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Results From a Channel Restoration Project: Hydraulic Design Considerations

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Abstract

Techniques for the hydraulic restoration of placer-mined streams and floodplains were developed in Denali National Park and Preserve, Alaska. The two-year study at Glen Creek focused on a design of stream and floodplain geometry using hydraulic capacity and shear stress equations. Slope and sinuosity values were based on regional relationships. Design requirements included a channel capacity for a bankfull discharge and a floodplain capacity for a 1.5- to 100-year discharge. Several bio-engineering techniques using alder and willow, including anchored brush bars, streambank hedge layering, seedlings, and cuttings, were tested to dissipate floodwater energy and encourage sediment deposition until natural revegetation stabilized the new floodplains. Permanently monumented cross-sections installed throughout the project site were surveyed every one to three years. Nine years after the project began, a summer flood caused substantial damage to the channel form, including a change in width/depth ratio, slope, and thalweg location. Many of the alder brush bars were heavily damaged or destroyed, resulting in significant bank erosion. This paper reviews the original hydraulic design process, and describes changes to the channel and floodplain geometry over time, based on nine years of cross-section surveys.

Introduction

Placer mining for gold has severely disturbed many watersheds in the Kantishna Hills region of Denali National Park and Preserve, where it continued until 1985. Placer mining involves removing vegetation and topsoil, excavating gravel down to bedrock from the active floodplain and channel, and processing the gravel to remove the gold. These mined streams now have unstable or excessively confined streambeds along many reaches (USNPS, 1990). Bed scouring continues to occur in the artificially confined reaches; in other areas, erodible banks, a steepened gradient and excessive sediment have created braided reaches.

The U.S. National Park Service (NPS) began long-term multi-disciplinary research in 1990 on methods to promote riparian ecosystem recovery in watersheds disturbed by placer mining. The primary study site is located on abandoned claims on lower Glen Creek (Figure 1). Projects included studies of natural plant succession, the role of mycorrhizae and other soil microflora, revegetation methods, and stream channel and floodplain restoration techniques. Testing of

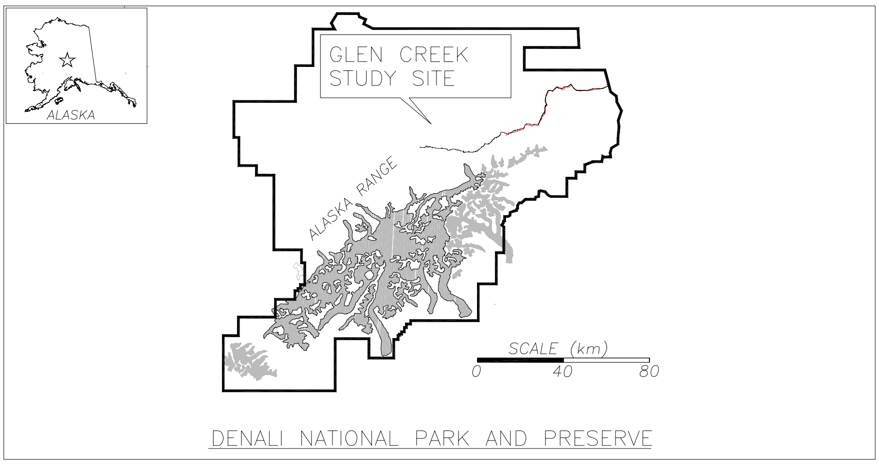

Figure 1. Glen Creek study site.

stream restoration methods took place in 1991 and 1992 along two adjacent reaches of Glen Creek, totaling 1400 m in length.

Permanently monumented cross-sections were placed in the test sections, as well as upstream and downstream of the test sections, to track changes to channel morphometry. Ten years of cross-section data are now available for reviewing the 1991-1992 channel work. Results from some of those cross-sections, as well as an analysis of the hydraulic conditions of the channels, are presented in the results section.

Study Area

The Glen Creek watershed study area lies within the Kantishna Hills, a group of rugged, low-lying hills located within Denali National Park and Preserve. The watershed is 17.2 km^2, with elevations ranging from 648 m at the mouth to 1372 m near Spruce Creek. Glen Creek originates as two forks, south and east of Glacier Peak, in a highly mineralized area. The east fork flows about 1.1 km to the confluence, while the west fork flows about 2.4 km to the confluence. The stream then flows 5.6 km to join North Fork Moose Creek.

The Glen Creek watershed is in the continental climatic zone of Interior Alaska (Selkegg, 1974). The temperature in July, the warmest month, averages 12º C, while January, the coldest month, averages -18º C. Precipitation averages 47.8 cm annually with 72% occurring from June through

September. Snow accumulation ranges from 50 to 150 cm. Discontinuous permafrost may be found throughout the Kantishna Hills area.

The Glen Creek watershed was hand-mined from 1906 to 1941, and subsequently mined with heavy equipment in the 1970s. The level of disturbance from this mining was extensive. The channel ran in an incised trench through many reaches, resulting in a non-functional floodplain. In other reaches, the channel was excessively steep and unstable, creating braided conditions. Most of the floodplain soil was buried beneath tailings or washed downstream, and riparian vegetation was sparse or absent.

Original Project Design Methods

The U.S. Bureau of Land Management (BLM) developed a scheme for designing stable channels in coarse alluvium, based on geomorphic, hydraulic, and hydrologic principles (Jackson and Van Haveren, 1984). This design was developed for a riparian zone recovery project on Badger Creek in Colorado, which was never conducted. The BLM design for channel adjustments is based on a stream channel capacity to contain a bankfull discharge, and a floodplain capacity to contain a 1.5 to 100-year flood. The design process considered channel capacity, channel geometry, and bed and bank stability.

The design objective was to duplicate geomorphic characteristics of the more stable channel reaches in the same physiographic setting. A key feature of the BLM design was the premise that a constructed channel, initially unvegetated, will increase in time as bank revegetation occurs. As bank cohesion increases through the revegetation process, channels would adjust by becoming narrower and deeper. As such, the design protocol suggested that the initial channel design should be shallower and wider than the final desired channel.

NPS Design

We began our design process by estimating design flood flows from regional multiple-regression techniques (Lamke, 1979). The estimated bankfull discharge was 1.44 m^3/s; however, a slightly larger value was used for the design flow as a factor of safety.

To select channel geometry, an iterative process is required. Manning's equation was applied to determine a range of channel configurations, based on a capacity of bankfull discharge. We determined the Manning's 'n' roughness factor from previous field discharge measurements (USGS, 1985). Slope and sinuosity determinations were made by regional comparisons to other Kantishna streams, based on regression with drainage area (USNPS, 1991).

Once a range of channel geometries which would accommodate bankfull discharge were calculated, shear stress equations were applied to determine both bed and bank stability.

Average shear stress is:

$$\tau_O bed = \gamma RS \tag{1}$$

where R is hydraulic radius, S is energy gradient, and γ is the unit weight of water. The average bank shear stress (Simons and Senturk, 1977) is then calculated as:

$$\tau_O bank = 0.77\tau_O bed \tag{2}$$

The object of the iterative design is to adjust channel geometry such that critical shear stress just exceeds average shear stress at bankfull discharge. By doing so for both bed and banks, the channel is stable at bankfull flow, though close to incipient instability. Critical bed shear stress is determined from Lane (1955) for coarse material:

$$\tau_C bed = 0.08D_{75} \tag{3}$$

where D_{75} is the diameter at which 75% of the bed particles are finer by size. Critical bank shear stress is calculated from Graff (1971), using an estimated angle of repose ϕ for coarse bank materials, and an estimated bank angle θ. The ratio of critical shear stress of the bank to the bed is:

$$\frac{\tau_c bank}{\tau_c bed} = \cos\theta\sqrt{1-\frac{\tan^2\theta}{\tan^2\phi}} \tag{4}$$

Iteration of the channel geometry continues until capacity requirements are met, as well as bed and bank stability requirements. The values selected for the channel design for Glen Creek are found in Table 1.

Floodplain design was based on a capacity for the 100-year flood discharge estimate. For many sections of the study reach, the floodplain was designed in a 2-terrace configuration, with the lower terrace designed to carry the 20- to 50-year flood, and the upper terrace capacity at the 100-year flood (Karle and Densmore, 1994a, 1994b). Floodplains were typically located on the inside of meanders, and on both sides through straight reaches.

Table 1-Values used for channel design for Glen Creek, Alaska study area.

Channel design parameter	Value
Bankfull discharge	1.83 m3/s
Slope	0.0224 m/m
Manning's '*n*'	0.051
Bankfull width	6.0 m
Bankfull depth	0.3 m
Width/depth ratio	20
Bed material D_{75}	61.5 mm
Average bed shear stress	5.70 kg/m^2
Critical bed shear stress	5.90 kg/m^2
Average bank shear stress	4.39 kg/m^2
Critical bank shear stress	4.91 kg/m^2
Sinuosity	1.12

Construction of the Glen Creek channel design occurred in 1991 (upper study reach-Section 1) and 1992 (lower study reach-Section 2). Most of the work along the two study reaches involved recontouring artificially raised floodplains to a lower elevation and leaving the existing channel undisturbed except for minor bank modifications. This effort served to reconnect the channel to the floodplain, by restoring natural floodplain processes and bringing the desired riparian/floodplain surface closer to the water table. In the lower study reach, a 150 m long section was moved from an incised location against the valley wall to the center of the valley.

Excavated gravels were used in some areas to fill in settling ponds, old channel beds, and other mining-related topographic features. Excess gravels were contoured into the valley slope at the floodplain's edge. A bulldozer, front-loader, and dump truck were used for the majority of the dirt work.

Brush bars were constructed of bundles of alder (Alnus crispa (Ait.) Uursh) and willow (Salix alaxensis (Anderss.) Coville) branches collected on site, tied together, and anchored laterally adjacent to the channel. These brush bars were installed on the floodplain in several configurations to test their effectiveness.

Methods

To track long-term changes to channel and floodplain geometry, permanently monumented cross-sections were installed throughout the two study reaches as early as 1990. More cross-sections were added as the work progressed downstream from the 1991 section to the 1992 work; by 1995, 14 cross-sections were installed to monitor this project. These cross-sections were surveyed using an engineering level and stadia rod, and referenced to a local benchmark. Cross-sections were surveyed every 1-3 years.

Surface bed and bank materials were sampled over time to characterize changes to the composition and caliber. Material size was quantified by a pebble count, in which the intermediate axis of 100 randomly picked particles are measured and the size distribution is expressed in size class percentages (Leopold, 1970).

Results

An earlier paper (Karle and Densmore, 1994b) described the completion of this project, and changes to the channel geometry after a small (5-year recurrence interval) flood occurred in the test section shortly after completion of the 1992 work. The flood damaged the alder brush bars in areas where they were spaced two or more channel widths apart. In the lower section (1992) where spacing was only one channel width, the brush bars acted as predicted; they protected the bank from erosion and allowed deposition of fines on the floodplain in between the bars. Channel changes in unprotected areas included some bank erosion and thalweg movement, and a slight decrease in channel slope.

As a result of the channel changes created by the 1992 flood, some additional work was conducted on both test sections in 1994. In the lower reach of the upper study section, hedge layering was constructed along the left bank, using buried willow and alder branches with the tops projecting 0.5 m from the stream bank (Densmore, 1999, 2000). In addition, vortex rock weirs were installed throughout this section, using 1-meter diameter boulders (Rosgen, 1996). In the lower study section, the channel width/depth ration was reduced from 20:1 to 15:1. Alder brush bars were extended to cover additional floodplain width, and additional monitoring cross-sections were installed.

Fourteen cross-sections throughout the two study reaches were surveyed in 1995, 1997, and 2000, and visual inspections of the channel were made annually. In both study sections, surveys revealed that the rate of channel movement had slowed considerably since the 1992 flood. In addition to the willow cuttings which were planted as part of the project, natural invasion of the new floodplains by vegetation was occurring, including willow, alder, spruce, grasses, and others (Densmore, 1999, 2000).

In August 2000, a flood with an estimated recurrence interval of 25-50 years occurred in the Glen Creek watershed. Changes to the channel geometry and the erosion control structures were immediate and significant in most areas of the two study sections, with two exceptions. Though space limitations prevent the inclusion of all fourteen cross-sections in this paper, the six cross-sections shown are typical of results for the study sections.

Cross-sections 1 and 2 are located in the upstream reach of Section 1. Though the floodplain through this area was entirely inundated by the flood, channel geometry changes were insignificant in the upper reach of Section 1, as shown by Cross-section 1 (Figure 2). However, severe bank erosion, thalweg migration, and brush bar destruction occurred just downstream of this reach (Cross-section 2, Figure 3).

In the lower reach of Section 1, channel changes were much less severe. Cross-sections 8 and 10 (Figures 4 and 5) display only moderate changes between 1995 and 2000.

Changes to the channel and floodplain geometry in Section 2 were substantial. Fifteen of the original 25 brush bars were partially or completely destroyed. Channel changes included extensive erosion of banks, displacement of the thalweg, and an increase in the width/depth ratio. Cross-sections 12 and 14 (Figures 6 and 7) are typical of the changes to channel and floodplain geometry throughout Section 2.

Discussion

In order to understand why the channel suffered such severe damage during the 2000 flood, we reviewed our design process from the earlier project. The underlying foundation for the hydraulic design process described above is the premise that six independent variables are considered to control the dimensions of natural channels. They include discharge, bed load discharge, bed material size, bank material characteristics, valley slope, and bank vegetation (Hey, 1978). These six variables provide the basis for evaluating the hydraulic and hydrologic analysis we conducted for the project design.

Discharge: The first error during the design process was most likely an underestimation of the design discharges, including bankfull discharge, the 5-year, 10-year, 25-year, and the 50-year flood magnitudes. Glen Creek was severely mined for 80 years prior to this project; as such, finding a remnant piece of original channel to determine bankfull discharge was an impossible task. Because of this, design discharges were estimated from regional multiple-regression equations (Lamke, 1979).

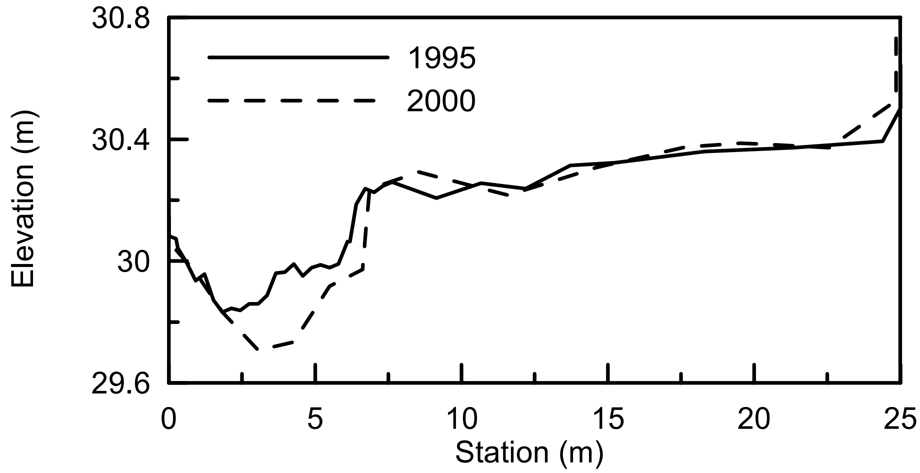

Figure 2. Cross-section 1, Glen Creek, Alaska.

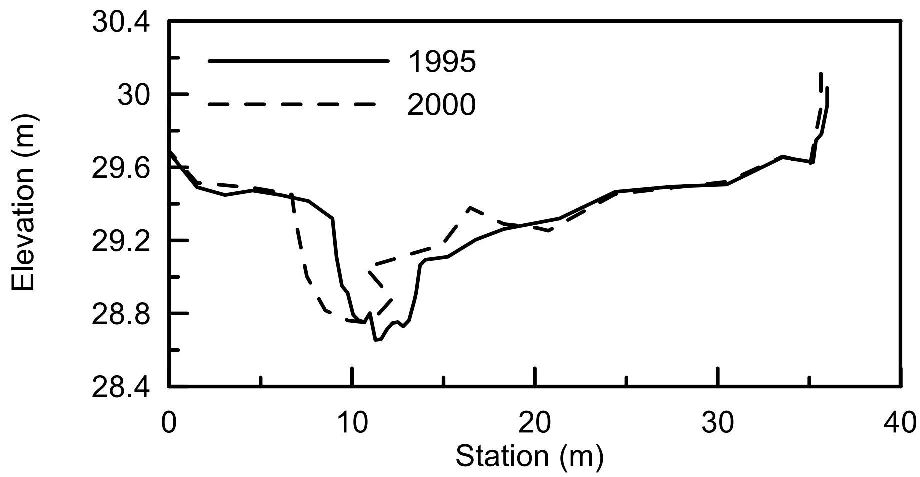

Figure 3. Cross-section 2, Glen Creek, Alaska.

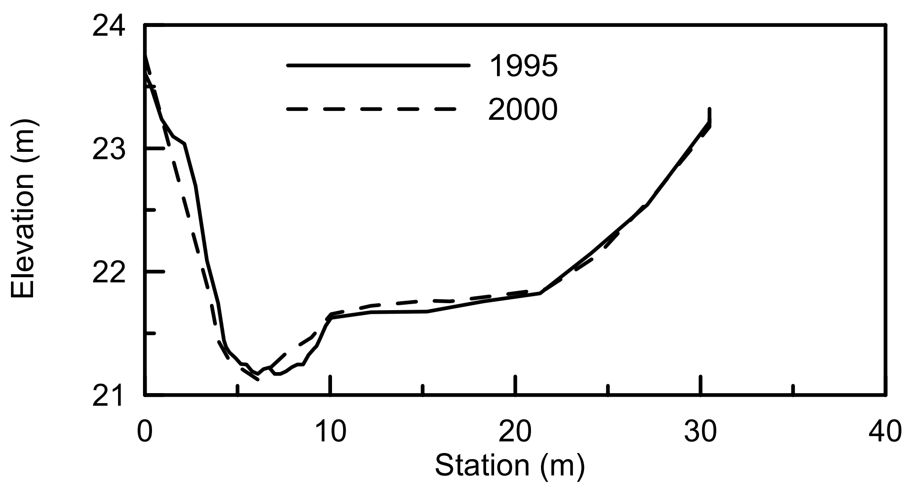

Figure 4. Cross-section 8, Glen Creek, Alaska.

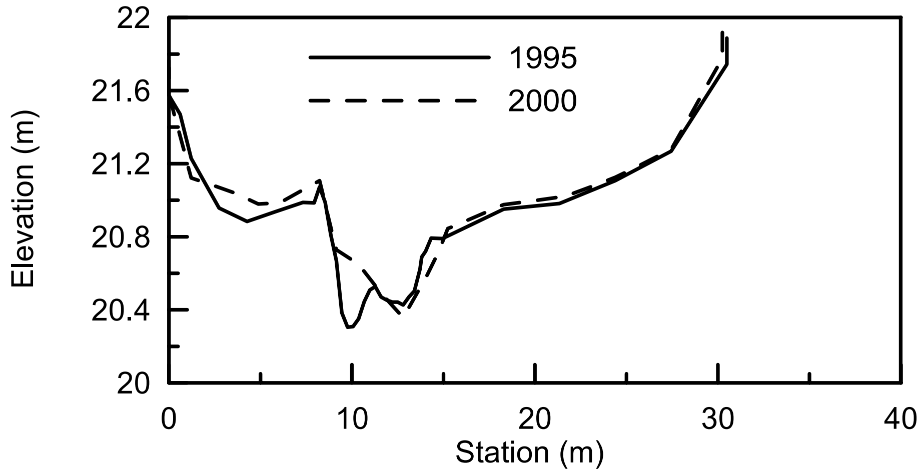

Figure 5, Cross-section 10, Glen Creek, Alaska.

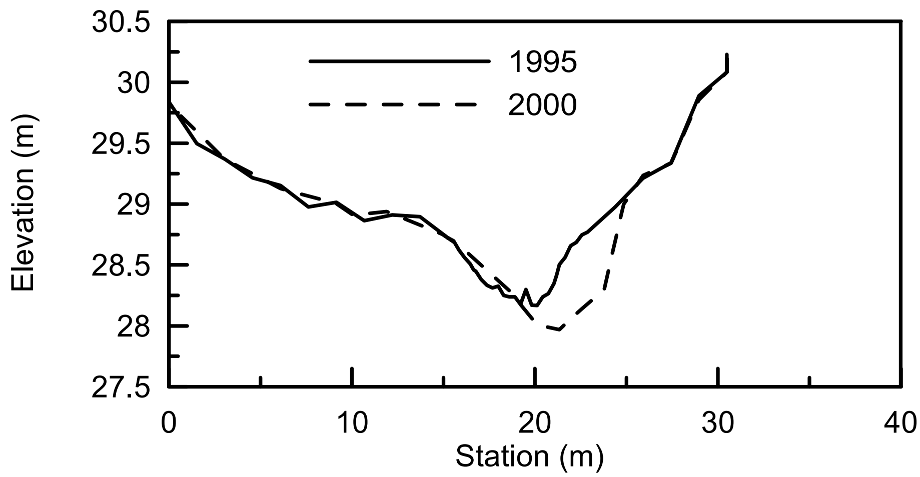

Figure 6, Cross-section 12, Glen Creek, Alaska.

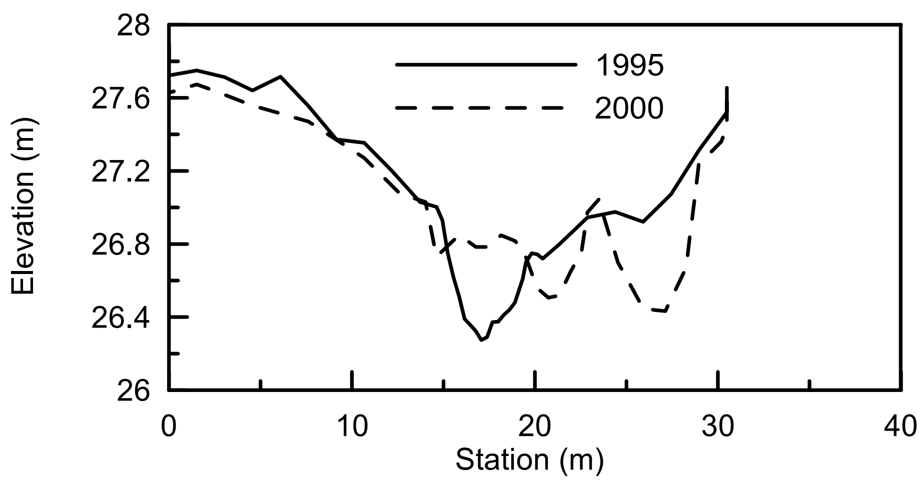

Figure 7, Cross-section 14, Glen Creek, Alaska.

The U.S. Geological Survey has published a more recent document to estimate flood magnitudes and frequencies in Alaska (USGS, 1994). Based on basin climatic and physical characteristics and peak-flow statistics from 260 gaged locations in Alaska and 72 gaged locations in Canada, this report divides the State into five flood-frequency areas having similar characteristics. Using such basin characteristics as drainage area, mean annual precipitation, mean basin elevation, mean minimum January temperature, and area of lakes and ponds, new estimations of design flows were calculated using the 1993 report. Comparisons using the two methods are shown in Figure 8.

We estimated bankfull discharge by interpolating a 1.5-year flood from the original flood frequency curve, and adding 25% as a factor of safety (1.83 m^3/s). A safer estimation technique would be to use the 2-year flood from the 1993 report as the bankfull discharge (3.18 m^3/s).

Bed Material Size/ Bank Material Characteristics: A number of pebble counts were used to describe the bed material size for calculations of critical shear stress as part of the design process. However, field conditions unveiled during project construction unveiled two areas of special problems. In the lower study area, construction of the new channel segment passed through a section of sorted undersized processed mine tailings. Such processed tailings are washed free of fines, and exhibit little or no cohesion. This decreased the average size of the bed material by 50%, and eliminated the old bed armour layer which it replaced. In the upper study area, floodplain lowering uncovered additional sites of fine unprocessed tailings on the right bank adjacent to the stream channel.

Our field solution at the time of construction was to protect these sites with alder brush bars. However, this proved to be inadequate. Equation 3 is used to calculate critical bed shear stress:

$$\tau_C bed = 0.08 D_{75}$$

In the two problem areas, we estimated the D_{75} at less than 30 mm. This results in a critical bed shear stress of 2.4 kg/m^2, which is less than half of our design estimate. The brush bars provided no reduction in average shear stress in the channel, and this was undoubtedly responsible for a significant portion of the bed and bank erosion in these areas.

Our original design objective was to adjust channel geometry such that critical shear stress just exceeds average shear stress at bankfull discharge. To determine if we met that criteria in the field, we used the 1995 Cross-section 12 data along with the revised estimation of bankfull discharge to determine the average shear stress at channel design flow, using Equation 1:

$$\tau_O bed = \gamma RS$$

At bankfull discharge, R = 1.07 m, S = 0.0212 m/m, γ = 1000 kg/m^3, and T_{0bed} = 22.6 kg/m^2. This value substantially exceeds both our original and revised estimations of critical bed shear stress.

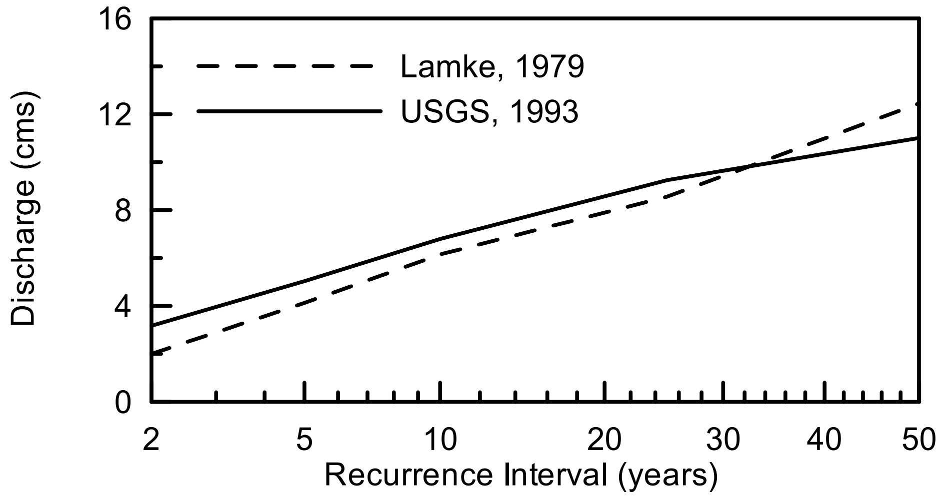

Figure 8. Original and revised flood frequency curves for Glen Creek study area.

Bank Vegetation: On undisturbed banks and floodplains, vegetation is an essential component of structure and stability (Yang, 1996). The root system anchors the substrate, and above-ground stems decrease water velocity, catch organic debris, and promote sediment deposition. The importance of vegetation to bank stability was apparent when comparing results from the two study sections. In the upper reach of Section 1, vegetation lines the original undisturbed left bank, which exhibited almost no channel instability over the 9-year study period. Cross-sections 8 and 10, in the lower reach of Section 1, also showed little bank or bed erosion. The left bank in this section received a brush layering treatment in 1994, using hundreds of willow cuttings and alder branches (Densmore et. al, 2000). These willow revegetated almost immediately, and provide a stable platform for the left bank and floodplain.

Along the remainder of the study sections, including the entire length of Section 2, mining had completely removed all vegetation along both banks. Streambank plantings of both willow cuttings and alder seedlings were established to anchor the substrate and catch organic debris (Densmore, 1994). Before the 1992 flood, one year after planting, the willows and alders had high survival rates (78% and 92% respectively) and well-developed root systems. The 1992 flood washed out all the willows planted on a point bar, and 40% of willows planted between the alder brush bars. One-third of the alder seedlings were also washed out. The 2000 flood washed out the majority of the remaining cuttings. Cross-sections 12 and 14 are located in the lower section, which was typical of a channel with no remnant bank vegetation.

As mentioned earlier, our design specified that the initial channel geometry should be shallower and wider than the final desired channel. As the banks revegetated and bank cohesion increased, we believed that the channels would adjust by becoming narrower and deeper. Given the difficultly with reestablishing bank vegetation in non-cohesive gravels with little or no organic fines, we would now change design guidelines to consider an initial channel geometry which is narrower and deeper than the final desired channel.

Slope: We obtained our design slope value by surveying 15 similar stream sites in the Kantishna Hills area, and regressing slope with drainage area (USNPS, 1991). All sites, with the exception of two headwater sites, had suffered from some mining disturbance. This skewed our regression and led us to use a slope biased by hydraulic instability.

Another indication that our design slope was too steep comes from a commonly used stream classification system. The Rosgen system is based on morphological characteristics to define eight major stream classes with about 100 individual stream types (Rosgen, 1996). Typical ranges of morphological measurements are given for a given stream type, including: entrenchment, width/depth ratio, sinuosity, slope, bed material particle size, and number of channels. Application of our original design variables for the Glen Creek project do not allow an easy fit into one of the Rosgen stream classes. A decrease in slope (and corresponding increase in sinuosity) would have resulted in a closer match for the Rosgen 'C' stream type.

Summary

Our original project design attempted to balance technique effectiveness with cost efficiency. Based on observations in adjacent watersheds, we predicted that the reconstructed floodplains would naturally revegetate within five to ten years. Based on a 23% probability that a 20-year flood would occur in a five year time period, we designed our protective brush bars for smaller (5- to 20-year) flood events.

Our estimates for new floodplain revegetation were accurate in areas where remnant topsoil and organic overburden materials were still available for use during construction. However, our use of the alder brush bars proved to be ineffective against large bed and bank shear stresses during high water events, even at the closer spacing of one channel width. The low critical shear stress of a non-cohesive, unvegetated gravel bank requires that substantial and continuous of bank stabilization, such as willow brush layering, be used during stream channel reconstruction. Additionally, it is important that hydraulic design calculations be as accurate as possible, and attempt to account for all possible conditions that may be encountered during field construction. The risk of failure will decrease with time, as revegetation occurs and banks and floodplains evolve to a stable condition. However, increasing the acceptable risks of flood event damage, while necessary from a budgetary point of view, may lead to premature project failure and the necessity to repair or reconstruct an inadequately designed channel.

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