Stream and floodplain restoration in a riparian ecosystem disturbed by placer mining

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Abstract

Techniques for the hydrologic restoration of placer-mined streams and floodplains were developed in Denali National Park and Preserve Alaska, USA. The hydrologic study 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 include a channel capacity for a 1.5-year (bankfull) discharge and a floodplain capacity for a 1.5- to 100-year discharge. Concern for potential damage to the project from annual flooding before natural revegetation occurs led to development of alder (*Alnus crispa*) brush bars to dissipate floodwater energy and encourage sediment deposition. The brush bars, constructed of alder bundles tied together and anchored laterally adjacent to the channel, were installed on the floodplain in several configurations to test their effectiveness. A moderate flood near the end of the two-year construction phase of the project provided data on channel design, stability, floodplain erosion, and brush bar effectiveness. The brush bars provided substantial protection, but unconsolidated bank material and a lack of bed armour for a new channel segment led to some bank erosion, slope changes and an increase in sinuosity in several reaches of the study area.

Key words: Floodplain erosion; Riparian restoration; Stable channel; Stream reclamation

1. Introduction

Placer mining for gold has severely disturbed many riparian ecosystems in northern regions. Placer mining involves removing vegetation and topsoil, excavat-

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ing gravel down to bedrock from the active floodplain, old terraces and/or the active stream channel and processing the gravel to remove the gold. Placer-mined streams in the Kantishna Hills region of Alaska's Denali National Park and Preserve have unstable or excessively confined streambeds along many reaches. Piles of mine tailings have replaced much of the native streambed material. Some floodplain soil was stockpiled, but most was buried beneath tailings or washed downstream. Riparian vegetation is sparse or absent and habitat value has been severely reduced (USNPS, 1983, 1990).

With such a disturbed riparian ecosystem, recovery through natural processes is hindered. In channel reaches where the stream bed is incised and straightened, bed scouring continues to occur. During annual flooding, erosion of over-steep banks results in excessive sediment loading of the stream. This sediment load is then deposited in the channel downstream in areas of shallower gradient, resulting in additional problems such as cementing of substrates and clogging of habitat for benthic invertebrates. Incised stream channels also prevent flooding, thus interrupting the natural process of floodplain sediment deposition.

The U.S. National Park Service (NPS) is conducting long-term multi-disciplinary research on methods to promote riparian ecosystem recovery. The primary study site is located on abandoned placer claims on lower Glen Creek in the Kantishna Hills. Projects currently in progress include studies of natural plant succession, the role of mycorrhizae and other soil microflora, revegetation methods, benthic invertebrate populations, water chemistry and suspended sediment. This paper focuses on the research to develop stream restoration techniques which would (1) reduce erosion, (2) allow the stream to develop floodplains, sinuosity and pools and riffles similar to premining conditions and (3) minimize construction needs. Testing of stream restoration techniques took place in 1991 and 1992 along two adjacent reaches of Glen Creek totaling 1400 m in length.

This paper presents results of flood effects on the experimental design. Results were obtained rapidly because a flood event occurred in the Glen Creek watershed in August, 1992, just after construction was completed.

2. 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 (Fig. 1). The watershed is 17.2 km^2, with elevations ranging from 648 m at the mouth to 1372 m near Spruce Peak. 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 bedrock geology of the Glen Creek watershed is composed of faulted and folded quartzite and hornblende schist of the Birch Creek formation. The study area on lower Glen Creek was covered in the middle Wisconsin glaciation from the
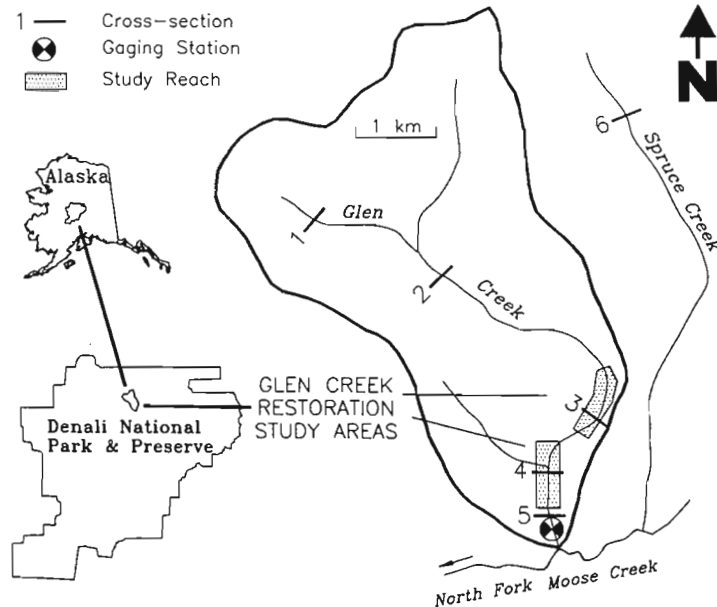
Fig. 1. Location of the Glen Creek study area in Denali National Park and Preserve, Alaska.

Alaska Range and gravel and rocks deposited by the glacier are mixed with bedrock material in the alluvial gravels.

The Glen Creek watershed is in the continental climatic zone of interior Alaska (Selkregg, 1974). The temperature in July, the warmest month, averages 12°C, while January, the coldest month, averages −18°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 study area is at treeline and trees are confined to favorable sites on alluvial terraces and south-facing slopes. Tall shrubs dominate riparian vegetation on the floodplain and younger terraces and low shrubs and herbs form the tundra vegetation on colder, more exposed sites. The mining severely disturbed the vegetation on the study area, but the predisturbance vegetation can be inferred from remnants and adjacent undisturbed watersheds. On these watersheds, the floodplain is dominated by *Salix alaxensis* (feltleaf willow) (Viereck and Little, 1972) 3–4 m tall, mixed with varying amounts of *Alnus crispa* (American green alder) 1–2 m tall. The floodplain is vegetated to the bankfull stream level; natural flood or ice events, which remove vegetation and initiate primary riparian succession, appear to be infrequent. Higher areas have *Populus balsamifera* (balsam poplar) and younger *Picea glauca* (white spruce) and old terraces have open stands of *Picea glauca* with an understory of low shrubs, including *Betula glandulosa* (dwarf birch) and *Salix planifolia* (diamondleaf willow).

The Glen Creek watershed was hand-mined from 1906 to 1941. The stream was diverted and dammed and some topsoil and fines were washed away, but the area extent of disturbance was limited relative to later mining. In the 1970s, the watershed was extensively remined with heavy equipment.

Restoration of the study area began in August 1988, when the area above the active floodplain was recontoured. Excavated material was redistributed to fill excavations, reduce and stabilize slopes and the available topsoil and fines were spread over some areas of gravel and rock substrate. The work described in this paper, the restoration of the active floodplain and stream channel, was initiated in 1991.

3. Methods

The U.S. Bureau of Land Management (BLM), in an attempt to enhance riparian zone recovery in a portion of Badger Creek, Colorado, has developed a scheme for designing stable channels in coarse alluvium based on pertinent geomorphic, hydraulic and hydrologic principles. This scheme was based on the premise that a channel in coarse alluvium is considered stable if design discharges and sediment loads can be carried without causing excess bank or bed erosion or deposition. This design, with modifications for subarctic conditions, was the basis for the NPS Glen Creek study. A brief outline of this design follows; for specific hydraulic design details, see Jackson and Van Haveren (1984).

3.1. Channel design

The BLM design for channel adjustments is based on a streambed capacity to contain a bankfull (1.5-year) discharge and a floodplain capacity to contain a 1.5- to 100-year flood. Sediment loading from bank erosion and other sources is minimized. Though recommended in the BLM design, we chose not to include the use of channel controls such as riprap or gabions, as we felt these generally hinder natural stream restoration.

The design process began with the estimation of design flood flows from regional multiple-regression estimations (Lamke, 1979; Kane and Janowicz, 1988; see Fig. 2). 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.

Manning's equation was applied to determine a range of channel configurations which would carry bankfull discharge. The roughness coefficient, Manning's 'n', is computed from hydraulic analysis of previous 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 bankfull channel configurations was found, shear stress equations were applied to each configuration to determine stability for both bed and bank. Typical values used for the design channel are presented in Table 1.
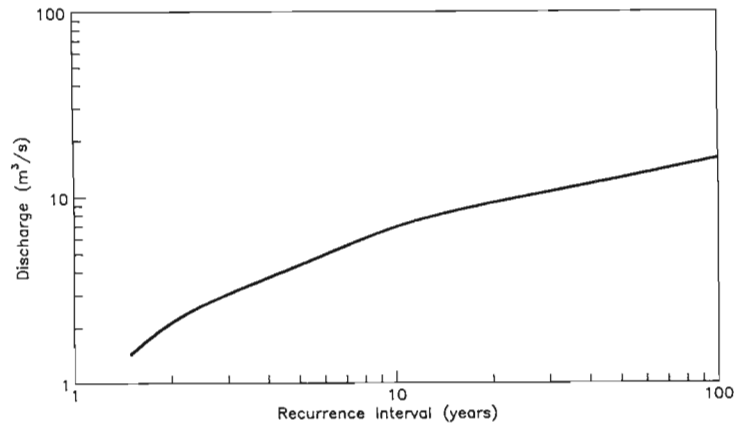
Fig. 2. Flood frequency curve for Glen Creek study area.

Floodplain design was achieved in the same manner. Using a 100-year flood discharge estimate of 16.0 m³/s, capacity equations were used to determine floodplain geometry. 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- ot 50-year flood and the upper terrace capacity at the 100-year flood. Depending on location along the study reach, floodplains were either situated on one or both sides of the streambed. Floodplains were typically located on the inside of meanders and bends and on both sides through straight reaches.

Once the design parameters were established and surveyed, earthwork took place along two reaches of Glen Creek, including a 425-m reach in 1991 (upper study area) and an adjacent 975-m reach in 1992 (lower study area). To achieve the design goal of a functioning channel and floodplain, two types of earthwork configurations were constructed along the test reaches. Most of the work involved recontouring artificially raised floodplains to a lower elevation, using a shallow slope to restore natural floodplain processes and leaving the existing channel undisturbed except for minor bank modifications (Section design 1, upper study area, Fig. 3). In one area, an entirely new channel of 150 m long was designed and

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

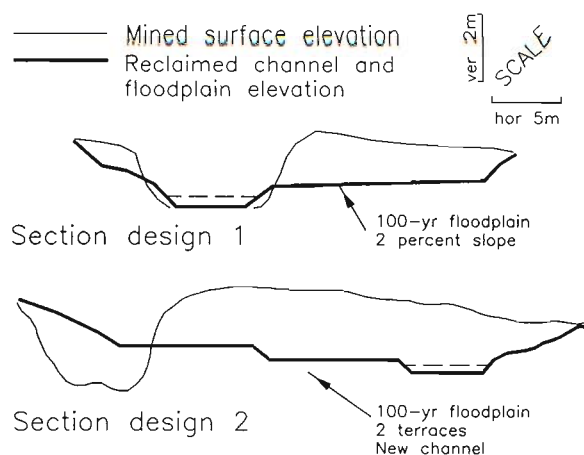|	
Bankfull discharge	1.83 m³/s
Slope	0.0224 m/m
Manning's 'n'	0.051
Bankfull width	6.0 m
Bankfull depth	0.3 m
Average bed shear stress	5.70 kg/m²
Critical bed shear stress	5.90 kg/m²
Average bank shear stress	4.39 kg/m²
Critical bank shear stress	4.91 kg/m²

Fig. 3. Typical cross-section designs. The channel is designed to carry bankfull discharge (1.5-year flood). Two floodplain configurations (single 2% slope and 2-terrace) were designed to carry the 100-year flood.

repositioned in the valley center, away from the valley wall where it was previously located (Section design 2, lower study area, Fig. 3). Additionally, the floodplains along this reach were constructed with two terrace levels instead of a single slope.

Excavated gravels were used in some areas to fill in settling ponds, old channel beds and other unnatural depressions. Excess gravels were blended into the valley slope at the floodplain's edge. A crawler-dozer, articulated front-loader and dump truck were employed to move the ground to the desired configuration.

2.2. Temporary floodplain stabilization

In conjunction with these restoration techniques, results from revegetation research currently being conducted in the Glen Creek watershed were applied to facilitate riparian zone recovery. On undisturbed floodplains, the vegetation is an essential component of floodplain structure and stability. The root system anchors the substrate, and above-ground stems decrease water velocity, catches organic debris, and promotes sediment deposition. Based on observations in adjacent less-disturbed watersheds, we predicted that the reconstructed floodplains would naturally revegetate within 5 to 10 years.

A major concern for this project was the occurrence of a large flood before revegetation occurs, which could seriously damage the new channel and floodplain. To address this problem, probabilities for annual floods to occur or be exceeded were estimated (Linsley et al., 1982). For example, in a 5-year time period, there is a 67% probability that a 5-year flood will occur, a 41% probability that a 10-year flood will occur or be exceeded and a 23% probability that a 20-year flood will occur or be exceeded.
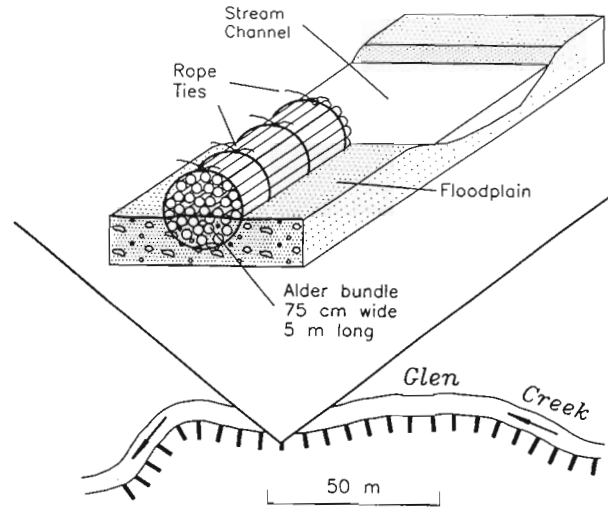
Fig. 4. Brush bar pattern, with one channel width spacing, along left bank of new channel reach in lower study area. Inset shows typical installation of alder bundle, adjacent to channel and anchored to floodplain.

Stage and bank shear stresses were estimated at various flood levels. We predicted that serious damage could occur to the new (unvegetated) floodplains from a 10-year flood or less. Based on the low probability of occurrence for a 50- or 100-year flood and the difficulty and expense of protecting against larger discharges, we decided to install protective devices for smaller (5- to 20-year) flood events. An additional goal with such devices was to encourage sediment deposition during flood events.

To meet these requirements, a series of alder brush bars were installed on various locations along the study reaches. Designed to slow flood water velocity and encourage sediment deposition, these were bundles of cut alder, approximately 50 to 75 cm in diameter and 4 to 5 m in length. The bundles were installed by first digging a trench into the floodplain perpendicular to the channel. Several rope lengths were placed across the open trench, the lower half of each bundle was set into the trench, the trench was then backfilled, the top half of the bundle was added and the ropes were tied around the bundle to anchor the bundle in place (see Fig. 4). In 1991, two groups of brush bars were installed on the upper reach. The bars were spaced three channel widths apart, with four bars in the first group and 22 bars in the second group. Bars in the first group included one 4- to 5-m-long feltleaf willow branch buried in the lower half of the bundle and five willow cuttings planted into the downstream side of the bundle. For the 1992 project, two groups of brush bars were installed on the lower reach, with the spacing at one channel width apart. One group contained eight bars and the second group, installed along the left bank of the new channel construction, contained 25 bars.

Additional techniques were also tested in the upper section to encourage sediment deposition. Small circular depressions 10 to 20 cm in depth and 1 to 2 m in diameter were created by the tracks of a bulldozer running a pattern of tight turns on the new floodplain surfaces. These depressions were designed to capture sediment and precipitation runoff and catch airborne seeds as they tumble across the roughened surface.

Streambank plantings of *Salix alaxensis* cuttings and *Alnus crispa* seedlings were also established to anchor the substrate and catch organic debris. In 1991, on the upper section, willow cuttings collected near the site were planted in rows of five perpendicular to the stream in a 0.5-m-wide band bordering the stream channel. A total of 250 cuttings were planted between the first five brush bars in the second group. An additional 130 cuttings were planted on a point bar without brush bars. Greenhouse-propagated containerized alder seedlings (from seed collected on site) were planted in rows of three perpendicular to the stream between two brush bars. On the lower section, in 1992, feltleaf willow cuttings collected near the site were planted in rows of five 1-m-long perpendicular to the stream, with three rows between each brush bar. Additional revegetation experiments were scheduled for 1993.

In order to assess the degree of success of the design, a comprehensive long-term monitoring program has been enacted on Glen Creek. Permanently monumented cross-sections have been established on the two test reaches to track changes over time in the channel and floodplain configuration. Additional cross-sections were also established for comparison purposes upstream and downstream of the reclamation work and in an undisturbed section of Spruce Creek, an adjacent watershed to Glen Creek. Table 2 provides descriptive information for six cross-sections used to monitor this project.

Surface bed material was periodically sampled to track changes in caliber over time. Size analysis was performed by a pebble count, in which the intermediate axis of 100 randomly picked particles are measured and the size distribution is expressed in percentage by number of particles (Leopold, 1970).

Table 2
Site characteristics of cross-sections used for long-term monitoring

Cross-section number	Site elevation (m)	Drainage area (km^2)	Channel slope (m/m)	Level of disturbance
1	900	2.2	0.0688	Undisturbed
2	760	11.2	0.0368	Mined
3	700	13.8	0.0242	Mined, restored 7/91
4	670	16.5	0.0224	Mined area, new channel constructed
5	645	17.2	0.0251	Mined diversion channel
6	900	2.93	0.0398	Adjacent stream, undisturbed

Additionally, sampling of benthic invertebrates, water chemistry, streambed material and suspended sediment was also incorporated into the long-term monitoring, being conducted jointly with the U.S. Geological Survey (USGS). A stream gage and weather station were located in the lower end of the Glen Creek watershed to provide pertinent hydrologic data.

4. Results

As the channel and floodplain work for the 1992 project neared completion, the Glen Creek study area experienced a moderate flood event. Flood peak discharge was calculated at 4.7 m^3/s on August 5, 1992 (the 5-year flood discharge is estimated at 4.4 m^3/s). This flood event and the resultant changes to the newly constructed channel and floodplains generated important preliminary information for this design project.

The major design goal was bed stability, which does not require bed immobility but rather occasional material movement and fluctuations in channel geometry about a long-term stable average (Andrews, 1982; Heede, 1986). However, at the time of construction we were concerned about bed instability and erosion potential in areas which had unconsolidated bank material and/or lacked an armour layer. Two areas presented special problems. In the lower study area, construction of the new channel segment passed through a section of undersized processed mine tailings, markedly decreasing the average size of the bed material and effectively eliminating the old bed armour layer which it replaced. Floodplain lowering in the upper study area uncovered additional sites of fine unprocessed tailings on the right bank adjacent to the stream channel. Both sites were protected with brush bars.

The passage of the August 5, 1992 flood event caused several significant changes to the channels in these areas. Severe bank erosion, channel widening and lateral migration of the channel were noted in both study areas. In the lower area along the new channel segment, enough erosion and lateral movement of this reach occurred to result in a slope decrease of almost 5%, with a corresponding increase in channel sinuosity. The erosion took place along the right bank, which was unprotected by alder brush bars (Cross-section 4, Fig. 5). Cross-section 3 in Fig. 5 also shows channel changes in the upper study area, which suffered bed and bank erosion and channel widening.

The first few brush bars in each group took the brunt of the flood. In the upper reach, the flood water eroded the floodplain in front of and the streambank under the end of, the first brush bar in each group and bent the brush bar around the resulting corner. This brush bar configuration prevented further erosion and remained stable throughout the remainder of the season, although the stream flow was now channeled against the front of the bar. On the lower reach, the first brush bar in the first group was entirely washed out and the second bar was bent around and stabilized the remainder of the floodplain. The first bar in the last group remained in place, but demonstrated the size and volume of bedload material
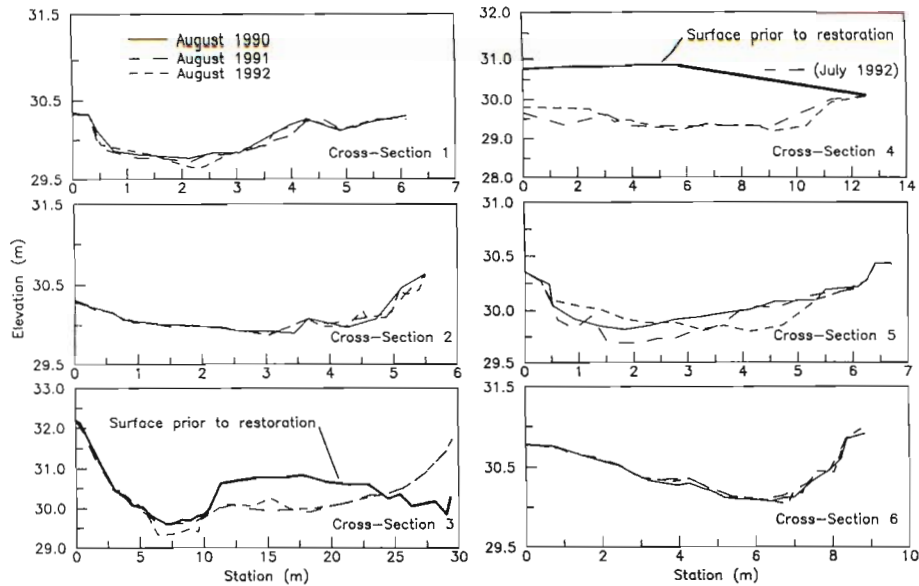
Fig. 5. Cross-section surveys along Glen and Spruce Creeks, from 1990 through 1992.

moving during the flood. Cobbles (to 20 cm) and gravel were deposited in front of and over the bar, to a depth of 0.5 m.

Floodwater cut behind most of the brush bars on the upper section, where the bars were three stream widths apart. The floodplain area containing the last three bars on the upper section was highly erodible tailing material. In this section a new channel was cut behind the brush bars, creating an island. Some deposition occurred in the upper reach, but much of the material was reworked and eroded by the floodwater flowing behind the bars and back into the stream between bars.
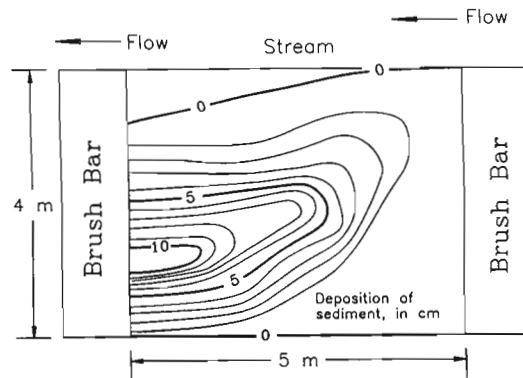
Fig. 6. Typical sediment deposition depths, in cm, for brush bars spaced one channel width apart along new channel reach.

Table 3
Stream bed material D_{50}, in mm, of six cross-sections before and after the August 5, 1992 flood

Cross-section	Sampled Aug 1990	Sampled Aug 1991	Sampled Aug 1992
1	23	36	24
2	15	14	16
3	16	34	22
4	–	17 [a]	44
5	23	35	17
6	25	29	24

[a] Sampled July 1992, immediately after construction of new channel.

Floodwater cut behind only the first few brush bars in each group on the lower reach, where the bars were only one stream width apart. Substantial amounts of sediment were deposited on the floodplain where water did not run behind the bars. Cross-section 4 in Fig. 5 shows substantial deposition on the left bank (where the bars were located). Fig. 6 depicts the average deposition of material adjacent to brush bars installed along the new channel section.

In mined reaches where no active floodplain or channel restoration took place, bed and bank instability was apparent, with significant channel movement during the first two years of monitoring (Cross-section 5, Fig. 5). The two control reaches in upper Glen and Spruce Creeks remained relatively stable during this same period (Cross-sections 1 and 6, Fig. 5).

Inundated circular depressions were very effective at trapping sediment, and average particle size was smaller than the sediment trapped by the brush bars.

The bed material caliber changed significantly as a result of the flood. Bed material sampling was conducted just before and after the flood at the lower study area and annually at all other permanently monumented cross-sections. The change in the D_{50}, or diameter at which 50% of the bed particles are finer by size, is shown for the six cross-sections before and after the flood in Table 3.

Before the flood, one year after planting, the willows and alders had high survival (78% and 92% respectively) and well-developed root systems. Nevertheless, all the willows on the point bar without brush bars were washed out. All of the willows between the first and second brush bar and approximately 40% of the willows between the second and third brush bar were washed out, but willows further down the point bar were not affected. One-third of the alder seedlings were washed out.

The willow cuttings effectively captured leaves, twigs and other organic debris.

5. Discussion

Natural river channels (disturbed and undisturbed) are extremely dynamic in nature and present a number of difficulties when designing for channel and floodplain geometries. 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). As these variables change during mining (and reclamation), changes in channel geometry should be expected.

For example, our original design did not account for the severe change in bed caliber for the new channel repositioned through the undersize sorted mining tailings. Investigators have found that slope changes may be attributed to bed material changes (Hey and Thorne, 1986). This may reflect the slope and sinuosity changes of the new channel reach, in which much coarser material was deposited as a result of the August 5, 1992 flood (Table 3).

The difficulty in estimating several other design variables probably led to additional channel changes in the test reaches. Without long-term discharge records, regional estimations of flood magnitudes may have been inaccurate. The estimations of ideal slope and sinuosity values are difficult tasks in an area which has undergone substantial mining and channelization for the past 80 years. The presence of permafrost in the watershed and the absence of functioning flood-plains along most of the channel length, probably resulted in a much 'flashier' flood hydrograph than we expected.

The development and use of alder brush bars in this project served two purposes. The first purpose was to encourage sediment deposition in areas where riparian area fines were absent as a result of mining processes. The second purpose was to stabilize and protect newly constructed and unvegetated flood-plains during large flood events.

A dominant discharge is that discharge of a given magnitude occurring at a given recurrence interval which shapes the river channel to accommodate it. Leopold and Wolman (1957) attribute the dominant discharge to the bankfull discharge. Through such smaller flood discharges and with the removal of the 'incised' condition, the channel has the ability for adjustments not accounted for in the design and construction process. We do not wish to impede this ability for self-adjustment by building permanent, rigid control structures such as rock-filled gabions on the floodplains. However, larger 10- to 20-year floods have enough erosive potential to cause major damage to newly constructed channels and floodplains and must be protected against until floodplain vegetation is reestablished. The alder brush bars seem to provide an adequate solution to this problem, offering some floodplain protection and a means to encourage sediment deposition while remaining a temporary structure constructed of native, biodegradable materials. The 'bulldozer circular depressions' were effective at trapping sediment, but will not provide much erosion protection in a large flood.

Reclamation project design involves deciding where to rely on natural recovery and where and how to manage recovery by altering or avoiding controlling factors to modify the pattern or increase the rate of ecosystem development. Effective reclamation requires knowledge of the structure and function of mined and unmined riparian ecosystems and the pattern and rate of natural recovery from natural and mining disturbances. This project design attempts to balance technique effectiveness with cost efficiency. The risk of failure will decrease with time,

as revegetation occurs and channel banks and floodplains evolve to a stable condition.

Much of the existing information on mine reclamation is not applicable to National Parks and many common mine reclamation practices are inappropriate for National Parks. The mandates of the NPS emphasize minimum interference in natural ecosystem processes. This design has been guided by those mandates.

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