge along each side of the stream to the pipeline crossing. The dikes had been placed to limit the lateral migration of the stream at the pipeline crossing and prevent erosion of the adjacent work pad. The site had historically required regular maintenance by APSC, as floods would cause streambed aggradation leading to overtopping of the dikes. Once the dikes were overtopped, the stream would down-cut through the dikes and form a gully as erosion proceeded rapidly during the flood event, leading to wash out of the dikes and work pad in the affected area. This was not a threat to pipeline integrity due to deep burial depth, but it created the need for frequent maintenance at the site. Following dike and work pad repairs in 1997 and again in 1999, APSC maintenance crews expressed a desire for a long-term solution.

Reference Reach

A stable reference reach was located at the access road bridge crossing, Figure 5. A topographic survey was taken of the channel and a portion of the floodplain over a 191 m (627 ft) reach, 116 m (380 ft) upstream and 89 m (292 ft) downstream of the bridge site. Nine cross-sections were developed from the topographic survey. Follow up surveys were conducted to collect more detailed cross section and longitudinal profile data and to characterize the bed surface pavement and sub-pavement. The reference reach was initially classified as a B3 stream type, although this was later changed to a C4b stream type after more detailed surveys were completed, Table 1. Calculated water surface profile elevations for the estimated bankfull discharge corresponded very closely with the field-identified bankfull stage indicators, so the initial bankfull discharge estimate was judged to be acceptable.

Channel Conversion Design

Objectives included controlling the position of the creek at the pipeline crossing; protecting fish passage and fish habitat at the site; and minimizing, to the extent possible, aufeis accumulations at the reach. The design concept involved converting the braided channel to a stable single thread channel between the highway-bridge and pipeline crossing, Figure 6.

Four factors have been attributed to the causes of braiding in gravel bed rivers: large and sudden variations in discharge, steep channel slopes, a high sediment supply, and highly erodible banks (Drage, 1977). Additionally, a relationship between channel braiding and aufeis is evident considering the distribution of aufeis throughout the braided channels of Phelan and McCallum Creeks.

The concept for a channel conversion was developed after observing braided channel to single channel transitions in Phelan Creek for several years. In reviewing the four factors commonly identified as the cause of braiding, it was evident that each must be addressed in order to effect a change in channel morphology. Discharge, slope, sediment supply, and bank composition were considered in relation to the morphology of the channel transitions observed in each of the single channel reaches in Phelan Creek. The same discharge was being transmitted through both the braided and single channel reaches, although the flood stage may be attenuated slightly in the braided channel reach due to a relatively larger flood plain area. The sediment throughput appeared to be equal based on no significant aggradation or degradation trends at the transitions. The channel slopes were relatively consistent through the transitions. Thus, it appeared that the dominant factor in braiding at these reaches was the bank composition. At each of the single channel reaches the stream had cut through deep deposits that resulted in a bank composition that was relatively more resistant to erosion than in the braided reaches.

It was therefore postulated that if a change in bank composition could be made, then converting the braided channel to a single channel would be feasible, provided that the channel could be designed to transmit the sediment load. As a design condition, bank composition may be addressed through bank protection, in this case rock vanes. The sediment supply and channel slope becomes a design condition: the channel dimension is balanced with the pattern and profile to develop a combination

of depth and slope, respectively, that will induce adequate shear stress to transmit the maximum bedload sizes expected to be routed through the reach.

Two routing options were considered: the first running straight along the top of the alluvial fan following the most direct path to Phelan Creek; the second following a mild curve upon exit from the Highway Bridge opening, down the side of the fan, and then along the right (northern) boundary of the fan to Phelan Creek. The first route had the flattest gradient (negatively influencing sediment transport capacity) but it had the advantage that the stream could still shift laterally across the alluvial fan where the single channel reach terminated and would therefore minimize the potential risk of head-ward aggradation into the design channel. The second route provided the benefit of a greater slope through the design reach but there was a concern that potential deposition near the slope break at the lower limits of the reach could lead to failure of the channel through head-ward aggradation. Therefore, the selected route was along the top of the fan, recognizing that the drawback of a flatter slope was balanced by the minimization of risk from head-ward aggradation.

The morphology and hydraulic characteristics of the reference reach were emulated as closely as possible at the design reach, Table 1. The bankfull channel was designed for the cross-sectional area of the reference reach while the floodplain was designed for flows exceeding bankfull. In order to minimize aufeis buildup in the new channel, the bed elevation was lowered approximately 1 meter (3 feet) from its original elevation along most of the reach to lower the water table and allow the adjacent bank fills to provide more surface insulation.

Sediment transport calculations included critical shear stress, critical dimensionless shear stress, and unit stream power. Relationships for critical shear stress vs. maximum particle size transported (Leopold, 1994) were utilized in estimating critical shear stress. Critical dimensionless shear stress may be calculated from the ratio between channel bed pavement and sub-pavement 50th percentile sizes (Andrews, 1983). The minimum mean depth required to transport a given bedload size can then be calculated from Shields entrainment function once the critical dimensionless shear stress has been determined. Published data by Rosgen (1996) and Annable (1995) of critical dimensionless shear stress by stream type was used for estimating critical dimensionless shear stress for the converted reach. This was not calculated directly due to anticipated bed coarsening and the resultant changes in the relationship between the channel bed pavement and sub-pavement sizes. Unit stream power is the time rate of work per unit width of channel. Throughput rates for both suspended sediment and bed material load have been correlated to unit stream power (Yang, 1996). Unit stream power was used as a means of evaluating hydraulic similitude between the reference and design reach.

Maintaining sediment transport capacity required the width to depth ratio to be minimized in the design reach. A straight pattern (plan-view) was selected to maximize slope for sediment transport. Even with minimizing the width to depth ratio and maximizing the slope, the design shear stress and unit stream power was not as great as at the reference reach, Table 1. However, sediment transport capacity was judged to be adequate given that the vanes produce strong secondary circulation cells and increase velocity gradients, which increases localized bed shear stresses and corresponding sediment transport capacity.

A water surface profile analysis was performed to verify the stage of both the bankfull and flood flows (USACE, 1996). The calculated stage of the bankfull discharge was within 0.05 m (0.18 ft) of the design bankfull channel, which was considered acceptable. The stage of the maximum flood of record was found to be approximately 0.6 m (2 ft) below the top of the dikes. The recurrence interval for the overtopping discharge exceeded 1000 years, which indicated that the elevation of the dikes was adequate for extreme flows.

Four rock vanes and three cross vane weir structures were selected to provide bank protection and grade control for the re-constructed reach. The rock vanes were placed on alternating sides of the channel at the estimated intersect position of the maximum velocity core at each opposing bank. Scour potential over the pipeline crossing was addressed through appropriate placement of the cross-vane weir structures. An initial re-vegetation effort was undertaken immediately following construction to provide bank stability and hydraulic roughness through the first summer. In the fall of 2000 an additional row of willows was placed as live siltation (Muhlberg *et al.*, 1998) along each bank slightly above the first row, Figure 7.

Due to the unique nature of the work, a failure mode analysis was conducted. Mitigative measures were determined for each potential failure mode, Table 2. Potential project risks were discussed with personnel responsible for the area. They chose to support the effort as a means of evaluating the feasibility and long-term effectiveness of the design concept.

Lessons Learned

Several lessons learned came as a result of this and several similar projects implemented along TAPS during the 2000 and 2001 seasons; the most relevant of which are described below:

- Determination of the stable channel form is the single most important criterion for natural channel design. A definition of *stability* has been presented earlier, and is stated in such a way that changes in dimension, pattern, profile, and bed material particle size distribution may be quantified. Recent publications on stream restoration and enhancement have placed considerable emphasis on the use of alternative bank protection measures, including bioengineering techniques and various flow control structures. However, bank protection and grade control measures are a secondary consideration. If *stability* is not addressed in the design then these measures alone may not be adequate to meet the restoration or enhancement objectives. The root cause of any observed channel instability must be addressed directly in the design if stream restoration or enhancement works are to be successful.
- Results from two flow seasons indicate that the design concept is viable. The lack of any aggradation or degradation in the channel indicates that, at the flow rates experienced, the sediment balance is being maintained.
- Changing the stream morphology to a single thread channel appears to have eliminated aufeis development in the converted reach. This indicates promise as a means of controlling aufeis in braided channels. Further evaluation will be necessary to quantify the influence of the channel conversion on aufeis growth.

- If cross sections and longitudinal profiles will be cut from a topographic survey, the survey should be conducted in sufficient detail that all relevant morphological features are captured. This includes surveying the full width of the flood prone area, the presence of terraces, bankfull stage, and sufficient shots in the active channel to adequately define the dimension, pattern, and profile. The reference reach was initially assessed through a topographic survey plotted in 0.6-m (2-ft) contour intervals. The cross-sections and longitudinal profile were then cut from the topographic survey. This resulted in some loss of accuracy and lead to suspicions by the design team that the morphology of the reference reach had not been captured as accurately as would have been desired. After construction, follow-up cross section and longitudinal profile surveys did indicate some discrepancy with the original topographic data, although it was not considered great enough to require modifications.
- Channels must be shaped as closely as possible to a naturally stable state to minimize post-construction adjustment. The design cross-section was a trapezoid proportioned for the required cross sectional area, mean depth, and maximum depth. The over-bank region was sloped directly from the bankfull stage to produce the desired entrenchment ratio. When this shape was built, rapid and immediate bank erosion resulted following water-in. Since the over-bank slope started directly from the bankfull stage, this resulted in over-steepened, over-heightened banks. Additional work was required, by trial and error, to excavate a channel and floodplain shape that was stable. Subsequently, attention was given to the shape of the channel and floodplain at several reference reach sites. The conclusion was that naturally stable stream channels are not shaped like a trapezoid. In several following restoration projects, reference reach cross-sections were evaluated to determine the correct shape. Cross sections were normalized to relate channel depth at a given percentage of the bankfull width to the bankfull maximum depth. This allowed design and construction of channels that were shaped as closely as possible to a naturally stable state. Floodplain benches at the bankfull stage were used so channel adjustments did not result in an over-steepened, over-heightened bank. This approach has been successful in preventing the erosion initially observed during the McCallum Creek project.
- The design called for material excavated from the channel to be side-cast and used to build dikes to define a floodplain and contain flood flows. The capacity of the floodplain dikes was evaluated and was found to be adequate to contain flows in excess of a 1000-year recurrence interval. However, this will lead to a water-surface elevation that is higher than the landform on the backsides of the dikes because the alluvial fan is concave downward in cross section. It would have been preferable to lower the channel more so that dikes projecting above the adjacent landform would not be necessary. This would eliminate the perched water surface elevation for flood flows and the associated transverse hydraulic grade through the dikes, thus reducing risk; and it would be more visually attractive by eliminating the look of a diked system. This approach was used on a similar alluvial fan channel conversion project constructed at Darling Creek in 2001. Further monitoring and comparison of these two sites will be necessary to

quantify the influence of adjacent bank fills on surface energy loss and aufeis growth.

- Use symmetric structures in a high-energy straight reach. Alternating vanes were used for bank protection and cross-vane weirs were used for grade control, recognizing that cross vanes also provide bank protection. The alternating vanes were placed so that the flow deflected off one bank would intersect the opposing bank some distance downstream, and the next opposing vane was located near where the flow intersection occurred. This is working well at McCallum Creek; the vanes appear to be properly located, as no bank erosion has occurred. However, it has led to some additional risks. The B3/B4 stream type is a relatively high gradient, high-energy stream with considerable erosive capacity. With a straight reach of this stream type, use of symmetric structures such as cross vane weirs throughout would be more appropriate, rather than alternating vanes. This would protect both banks, provide a greater degree of grade control, and keep the flow-lines oriented downstream and off the banks.
- Careful attention must be given to structure geometry and quality of construction, some important considerations follow: (1) Maintaining bank angles between 20 and 30 degrees, with angles less than 25 degrees preferred. Angles less than 20 degrees still provide bank protection but result in long structures requiring more rock. Angles greater than 30 degrees may cause bank erosion by eddy rotation, protect less bank, and place greater demand on the structure due to sharp bank and dip angles – resulting in an increased risk of structure damage and scour of the footers. (2) Maintaining a consistent slope (dip) into the bed without gaps or low-spots in the vane. Gaps and low spots create flow convergence, reduce the effectiveness of the structure, and create the potential for bank erosion – particularly if they occur high in the structure near the tie-in with the bank. (3) Correct placement of the footers to fully support the top rocks; if the top rocks are supported by gravel rather than bearing on the footers then flows may scour the underlying gravel away causing the top rocks to settle and the structure to become ineffective. This is particularly true if gaps are present that can increase the scour potential. (4) Design specifications typically include bank angle, dip angle, and intersect with the bed at approximately 1/3 the bankfull width. In some cases these criterion cannot all be satisfied simultaneously and a compromise must be made. Carefully evaluating the structure geometry relative to the channel will help determine the best fit. (5) Sills must be placed so that they do not protrude above the floodplain. If sills project above the floodplain they can cause a hydraulic jump and erosion downstream of the sill during floods. Place sills flush with the floodplain or slightly below grade and cover with a veneer of fill to blend in smooth.
- Use of bank and floodplain re-vegetation in combination with structures has proven effective in minimizing post construction erosion. Immediately following construction the floodplain and banks can be highly disturbed, which places a greater emphasis on re-vegetation.
- Effective communication between the equipment operator and the on-site construction supervision is critical to achieve a good outcome. Building the structures involves careful placement of rocks with varying sizes and shapes that

must be fit together to form the required geometry. This is a trial-and-error process and may seem slower than many operators are accustomed to. The operator and the on-site supervision must be willing to dismantle and rebuild a structure if the geometry is not correct and should understand this is likely to occur. In-process verification of structure geometry is helpful to avoid backtracking. Production has come in at a maximum of about three rock vanes or two cross-vanes per 12-hour shift once the hoe operator becomes familiar with building the structures. Experience on TAPS has shown that the incidence of re-work has increased when production rates were pushed beyond this. This applies to streams with a bankfull width of about 15-m (50-ft).

- Adequately sized rock is a critical component of the structures. Boulders with a minimum equivalent spherical diameter of 1-m (3-ft) were used, figured as the average of the dimension of the three primary axes. This has proved to be a reasonable minimum size for handling and placement. The maximum size range is dependent on the lifting capacity of the equipment. Work along TAPS utilized a Hitachi 450 excavator equipped with a hydraulic thumb and a GVW of approximately 50,000-kg (110,000 lb.). This provided lifting capacity for boulders up to about 2-m (6.5-ft) equivalent spherical diameter. In-process inspection of the rock has proved invaluable to ensure that the specified rock gradation is loaded for transport from the source. This project used approximately 42 cubic meters (500 cubic yards) of rock, or 0.16 cubic meters per lineal meter (0.67 cubic yards per lineal foot).

Summary

This project involved converting a multiple thread channel on an alluvial fan to a stable single thread channel using a natural channel design (NCD) methodology. Design objectives included controlling the channel location at a belowground crude-oil pipeline crossing; minimizing, to the extent possible, aufeis accumulations through the converted reach; and maintaining fish passage and fish habitat. The site has been subjected to at least one bankfull flow event since construction was completed in the spring of 2000. No significant bank erosion, aggradation, or degradation was apparent following the event. Post-flood maintenance of one cross vane weir was required during the summer of 2000 to change the structure geometry due to some shifting of the rocks. Observations during the summer 2001 season indicate that the structures all performed well. Aufeis accumulations have not recurred since the channel conversion project. Lessons learned from 14 NCD projects constructed along TAPS in 2000 and 2001 were presented. The cost for this work was approximately 25% of a comparable project with riprap-protected guide-banks based on historical APSC data.

The site is included in a two-year monitoring study by the University of Alaska, Fairbanks. APSC and the Alaska Science and Technology Foundation (ASTF) provided funding. Objectives include evaluating post-construction geometric response, hydraulic and sediment characteristics, and calibrating hydraulic models to field data. Conclusion of the study is scheduled for fall 2002.

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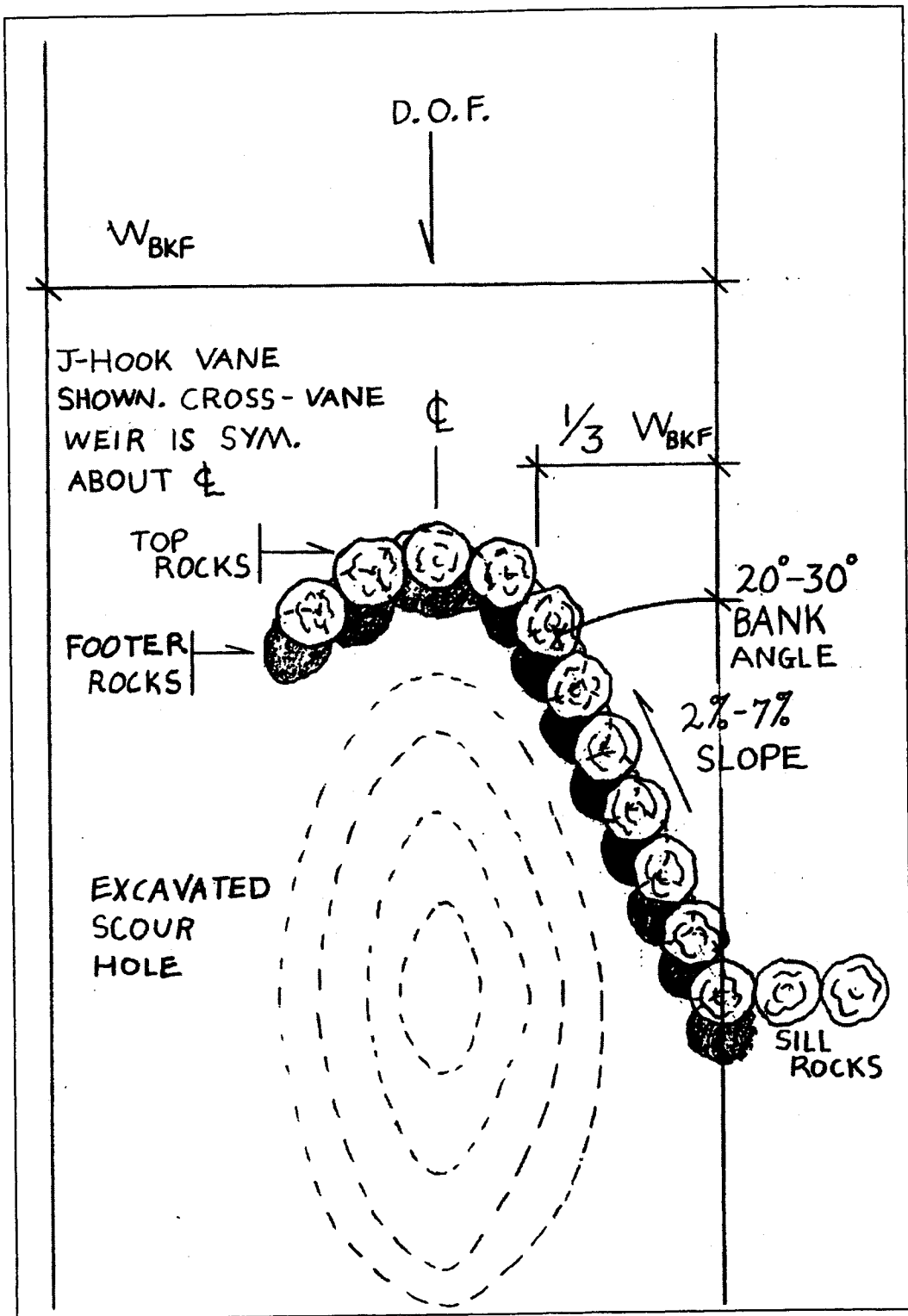
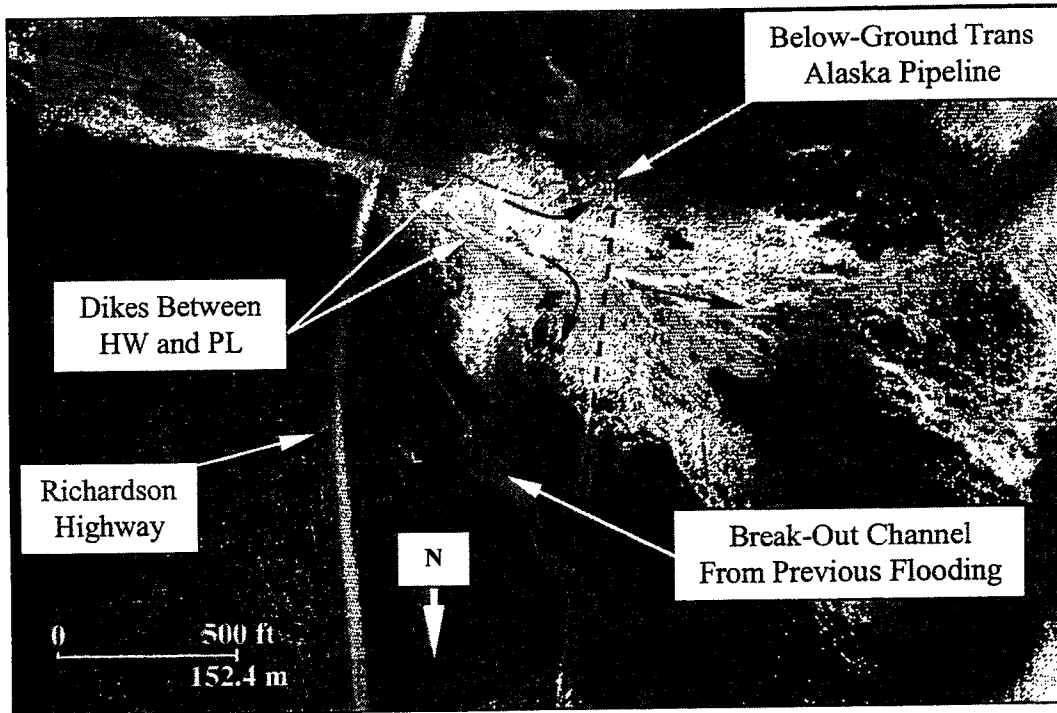
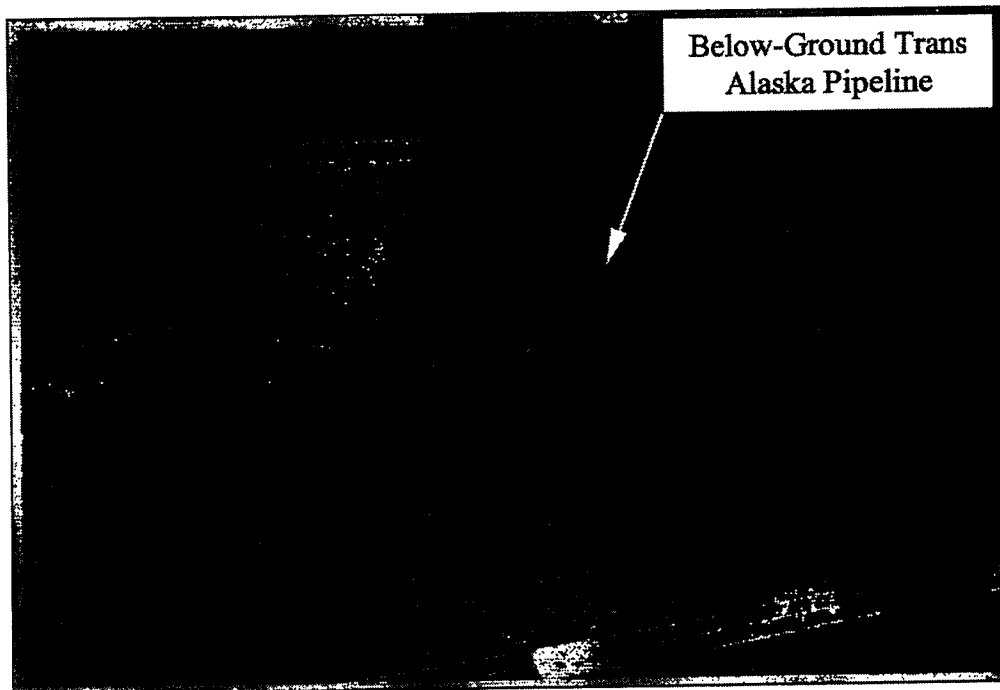


Figure 1. Typical Vane Structure (Plan View)



2 (a).



2 (b).

Figure 2. McCallum Creek Prior to Channel Conversion



Figure 3. Braided Channel to Single Channel Transition, Phelan Creek

**McCallum Creek Annual Peak Flow
1967 to 1991**

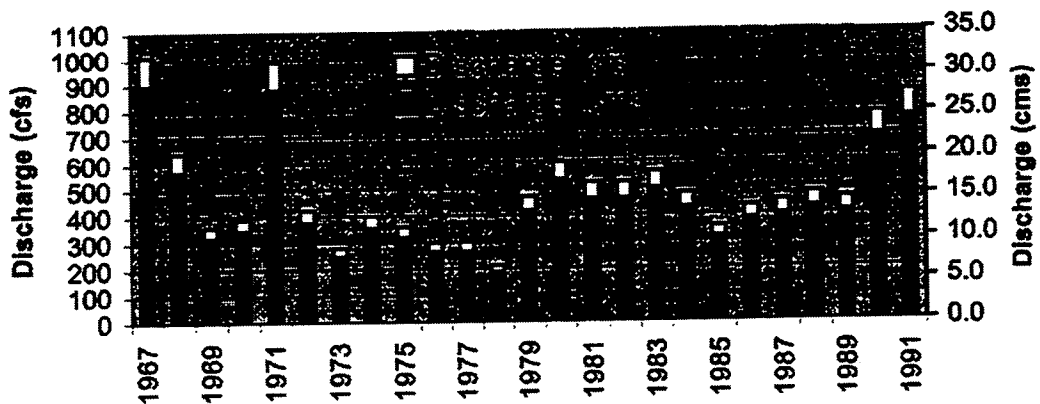


Figure 4. Peak Flow Histogram, USGS McCallum Creek Gage

Variable [SI] (Eng.)	Reference Reach		Pre-Conversion		Design		As-Built	
	[SI]	(Eng.)	[SI]	(Eng.)	[SI]	(Eng.)	[SI]	(Eng.)
Valley Type	II	II	III	III	III	III	III	III
Stream Type	C4 _b	C4 _b	D3	D3	B3	B3	B3	B3
Morphology	Rapids	Rapids	Braided	Braided	Rapids	Rapids	Rapids	Rapids
Drainage Area [km ²] (mi ²)	39.4	15.2	40.1	15.5	40.1	15.5	40.1	15.5
Glacial Influence (%)	19	19	19	19	19	19	19	19
Mean Annual Precipitation [cm] (in)	152	60	152	60	152	60	152	60
Mean Basin Elevation [m] (ft)	1487	4880	1487	4880	1487	4880	1487	4880
Bankfull Discharge [cms] (cfs)	11.3	400	11.3	400	11.3	400	11.3	400
Cross-Section Area [sm] (sf)	6.4	69	9.4	101	6.3	68	4.6	50
Bankfull Width [m] (ft)	12.2	40	31.7	104	7.3	24	9.4	31
Bankfull Mean Depth [m] (ft)	0.5	1.7	0.3	0.97	0.9	2.8	0.5	1.6
Bankfull Max Depth [m] (ft)	0.9	2.9	0.5	1.5	1.1	3.5	1.3	4.2
Ratio Max to Mean Depth	1.7	1.7	1.5	1.5	1.3	1.3	2.6	2.6
Width Depth Ratio	23	23	107	107	9	9	19	19
Flood Prone Area Width [m] (ft)	30.2	99	N/A ⁽¹⁾	N/A ⁽¹⁾	14.6	48	19.8	65
Entrenchment Ratio	2.5	2.5	N/A ⁽¹⁾	N/A ⁽¹⁾	2.0	2.0	2.1	2.1
Bankfull Mean Slope (%)	2.8	2.8	1.3	1.3	1.3	1.3	1.4	1.4
Bankfull Mean Velocity [m/s] (ft/s)	1.8	5.8	1.2	4.0	1.8	5.9	2.4	8
Shear Stress [kg/sm] (lb/sf)	13.5	2.8	3.8	0.8	9.1	1.9	6.4	1.3
Critical Dim. Shear Stress	0.096	0.096	0.020	0.020	N/A ⁽²⁾	N/A ⁽²⁾	N/A ⁽³⁾	N/A ⁽³⁾
Unit Stream Power [kg/m ² s] (lb/ft ² s)	79	16	15	3	54	11	51	11
Note 1: Width of Flood-Prone Area at 2 x d _{max} is above alluvial fan landform (infinite), so E.R. not calculated								
Note 2: Considered tabulated values from Rosgen (1996) and Annable (1995). Not calculated directly in design due to anticipated shift in D ₅₀ (Pavement/Sub-Pavement)								
Note 3: Not calculated. Bed pavement and sub-pavement samples not obtained due to flow conditions								

1 (a). Geometric and Hydraulic Data

% Finer	Reference Reach		Project Reach	
	Pavement (mm)	Sub-Pavement (mm)	Pavement (mm)	Sub-Pavement (mm)
D ₁₀₀	350	180	256	180
D ₈₄	180	120	110	100
D ₅₀	55	65	73	14
D ₁₆	16	4	35	3
Sample Location	Approx. 30 m (100') above access road bridge.	Approx. 90 m (300') above access road bridge	At XS D.S. of Highway Bridge	U.S. of Hwy bridge - from lower 1/3 of mid- channel bar

1 (b). Sediment Data

Table 1. Morphological Data for McCallum Creek



Figure 5. Reference Reach

Potential Failure Mode	Mitigative Measure
General aggradation	Design channel with high shear stress and unit stream power
Headward aggradation from deposition in downstream braided reach	Route channel along top of alluvial fan. No slope break at termination of single channel reach. Allows braided reach downstream to migrate laterally across full width of fan
General degradation	Use robust grade control structures at midpoint and end of single channel reach to prevent down-cutting (Cross-Vane Weirs)
Bank erosion & collapse from lateral migration	Protect bank using rock vanes, cross-vane weirs, and re-vegetation
Stream bank breach: piping failure of dikes bounding floodplain.	Keep channel bed elevation as low as possible to minimize transverse hydraulic grade through dikes, maximize through-thickness of adjacent dikes
Stream bank breach: overtopping during floods	Provide adequate capacity for both bankfull and extreme flood events within adjacent dikes
Stream bank breach: overtopping during spring flows over aufeis	Install robust floodplain sills to prevent downcutting. Could install spring overflow channel at upstream limits of single channel reach and/or cut a pilot channel in the ice directly over the main channel if warranted in future. Non-issue if conversion eliminates aufeis.

Table 2. Failure Mode Analysis Summary

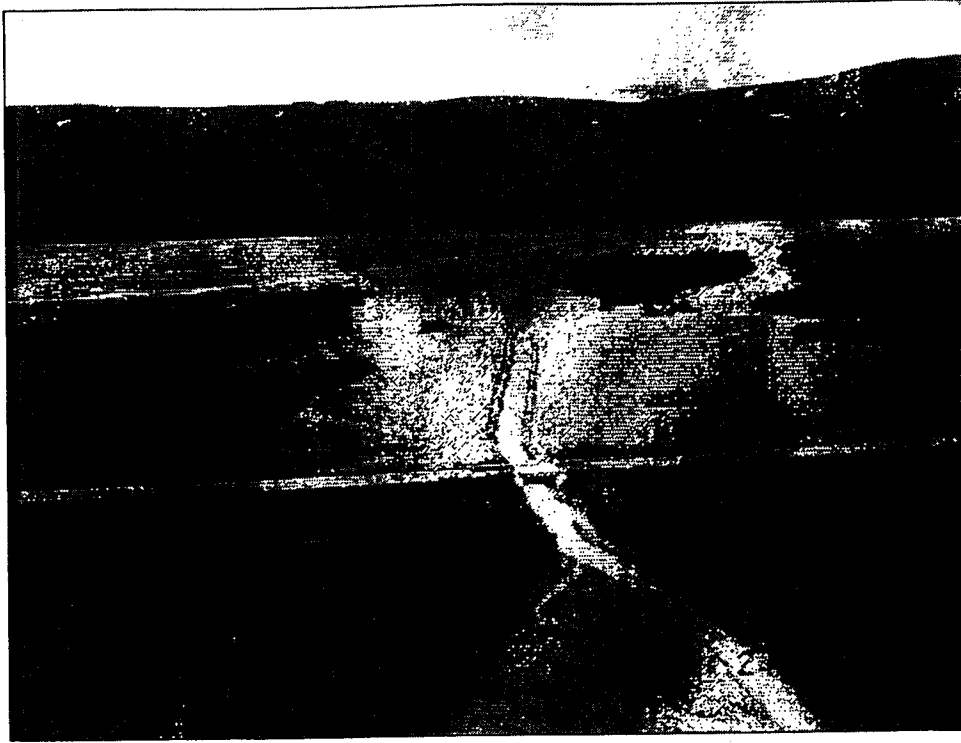


Figure 6. McCallum Creek Following Channel Conversion

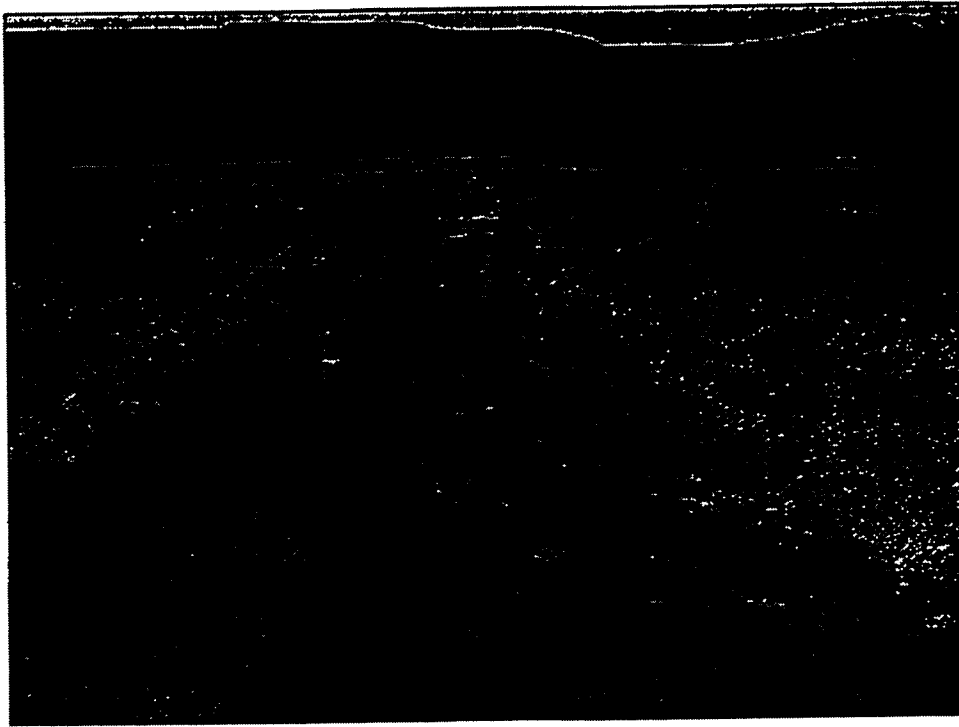


Figure 7. Re-Vegetation Using Live Siltation, Fall 2000