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# The effects of woody debris on sediment fluxes in small coastal stream channels



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**Information Report BC-X-367**
**Pacific Forestry Centre, Victoria, B.C.**

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# Contents

Abstract

Two first-order streams located on the south coast of British Columbia were studied to determine the role of woody debris in controlling the routing and storage of sediment within high gradient channels in logged areas. The removal of logging slash from one of the two channels resulted in a reduction in the trapping and storage of sediment compared to the control channel over a one-year period following logging. For the control, the steps created by the woody debris provided storage locations and reduced the transport of sediment, especially the larger sizes. About 37% of the sediment inputs were stored in the treated channel, whereas 66% of the sediment inputs were stored in the control channel. The remainder of the sediment inputs went through each channel. The sediment storage potential within the channels was limited, and in this study, the debris storage sites were filled in the first year following logging. Bedload (including some sediment transported in suspension but deposited within the weir/box) represented 30-35% of the total outputs for each channel. Over 90% of the bedload was finer than 2 mm for the control channel, whereas less than 40% consisted of particles finer than 2 mm for the treated channel. The role of woody debris in reducing stream sedimentation is briefly discussed.

# Résumé

Nous avons étudié deux cours d'eau primaires situés dans la partie sud du littoral de la Colombie-Britannique pour déterminer l'effet de débris ligneux sur le transport et l'accumulation des sédiments dans des cours d'eau qui s'écoulent en pente raide dans des secteurs forestiers en exploitation. L'enlèvement des rémanents dans l'un de ces cours d'eau a donné lieu, dans l'année qui a suivi la coupe, à une réduction de la quantité de sédiments captés et emmagasinés. Cela n'a pas été le cas dans le tronçon-témoin où les gradins créés par l'empilement des débris ligneux freinaient le transport et favorisaient la sédimentation, notamment des particules plus grossières. Environ 37% et 66% de la charge sédimentaire ont été stockés dans le tronçon aménagé et dans le tronçon-témoin, respectivement. Le reste a été entraîné en aval. Ces cours d'eau ont un potentiel limité d'emmagasinement des sédiments et, dans notre étude, les sites d'accumulation se sont saturés dans l'année qui a suivi l'exploitation. La charge de fond (notamment une partie des matières en suspension qui se sont déposés dans le piège à sédiments) correspondait à 30-35% de la charge totale de chaque tronàon. Dans le tronçon-témoin, les particules ayant un diamètre inférieur à 2mm constituaient plus de 90% de la charge de fond alors quíil y en avait moins de 40% dans l'autre. Le rapport traite sommairement de l'importance des débris ligneux dans la réduction de la sédimentation dans les cours d'eau.

# Foreword

ENFOR is the acronym for the Canadian Forest Service's ENergy from the FORest (ENergie de la FORêt) program. This program of research and development is aimed at securing the knowledge and technical competence to facilitate in the medium to long term a greatly increased contribution from forest biomass to our nation's primary energy production. It is part of the federal government's efforts to promote the development and use of renewable energy as a means of reducing dependence on petroleum and other non-renewable energy sources. The ENFOR program is concerned with the assessment and production of forest biomass with potential for energy conversion and deals with such forest-oriented subjects as inventory, harvesting technology, silviculture, and environmental impacts. Most ENFOR projects, although developed by Canadian Forest Service scientists in light of program objectives, are carried out under contract by forestry consultants and research specialists. Contractors are selected in accordance with science procurement tendering procedures of the Department of Supply and Services. For further information on the ENFOR Biomass Production Program, contact:

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# Introduction

In mountainous watersheds of coastal British Columbia, soil erosion can be high on sites where timber harvest has taken place. This results from steep slopes, high rainfall, and relatively cohesionless and thin soils. Much of the erosion occurs as soil mass wasting, and can include debris flows and torrents, landslides (e.g., slumps and debris slides) and soil creep (Ryder 1983). Surface soil erosion can also occur on areas of exposed mineral soil within clearcut areas, but is more often associated with forest roads (Standish *et al.* 1988). Not only is there a potential reduction in site productivity due to the loss of soil materials (Swanson *et al.* 1989), but eroded sediment can have serious off-site impacts on streams and lakes, including changes in water quality, reduced habitat quality for fish and benthos, clogging of water works, and impairment of recreational opportunities.

Although soil loss rates (Dietrich and Dunne 1978; Swanston 1991) and stream sedimentation (Brown and Krygier 1971; Beschta 1978) have been documented in some coastal watersheds, the processes responsible for the generation, transport, storage and delivery of sediment in these watersheds are not well understood. Only a few studies have examined sediment storage and delivery processes in first and second order channels. Smith *et al.* (1993) observed a fourfold increase in bedload transport in a second-order low gradient stream located in southeast Alaska after the experimental removal of woody debris. A study by Duncan *et al.* (1987) examined the transport and storage of road-surface sediment in steep second-order ephemeral stream channels in southwestern Washington State. Woody debris was found to be very effective at trapping sediment, especially the coarse-size sediments (> 0.063 mm). Although not in a coastal environment, some relevant research has been conducted in Idaho (Johnejack and Megahan 1991; Ketcheson and Megahan 1991) in relatively undisturbed (i.e., disturbed only by road building) first-order channels. The Idaho researchers examined the effects of step-pools, boulders, logs and brush on sediment transport and storage. They found that the major sediment storage sites were located behind the steps created by woody debris. Transport through the channels was proportional to “effective” gradient and flow rate. The effective gradient was defined as the gradient of the stream bed, not including the vertical steps created by the large woody debris.

One of the major unknowns in the study of sediment transport through harvested areas is the role of waste biomass or slash. Considerable volumes of woody slash are often left behind following harvest, due to wood quality considerations or harvest logistics. However, advances in harvesting technology, higher utilization standards or increased demand for slash as fuel, may lead to significant reductions in the volumes of slash left on site. Since such reductions may have implications for patterns of sediment entrainment and transport, a need exists to quantify the effects of slash on sediment movement through harvested areas.

The objective of the study was to determine the effect of waste biomass left in channels following harvesting on patterns of sediment movement in steep first-order channels.

# Methods

A case study of treated and untreated (control) channels was conducted. Two similar channels were selected for study, one was designated Treated (slash removed from the channel prior to start of experiment) and the other was designated Control (no modification to channel following harvest). Over the course of the study, sediment inputs to, movement through, and outputs from the two channels were compared quantitatively, on the basis of the sediment budget equation:

$$QS_{in} - QS_{out} = \Delta S / \Delta t \qquad [1]$$

where:

$QS_{in}$ = rate of sediment input to a channel
$QS_{out}$ = rate of sediment output from a channel
$\Delta S$ = change in sediment storage within a channel
$\Delta t$ = time period

## Study area

The stream channels that were selected for the study are located within Cutblock 12-49 of Weldwood of Canada, Empire Logging Division Tree Farm Licence 38. This site is located about 30 km northwest of Squamish, British Columbia (lat. 49°57', long. 123°25'), within the Ashlu Creek watershed, a tributary of the Squamish River (Fig. 1). The site is within the Coastal Western Hemlock biogeoclimatic zone of British Columbia and is characterized by a wet humid climate with cool summers and mild winters (Green and Klinka 1994). The nearest Environment Canada climate station (20 km northwest of study site) having a similar elevation to the study site, Daisy Lake Dam (elevation 380 m), has a mean annual temperature of 6.4°C (1951-1980 average) and a mean annual precipitation of 2054 mm with 383 mm falling as snow (Atmospheric Environment Service 1982).

The study area was located in the upper part of the cutblock and was clearcut harvested in Spring 1991 (Fig. 2). Grapple yarding (85%) and high lead (15%) were used to harvest western red cedar (*Thuja plicata* Donn), Douglas-fir (*Pseudotsuga menziesii* (Mirb.) Franco var. menziesii), with some western hemlock (*Tsuga heterophylla* (Raf.) Sarg.). The roads located within the study area were constructed in the fall of 1989. The stream channels are located on a south-facing slope, and the test reaches are found at elevations between 485-505 m, and 550-575 m, for Treated and Control, respectively, immediately below the main road (Fig. 2). Prescribed burning was carried out at the site on October 8, 1992. A cut-off date of September 29, 1992 (last sampling trip before prescribed fire) was used when constructing sediment budgets.

The bedrock on the site is primarily intrusive plutonic rocks, including quartz diorite and granodiorite (J.A. Roddick and G.J. Woodsworth 1979. Geology of Vancouver map area; west half. Geological Survey of Canada. Open file report 611. Vancouver, B.C.). A thin mantle of morainal material covers the site, and bedrock outcrops are common. Mineral soils are coarse-textured Brunisols and Podzols, with small pockets of organic soils associated with surface seeps.

The Control reach was 59 m in length, whereas the Treated reach was 49 m in length. The channels are 60 to 100 cm wide and 15 to 30 cm deep at bankfull stage. Average stream discharge varies between 3 and 12 L/s, and peak discharges up to 50 L/s are not unusual. The Treated stream banks are mostly well-vegetated and humus covered, and moderately sloped (20-30% gradient). The upper part of Control traverses a bouldery area, whereas the stream banks along the middle to lower sections are well-vegetated gentle slopes (10-20% gradient). The substrate in the upper part of Treated is a thin layer of coarse sand and gravel on bedrock, while in the lower part of the reach the stream runs over bedrock. The Control reach substrate is mostly composed of mineral materials similar in texture to the upper part of Treated.

The volume of slash removed from the Treated channel and adjacent stream banks on September 10-12, 1991 equaled 610 $m^3$/ha or 0.13 $m^3$ per m of channel, and included everything down to fine slash (≥ 1.0 cm diameter). The large woody debris (≥ 10 cm diameter) had a mean diameter of 35 cm (SE = 2.9 cm) and was 0.65 to 3 m long (mean = 1.7 m, SE = 0.14 m). The volume of woody debris in the Control channel was estimated by measuring all the slash found within a random sample of five 3-m-wide by 2-m-long plots located within the test reach. The volume of debris was 900 $m^3$/ha or 0.20 $m^3$ per m of channel, assuming an average floodplain width of 2.2 m. On average there were 13 pieces of woody debris per m of channel. The debris were 3 cm to 72 cm in diameter (mean = 17 cm, SE = 1.3 cm) and 0.08 m to 4.4 m long (mean = 0.71 m, SE = 0.06 m).

The drainage areas of the Control and Treated watersheds above the test reaches (as determined from 1:4800 topographic maps) are approximately 7.4 and 7.0 ha, respectively. The overall slope of the Control watershed is 56%, whereas the overall slope of the Treated watershed is 47%. The slopes of the two test reaches are very similar, 41% for Control and 40% for Treated. Both streams originate from surface seeps located just above the cutblock. Two roads (upper and main) cross the creeks. The Control Creek flows across the upper road and through a culvert where it crosses the main road. The Treated Creek flows across both roads (no culverts). A temporary bridge was constructed where Treated crosses the main road to minimize channel disturbance due to vehicular traffic during the study period. Both channels receive inflow from roadside ditches located along the main road.

## Monitoring system

The methods to quantify each of the sediment budget elements are summarized in Table 1 and described below (Fig. 3). Rainfall (two Weathermeasure model 6011-B tipping-bucket rain gauges) was measured at a site halfway between the Control and Treated channels and was used to help explain patterns of sediment production and channel discharge.

## Sediment storage

Two methods were employed to quantify sediment movement and changes in sediment storage in the Control and Treated channels: cross-sectional channel profiles and bedload tracers.

### Cross-sectional surveys

At approximately 3-m intervals along each reach, cross-sectional profiles were measured using a transit and survey rod prior to the start of the experiment (October 1991) and following the first winter of operation (March 1992). The survey grids consisted of 19 and 18 cross-sections, respectively, for Control and Treated. Changes in sediment storage were determined by comparing profiles taken at each section between surveys. The change in cross-sectional area was designated as either aggradation (average increase in surface elevation along cross-section) or degradation (decrease in surface elevation). The change in cross-sectional area of each cross-section was multiplied by the length of channel represented by the cross-section to arrive at a change in volume. The changes in volume were then summed over the length of the test reach to obtain the change in storage. A sediment density of 1 Mg/$m^3$, which is comparable to the density of bedload collected in the Control (mean = 1.06 Mg/$m^3$) and Treated (mean = 1.25 Mg/$m^3$) weirs, was used to estimate mass of sediment from volume.

### Bedload tracers

To quantify sediment movement, two sizes of coloured tracer sediments were placed in both stream channels on November 18, 1991. Small cobbles with diameters ($D_{50}$) of 65 mm (SE = 1.5 mm) and 51 mm (SE = 1.6 mm) for the long and short axes, respectively, were painted, numbered and placed at each cross-section in each reach (19 in Control and 18 in Treated). Three additional cobbles were placed in the deposition zones above and below the ditch along the main road, and four were placed in the ditch. 2.5 kg of fine gravel (coloured aquarium gravel) with a diameter ($D_{50}$) of 6 mm was placed at two locations in each channel and in each roadside ditch (Fig. 4). An assessment of the movement of these materials was done 3 weeks, 13 weeks (gravel only), and 24 weeks (cobbles only) following placement.

## Sediment outputs

A combination sediment box and weir measuring 90 cm wide by 90 cm deep by 240 cm long was installed at the downstream limit of each test reach (Fig. 5a). The boxes were set into the stream channels so that water flowed through the box and out through a 90° V-notch cut out of the front plate. The sediment box/weir acted as a sediment trap and collected all material that dropped out of the flow. The sediment trapped in the sediment box/weir was surveyed and cleaned out periodically and samples were collected for bulk density and particle size distribution analysis.

In order to estimate suspended sediment yield, stream discharge and suspended sediment concentration were measured at each weir. The water level (stage) at each weir was measured with a mercury manometer water level recorder. The Treated recorder was installed on December 5, 1991, whereas the Control recorder was installed on February 6, 1992. Both weirs were also equipped with a gauge pressure transducer (Vernitech 0-3 PSIG model 4000) such that stage was recorded electronically. A CSI 21X data logger was used for program control and data storage, and also to activate a tipping bucket/flow splitter mechanism for the collection of suspended sediment samples (Fig. 5b). The data logger controlled the frequency of sampling which was proportional to stage (and hence discharge) in the sediment box/weir. The frequency of sampling ranged from 1 sample every 2 hours at low flow rates (< 2.5 L/s) to 20 samples per hour at high flow rates (≥ 60 L/s). The samples were routed through a PVC pipe to a 200-L barrel to form a composite sample from which a sub-sample was collected for analysis each month. The sub-sample was taken after the water/sediment mixture in the barrel was thoroughly aggitated with a specially designed paddle. The suspended sediment sampler at the Treated weir was installed on December 5, 1991, whereas the suspended sediment sampler at the Control weir was not installed until August 26, 1992.

The discharge equation for a 90° V-notch weir was used to convert the stage data into discharge data. Suspended sediment yield was calculated by multiplying total period flows (Appendix 1) by the average suspended sediment concentration of the proportional samples collected in the barrels.

In addition to the automated suspended sediment sampling, duplicate 1-L samples were obtained monthly at the weir outflows. Stage, crest gauge stage (highest water level over a given period of time) and flow rate were recorded manually at the time of sampling. The crest gauges were made of 1 cm outside diameter tygon tubing fitted with a floating styrofoam plug that wedged in the tube when the water level dropped. The crest gauges provided back-up data for the automatic stage recording instruments. Flow was measured by timing the rate of filling of a 200-L barrel.

## Sediment inputs

For each channel, several potential sources of sediment were identified: the creek upstream of the road, the roadside ditch, the road surface and the cutblock surface adjacent to the test sections. The contribution from each of these potential sources was estimated. Because of the difficulty in measuring sediment inputs from this complex of sources, total inputs were quantified as the sum of the output and storage terms. Sediment sampling was used to estimate the relative importance of surface erosion from the roadside ditch, the road surface and the cutblock surface, and for determining particle size distribution.

A number of small aperture sediment traps (Wells and Wohlgemuth 1987) were installed on October 18, 1991 within each stream channel catchment. The 30 cm wide by 20 cm deep by 15 cm high traps were made of galvanized sheet metal and were installed to lie flush with the soil surface. Six were installed in the Control basin with two on the road surface and four on the road cutslope (Fig. 4). Seven were placed in the Treated basin with one on the road, four on the cutslope and two on the soil surface above the cutslope. The road surface traps were placed on the running surface of the road. The sediment supply from the cutblock surface adjacent to the test reaches was assumed to be zero. The traps were cleaned approximately once every month and the sediment samples were dried and weighed. For the cutslope, a measured average contributing area of

0.3 $m^2$ was used to convert the mass of sediment captured by the traps into mass per area (kg/ha). The measured cutslope area contributing to each stream (0.01 ha) was used to estimate cutslope sediment inputs to Control and Treated. A sub-sample of the trap samples was analyzed for particle size distribution.

Arrays of erosion pins were installed within the ditches along the main road to assist in determining the fate of sediment introduced to the ditch from the road cutslope (Fig. 4). Each array was made up of five 20-cm spikes equipped with washers and installed to a depth of 10 cm. Depth of net erosion or deposition over time was determined by measuring the distance the washer dropped below a notch or by measuring the depth of sediment lying over the washer (Hudson 1981). These measurements were taken monthly.

# Results

## Precipitation

In general, the mean monthly and total annual precipitation values obtained at the research site were similar to the 30-year averages for the Environment Canada Station at Daisy Lake Dam (Appendix 2). The total precipitation from January 1 to December 31, 1992 was 2280 mm, which compares to the average annual precipitation of 2054 mm at Daisy Lake Dam. Major differences between the monthly means during the study period and historical monthly means occurred in January 1992 (720 mm versus 297 mm mean at Daisy Lake) and December 1992 (140 mm versus 341 mm mean).

Because of missing climate station data associated with equipment malfunction or the prescribed fire (October 10 to December 5, 1991 and October 1 to 21, 1992), the Squamish STP climate station (Atmospheric Environment Service 1994) precipitation data for the period October 1991 to December 1992 was used to estimate missing data for Ashlu Creek for the months of October to December 1991, and October and December 1992. Although the Squamish STP station is located at a lower elevation than Ashlu Creek, this station was used rather than the Daisy Lake Dam station because, during this time period, storm tracks better matched the Ashlu Creek site and reliable estimates of missing data could thus be obtained.

## Stream discharge

Stream discharge at Treated was highly responsive to daily precipitation. Daily peak discharge was as high as 58 L/s, and greater than 10 L/s on nearly half the days (44%) during the wet 2-month period of December 5, 1991 to February 5, 1992 (Fig. 6). Average discharge was greater at Treated compared to Control during the wet fall and winter months, but similar during the spring and summer low flow period (Fig. 7).

## Sediment storage

### Cross-sectional surveys

Both channels experienced aggradation between October 1991 and March 1992. Channel width changes as a result of aggradation were relatively minor. Storage of sediment amounted to 9.69 $m^3$ for Control and 2.55 $m^3$ for Treated (Appendix 3). The sediment storage in Control is reasonable considering the maximum possible storage volume that could be provided by the slash. Assuming a mean piece length of 0.71 m and diameter of 0.17 m, 41% slope, 13 pieces/m, and a 59 m reach, the maximum possible volume that could be trapped if all pieces were perpendicular to the stream is about 19 $m^3$. Control trapped more than three times as much sediment per m of channel than did Treated (0.164 $m^3$/m versus 0.052 $m^3$/m). This result is consistent with the visual observation that the small sediment storage sites located behind organic debris jams in the Control channel were filling during this period. Conversely, relatively few sediment storage locations existed in the Treated channel. Photographs and observations made between March and September 1992 suggest that the channels remained in a state of approximate dynamic equilibrium after the initial period of sediment accumulation.

### Bedload tracers - fine gravel

Movement of the fine gravel placed at mid-length in the reach on November 18, 1991 occurred in both Control and Treated. In Control, much of this gravel was trapped behind boulders and woody debris, although some was found in the weir box. Since much of the lower Treated channel is bedrock, it can be reasonably assumed that virtually all the gravel was transported to the weir.

The most significant movement of tracer gravel was the complete removal of gravel that was placed in the Control channel below the upper road. The gravel was discovered in the deposition zones both above and below the main road at the head of the test section of the channel. The movement occurred between December 10, 1991 and February 18, 1992, likely at the same time as the event which resulted in the deposition of the large amount of fine sediment in the Control weir box. The cutslope above the upper road is the site of several seepage zones and is the source of Control Creek. The seeps saturate the cutslope sediments, increasing the potential for erosion during rainfall events.

None of the gravel placed in the Treated channel below the upper road moved to the main road. There was only slight movement of the gravel placed in the road ditches near the test reaches. It appears that the series of micro-dams and pools in these ditches was effective at trapping this gravel-sized sediment.

### Bedload tracers - cobbles

Three weeks after placement, all 18 cobbles in Treated had moved, and the majority were eventually found in the weir box. In Control, only 5 out of 19 had moved and the maximum distance moved was 1 m. Four cobbles were not found, suggesting that they had been buried with sediment or organic debris, since no cobbles were found in the weir box. Only one cobble was found in Control 24 weeks after placement, yet none was found in the weir box. It appears that the Control cobbles moved some distance downstream in most cases, and likely became wedged among the coarse woody debris in the channel and eventually were buried by sediment.

## Sediment outputs

### Suspended sediment yield

In this report, suspended sediment refers to sediment which passed through the weir (since it was sampled manually at the outflow or automatically from a location adjacent to the outflow). Suspended sediment thus represents a subset of the sediment which traveled to the weir in suspension, some of which deposited in the weir.

The total suspended sediment yield at Treated for the time period December 5, 1991 to September 29, 1992 was 1,579 kg (Table 2, Fig. 8). A suspended sediment load of 1,277 kg for the first 8 weeks (October 10 to December 5, 1991) at Treated was estimated from the regression of suspended sediment yield (SS) versus bedload yield (BED) for the period during which coincident data were available (SS = 161.2 + 1.109 BED, $r^2 = 0.86$). The suspended sediment sampling equipment at Control was not operational until late August, 1992. The suspended sediment to bedload ratio for Treated (2.26) over the period December 5, 1991 to September 29, 1992 was applied to the bedload yield at Control to obtain an estimate of the total suspended sediment yield for the October 10, 1991 to August 26, 1992 period (3,298 kg). This estimate is considered conservative since the ratio of suspended sediment to bedload at Control should be greater than at Treated because of the trapping of coarse sediment behind the woody debris. For the time period August 26 to September 29, 1992, the measured suspended sediment yield at Control was 313 kg.

### Bedload yield

The sediment trapped in the weirs included both sediment which traveled as bedload and a portion of the sediment which traveled in suspension.

Bedload began accumulating in the Treated weir immediately following installation, whereas very little accumulation was observed over the first 8 weeks in the Control weir (Fig. 9). Between 9 and 17 weeks, a large pulse of sediment (1091 kg) was deposited in the Control weir, an event which was not observed at Treated. During this time period, daily precipitation exceeded 50 mm on five occasions and resulted in peak discharge generally exceeding 25 L/s (up to 43 L/s) as recorded at the Treated weir (Fig. 6). The Control stage record is not reliable (chart recorder malfunction) over this time period. Based on the three times when coincident data were recorded manually during higher flows (Table 3), it appears that peak discharges at Control are lower than those observed at Treated during larger precipitation events. Thus, between 9 and 17 weeks, the Control peak flows were probably somewhat smaller than the Treated flows, yet large enough to result in much greater sediment movement as evidenced by the sediment trapped in the weir box. This event (or events) represented over 70% of the total bedload trapped in the Control weir over the entire study, and brought the cumulative bedload sediment yield of Control (1320 kg) to virtually the same level as recorded at Treated (1385 kg) at 19 weeks.

For the last 32 weeks of the study, sediment accumulation in each weir was approximately equal, such that for the full study period (to September 29, 1992), 1519 kg was recorded in the Control weir and 1559 kg was recorded in the Treated weir.

### Bedload particle size distribution

A clear difference between Control and Treated was the lack of bedload particles greater than 8 mm for Control, whereas particles greater than 8 mm accounted for 30-50% or more in some cases for Treated (Appendix 4).

## Sediment inputs

### Sediment traps

Sediment input estimates from the sediment traps are summarized in Table 4. In general, more sediment was collected from the cutslope than from the road surface, and more sediment was collected from the road surface than from the hillslope. Approximately five times more sediment was produced from the cutslope above the Treated (1.13 Mg) than the Control cutslope (0.21 Mg) during the one year sample period. While the Treated cutslope showed a relatively consistent pattern of sediment input during the study period, with the rate decreasing somewhat during the drier months of 1992, the input rate at Control slowed considerably during the study (Fig. 10). In general, the Control cutslope had greater plant cover than the Treated cutslope, particularly with respect to the growth of mosses.

### Erosion pins

During the period October to December 1991, the erosion pins did not indicate any significant (> 0.5 cm) net erosion or deposition in the ditches beside the main road. In February 1992 both Control and Treated ditches showed very small amounts of net deposition (≤ 0.5 cm). By May 1992 the weighted average depth of deposited sediment in Control had increased to 1.4 cm (SE = 1.04 cm), but this value was not significantly different than zero. No data are available for Treated in May because the erosion pins were missing at that time. Overall, the erosion pin data suggest that the roadside ditches are neither a significant source nor sink or sediment, but rather are in a state of general equilibrium, and that all sediment introduced from the cutslopes into the ditches entered the test reach of each channel.

### Sediment budget

A sediment budget was constructed for the one year period of October 10, 1991 to September 29, 1992 (Table 5). The generation and transport of the relatively large mass of sediment in Control was the most significant event over the monitoring period. As a result, the total inputs to Control (14.8 Mg) were considerably higher than to Treated (7.0 Mg). Sediment inputs suggested by the budget approach are much larger than estimated from the sediment traps, which implies that sediment inputs via the stream channel from sources upstream made up a larger proportion of the total inputs. Sixty-six percent of the Control inputs went into storage (9.7 Mg), compared to 37% for Treated (2.6 Mg). The difference between these two figures is attributable to the trapping effects of the woody debris in the Control channel.

## Discussion and Conclusion

By employing a sediment budget approach, an attempt was made to quantify inputs, outputs and changes in storage in the test reaches of two creeks, one containing logging debris and one cleared of logging debris. However, the reliability of measurements of sediment outputs was greater than measurements of inputs because of the distributed nature of the inputs. Measurement of channel storage changes were of intermediate reliability. Although outputs were easier to determine, differences in the timing of installation of the continuous suspended sediment sampling apparatus lead to a better record of sediment outputs at Treated than at Control.

Measurements of bedload and suspended load transport rates indicated that the bedload portion represented in the order of 30-35% of the total load (in this study, bedload included some sediment transported in suspension). This figure is consistent with expectations of small, high-gradient mountain streams affected by logging (Church *et al.* 1989), in which the bedload component assumes a relatively large proportion of the sediment load.

Over the 1-year study period, the main road cutslopes provided less than 1 Mg of sediment to each channel on average (Control = 0.2 Mg; Treated = 1.1 Mg). Therefore, the main source of sediment was the inflowing channel at the head of each test section. The development of sediment rating curves for these input channels was not possible with the limited number of water samples collected. Thus, it was necessary to estimate sediment inputs by residual calculation (i.e., Inputs = Outputs + DS). Since measurement of sediment inputs via the channel is virtually impossible without interrupting the rate of sediment supply to the test reach, reliable sediment rating curves will be required in future studies. One approach would be the deployment of automatic pumping samplers for the collection of water samples at various flows, from which a sediment rating curve could then be developed. Another approach would be to measure turbidity, essentially a surrogate property, with the use of electronic turbidity sensors. Turbidity could then be related to suspended sediment, but this would still require the collection of numerous water samples with which to develop a suspended sediment-turbidity curve.

Notwithstanding the difficulties encountered in collecting data over the course of the study, comparisons between Treated and Control in terms of general trends and effects of woody debris on channel storage and routing are still possible. The rate of sediment input to the Control channel exceeded that at Treated, primarily because of the presence of a single significant sediment source on the upper road cutslope. This resulted in a large pulse of sediment during one or more events in early 1992.

Observations of the rates of transfer of gravel and cobble-sized tracers during the early part of the study period indicated that transport was significantly slower in the Control channel, since the steps created by the organic debris provided greater opportunity for trapping and storage. For this reason, Control experienced greater aggradation of sediment than Treated. Opportunities for sediment storage were much less in the Treated channel because woody debris was no longer available for trapping and storage. The visual observation that no further aggradation occurred in either channel after the second channel survey (March 5, 1992) suggests that the sediment introduced up to that point was sufficient to fill the available storage.

Discharges recorded in each channel were similar during low flow periods, but discharge at Treated appeared to be significantly greater than at Control during the wet winter months, particularly during larger precipitation events. Thus, the Treated channel may have experienced greater transport capabilities and, therefore, less probability of sediment deposition during high flow events compared to the Control channel. However, at least some of the differences observed in sediment transport and storage in the two channels are attributable to the removal of woody debris in the Treated channel.

During the first two months of the study, very little sediment was conveyed to the Control weir, whereas the Treated weir recorded significant sediment accumulations. This observation is consistent with the interpretation that sediment storage locations in the Control channel were still filling during this time. The major pulse of sediment introduced to Control in early 1992 virtually filled the weir box (1.97 $m^3$ volume). Following this period, sediment delivery to the weirs occurred at approximately equal rates. This supports the hypothesis that storage locations were filled, that further channel aggradation did not occur in any great measure, and that sediment input rates were approximately equal.

Differences in the size distribution of sediment trapped in each weir were apparent, and these differences remained consistent throughout the study. The differences between Control and Treated cannot be attributed to differences in the size distribution of the input sediment. The two contributing cutslopes were similar with respect to soil type, and the beds of the two channels upstream of the test sections each contained sand, gravel and cobbles. These observations confirm that the steps created by organic debris jams reduced the ability of the flows to transport the larger sizes of available sediment in the Control channel. Reduced transport of coarse sediment continued despite the filling of the storage locations, because the reduced slope behind the jams allowed deposition of, and continued to prevent the entrainment of, coarser material.

The results suggest that slash left in first-order streams restricts the movement of coarse sediments until the storage sites are filled. In this study the storage sites in the Control stream were probably filled in the first winter following harvest. Steps and micro-dams caused by debris accumulation mainly trap coarse sand, gravel and cobbles. The study suggests a benefit from leaving slash in first-order channels, to reduce the risk of transport of large sediment generated within harvested areas to higher order streams. However, the ready transportability of fine sediment, even in slash-filled channels, indicates that preventing the generation and transport of sediment at source areas should continue to remain a priority to prevent degradation of downstream habitats and water quality.

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**Table 1. Summary of monitoring system used in Control and Treated channels**

| Component | Element | Primary Measurement | Backup Measurement |
|---|---|---|---|
| $QS_{sin}$ (sources) | ■ total<br>■ road<br>■ cutslope-ditch<br>■ creek | ■ sum ($QS_{out} + \Delta S$)<br>■ sediment traps<br>■ erosion pins<br>■ discharge and suspended sediment concentration | ■ ditch discharge and suspended sediment concentration |
| $\Delta S$ (storage) | ■ channel | ■ cross-sectional surveys<br>■ tracer gravel<br>■ tracer cobbles | ■ channel photos |
| $QS_{out}$ (outputs) | ■ discharge<br>■ bedload<br>■ suspended load | ■ continuous stage record + rating curve<br>■ volume, density and size distribution of trapped sediment<br>■ continuous integrated sampling of suspended sediment concentration | ■ suspended sediment rating curve |
| Climate | | ■ precipitation (tipping bucket gauge) | |

**Table 2. Total period discharge, average suspended sediment concentration, and suspended sediment yield**

| Time Period | No. of Weeks | CONTROL | | | TREATED | | |
|---|---|---|---|---|---|---|---|
| | | Est. Total discharge ($m^3$) | Average Sediment Conc. (mg/l) | Total Yield (kg) | Total discharge ($m^3$) | Average Sediment Conc. (mg/l) | Total Yield (kg) |
| Dec. 5, 91- Feb. 5, 92 | 9 | 23,385 | | | 41,217 | 7.07 | 291.4 |
| Feb. 5 - Mar. 5, 92 | 4 | 7,985 | | | 6,012 | 81.1 | 487.6 |
| Mar. 5 - May 13, 92 | 10 | 19,157 | | | 14,912 | 29.3 | 436.9 |
| May 13 - June 16, 92 | 5 | 9,019 | | | 5,230 | 1.41 | 7.4 |
| June 16 - Aug.26, 92 | 10 | 21,074 | | | 20,584 | 13.1 | 269.7 |
| Aug. 26 - Sep. 29, 92 | 5 | 9,626 | 32.5 | 312.8 | 8,137 | 10.6 | 86.3 |
| | | **TOTAL** | | 313 | | | 1579 |

**Table 3. Coincident higher flow measurements at Control (QC) and Treated (QT)**

| Date | $Q_C$ (L/s) | $Q_T$ (L/s) |
|---|---|---|
| December 5, 1991 | 7.1 | 15.4 |
| January 10, 1992 | 8.7 | 18.6 |
| April 16, 1992 | 4.2 | 13.5 |

$Q_C = -6.7 + 0.84\ Q_T$ ($r^2 = 0.95$)
valid over range 13 L/s < $Q_T$ < 19 L/s

**Table 4. Sediment mass collected in sediment traps from October 10, 1991 to September 19, 1992**

**Control**

| Units | Road Trap No. | | Cutslope Trap No. | | | | | |
|---|---|---|---|---|---|---|---|---|
| | 1 | 2 | 1 | 2 | 3 | 4 | Mean[1] | SE[1] |
| kg | 0.204 | 0.019 | 1.068 | 0.087 | 0.872 | 0.529 | 0.639 | 0.215 |
| Mg/ha | | | 35.6 | 2.90 | 29.1 | 17.6 | 21.3 | 7.17 |

**Treated**

| Units | Road Trap No. | Hillslope Trap No. | | Cutslope Trap No. | | | | | |
|---|---|---|---|---|---|---|---|---|---|
| | 1 | 1 | 2 | 1 | 2 | 3 | 4 | Mean[1] | SE[1] |
| kg | 0.042 | 0.011 | 0.026 | 2.259 | 4.494 | 1.089 | 1.136 | 3.377 | 1.118 |
| Mg/ha | | | | 75.3 | 149.8 | 36.3 | 37.9 | 112.6 | 37.3 |

[1] Means and SEs are for cutslope traps for which continuous data exists (traps 1-4 for Control, and traps 1 and 2 for Treated).

**Table 5. Sediment budget for October 10, 1991 to September 29, 1992**

| Budget Element | CONTROL channel (Mg) | TREATED channel (Mg) |
|---|---|---|
| Change in Storage ( DS) | 9.7 (Aggradation) | 2.6 (Aggradation) |
| Outputs | | |
| Bedload | 1.5 | 1.6 |
| Suspended Sediment | <u>3.6</u> | <u>2.8</u> |
| Total Outputs | 5.1 | 4.4 |
| Total Inputs (by residual) | 14.8 | 7.0 |

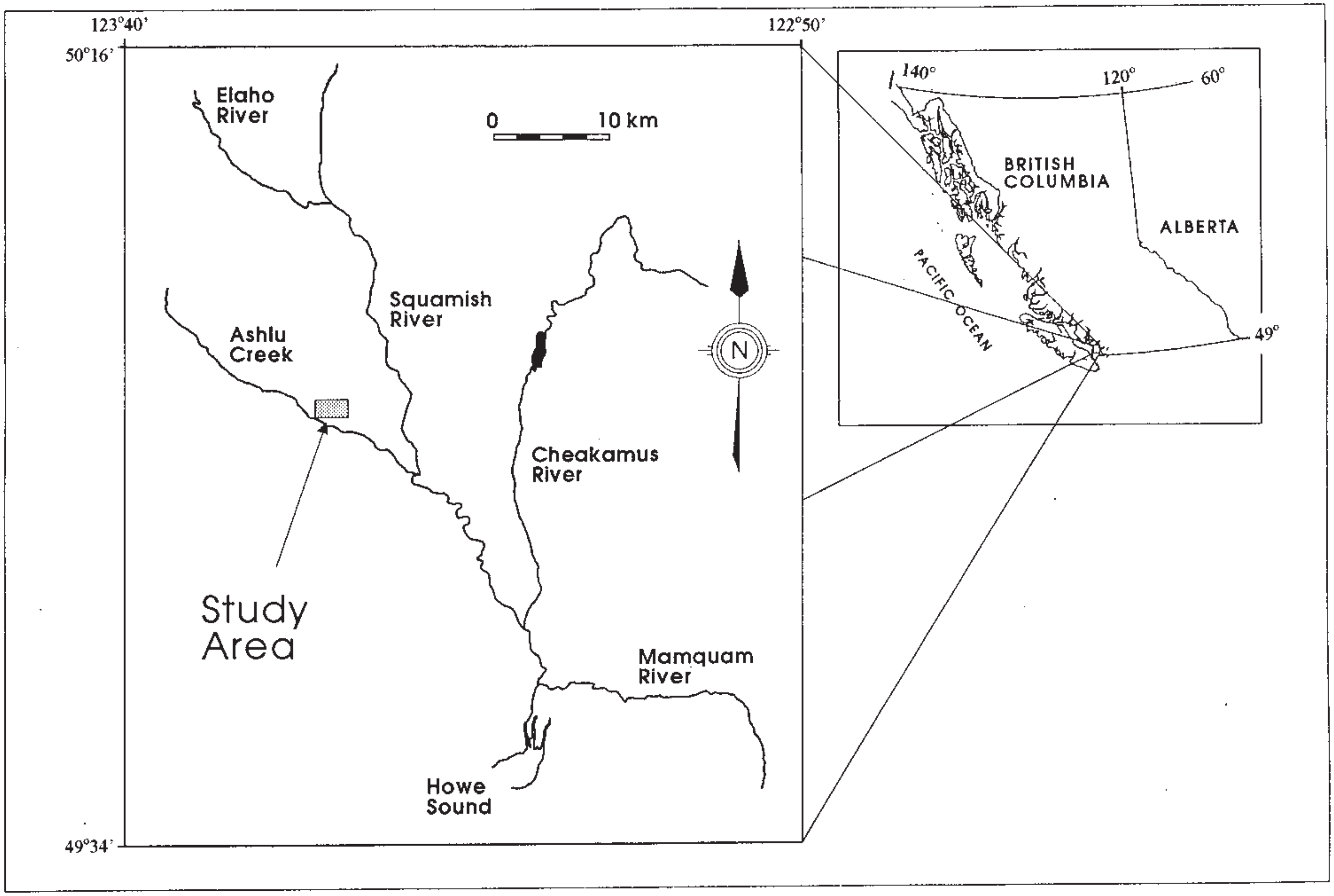


**Figure 1. Study area location map.**

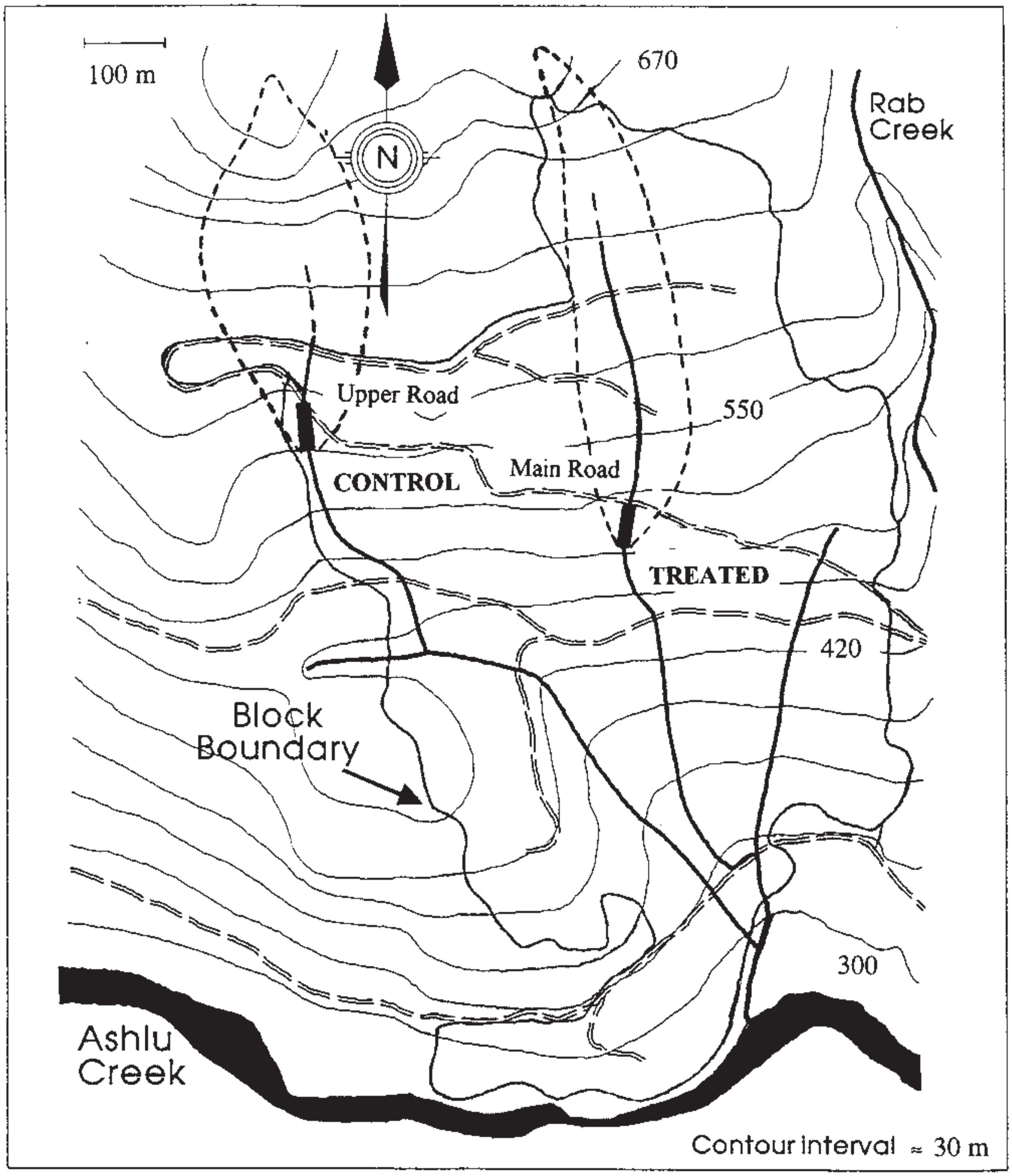


**Figure 2. Study area road layout, drainage patterns and selected reaches.**

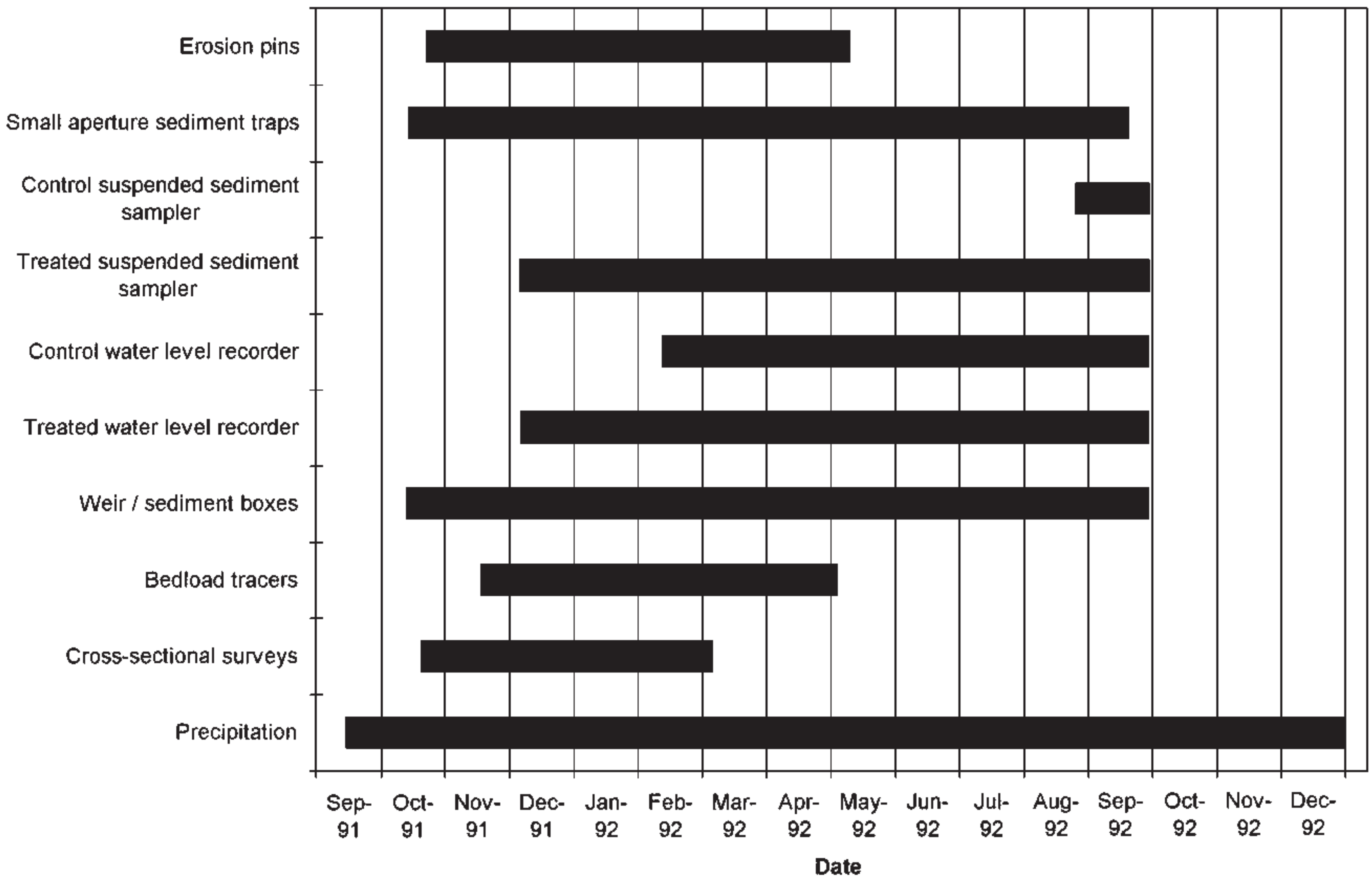


**Figure 3. Time period over which monitoring elements employed.**

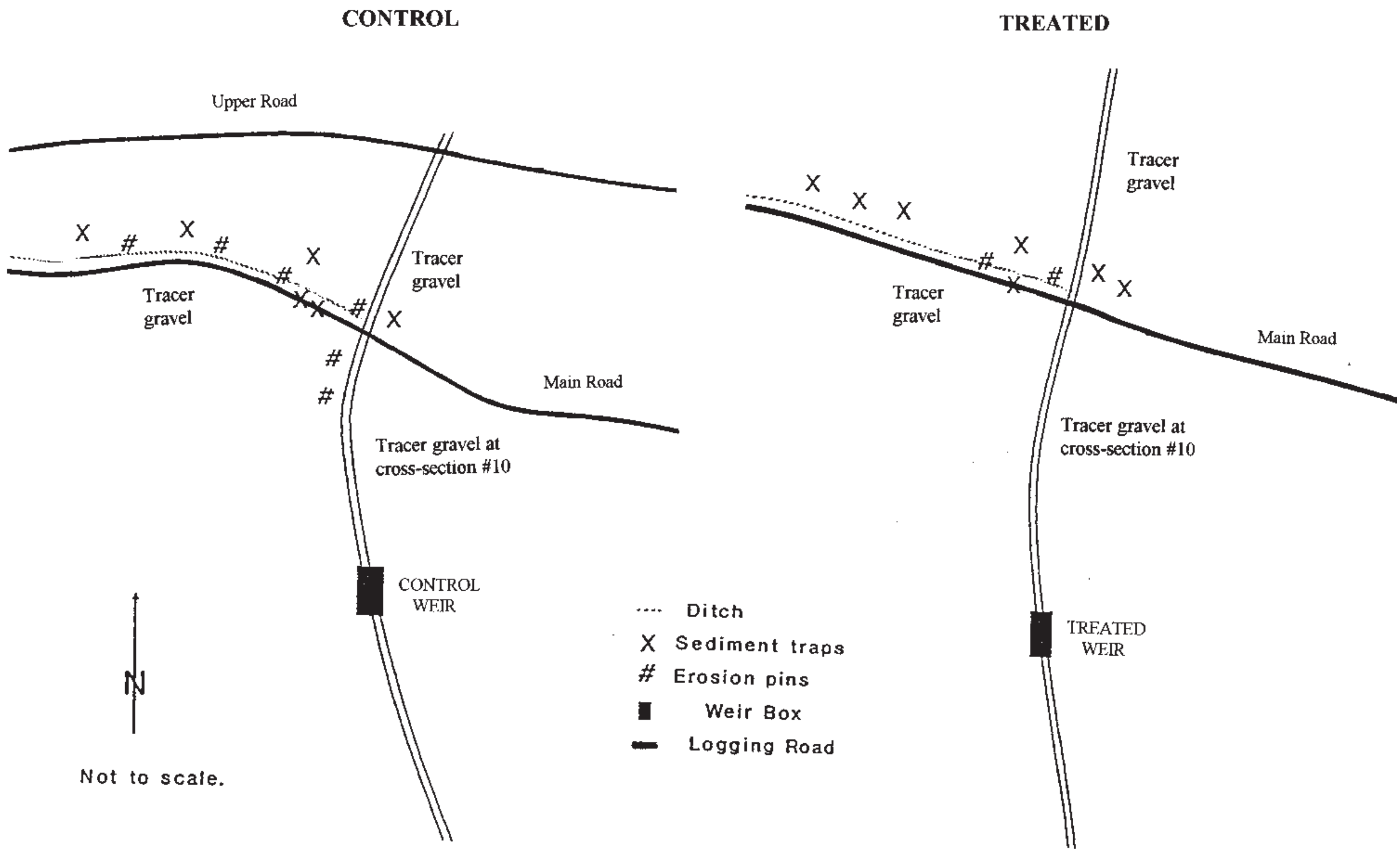


**Figure 4. Location of sediment traps, erosion pins and tracer gravel at Control and Treated.**

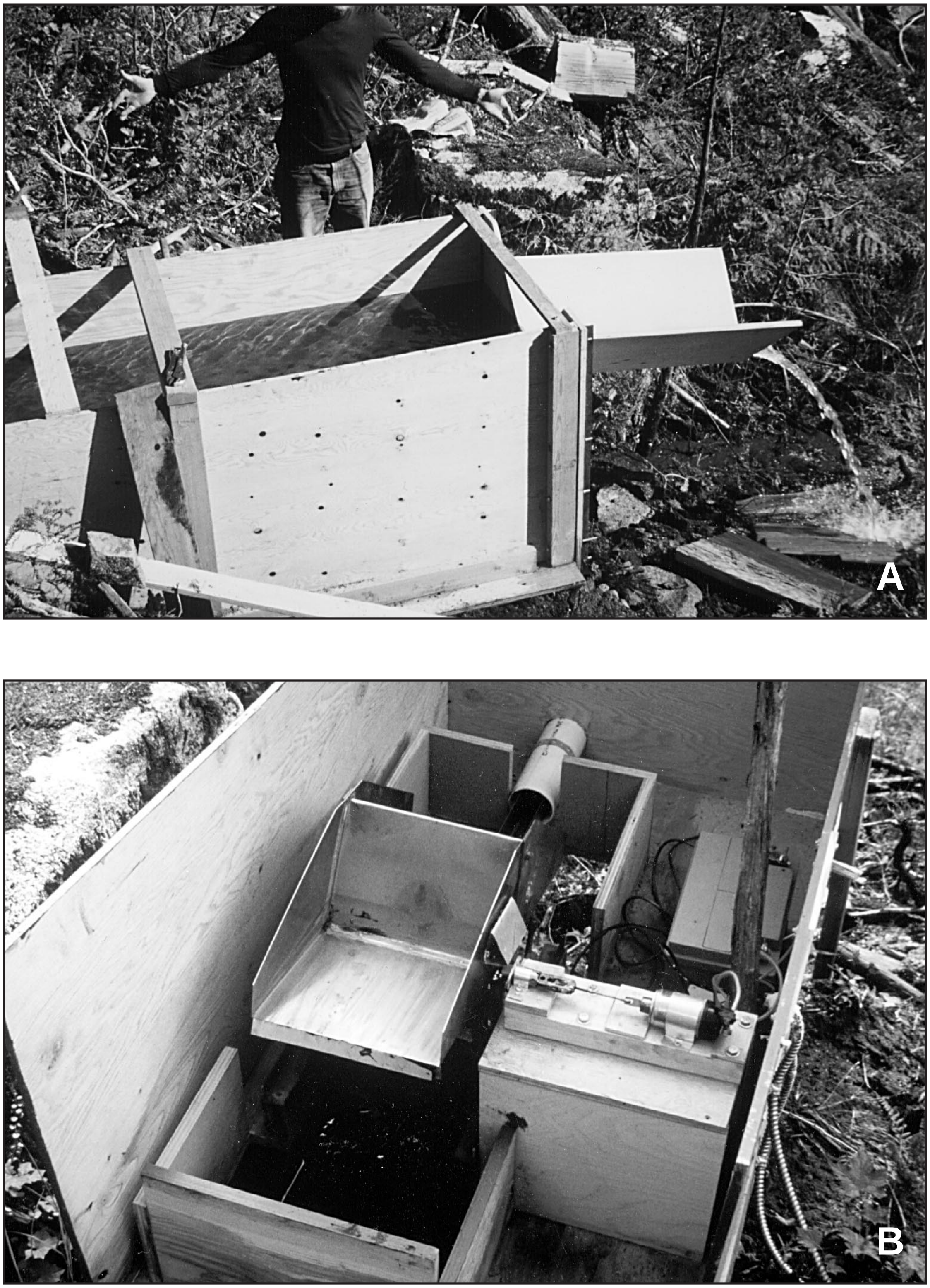


**Figure 5. Sediment box/weir and (b) suspended sediment proportional sampling equipment at Control.**

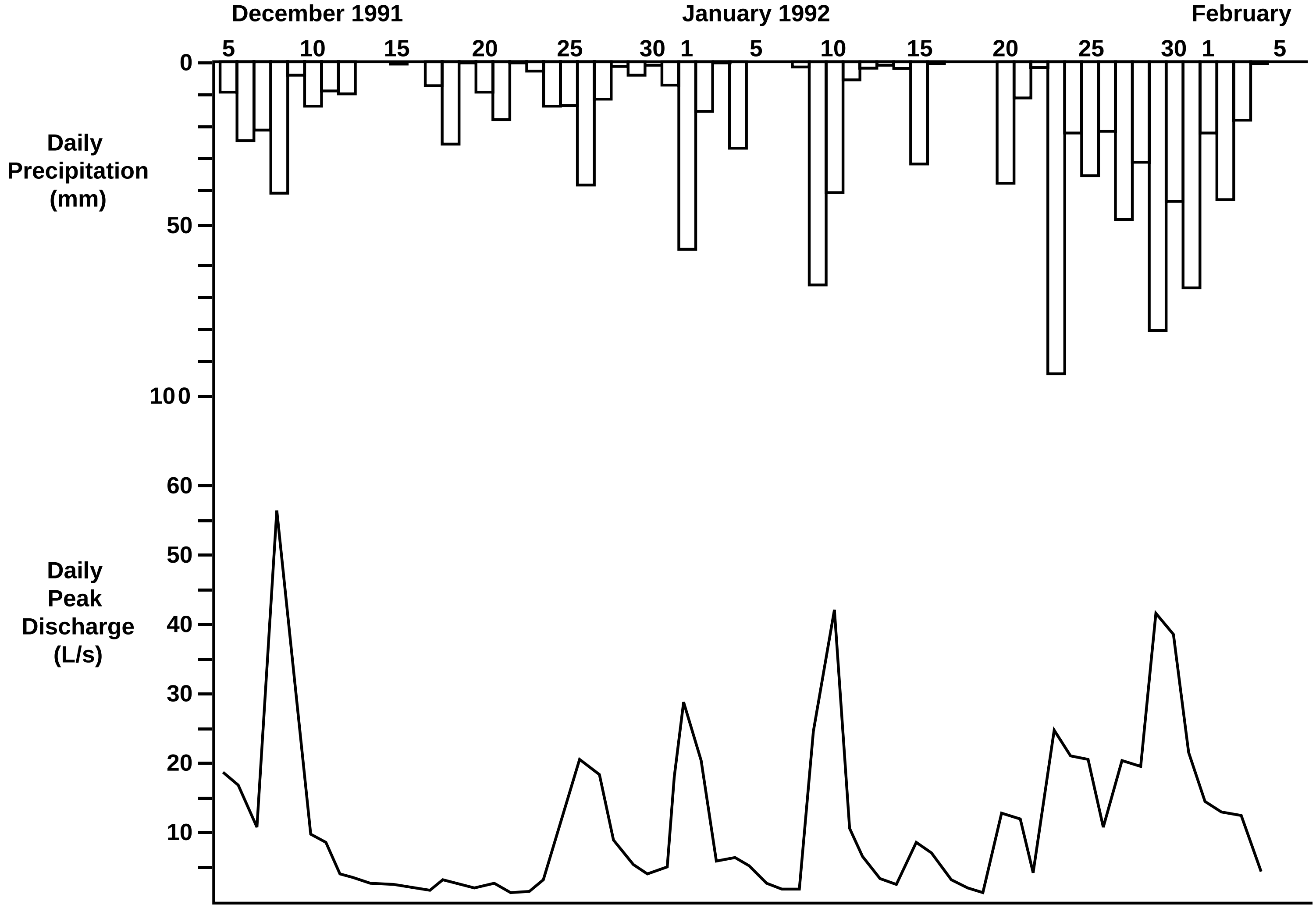


**Figure 6. Daily precipitation and peak discharge at Treated for December 5, 1991 to February 5, 1992.**

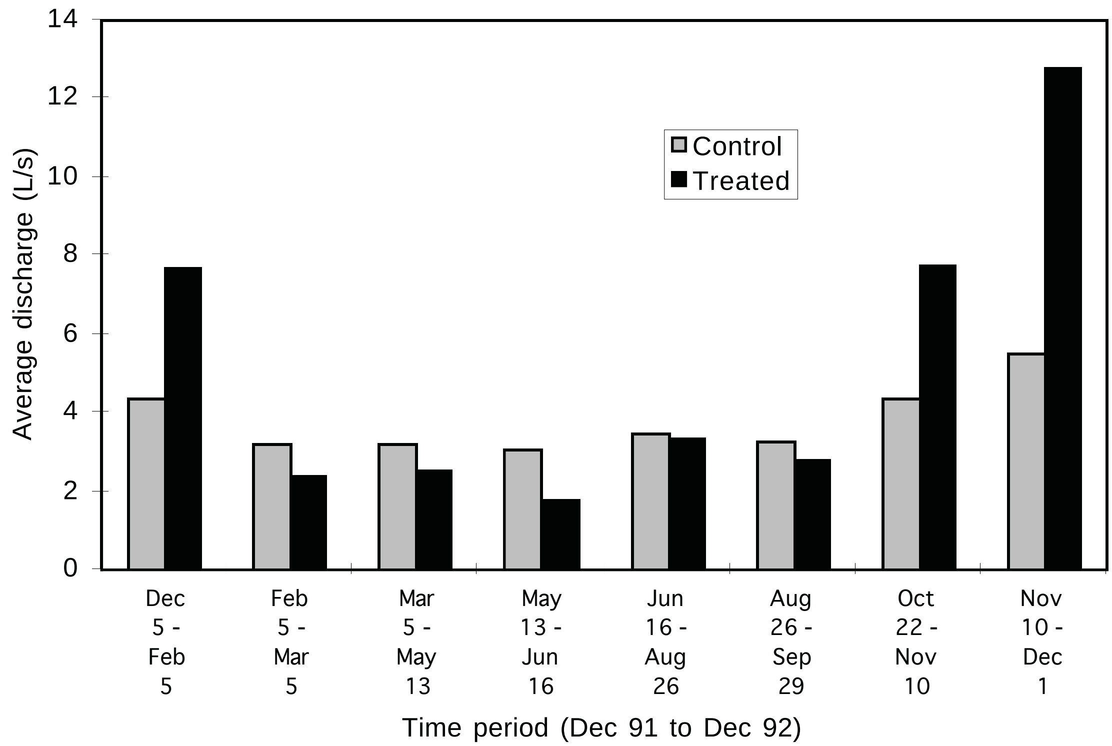


**Figure 7. Average discharge of Control and Treated Creeks during period when water level recorders were operational (Control discharge estimated from Treated discharge - see Appendix 1).**

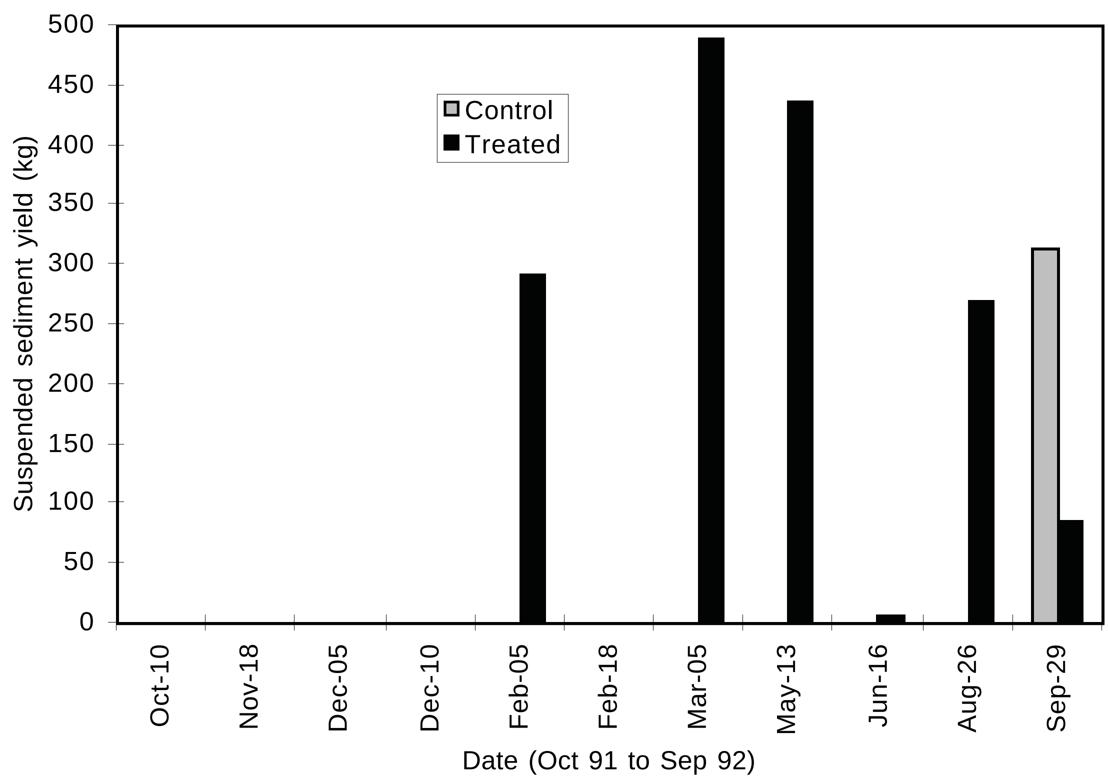


**Figure 8. Suspended sediment yield at Control and Treated (deployment of suspended sediment sampling equipment started at 8 weeks for Treated and 46 weeks for Control).**

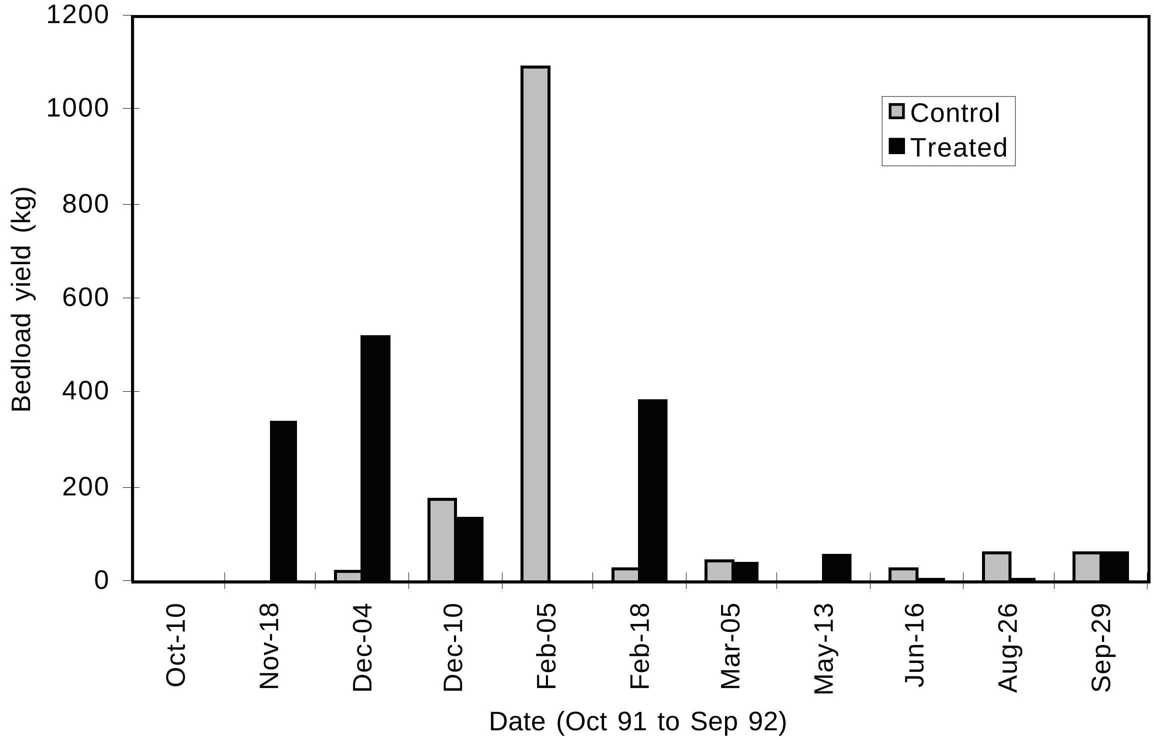


**Figure 9. Bedload yield at Control and Treated.**

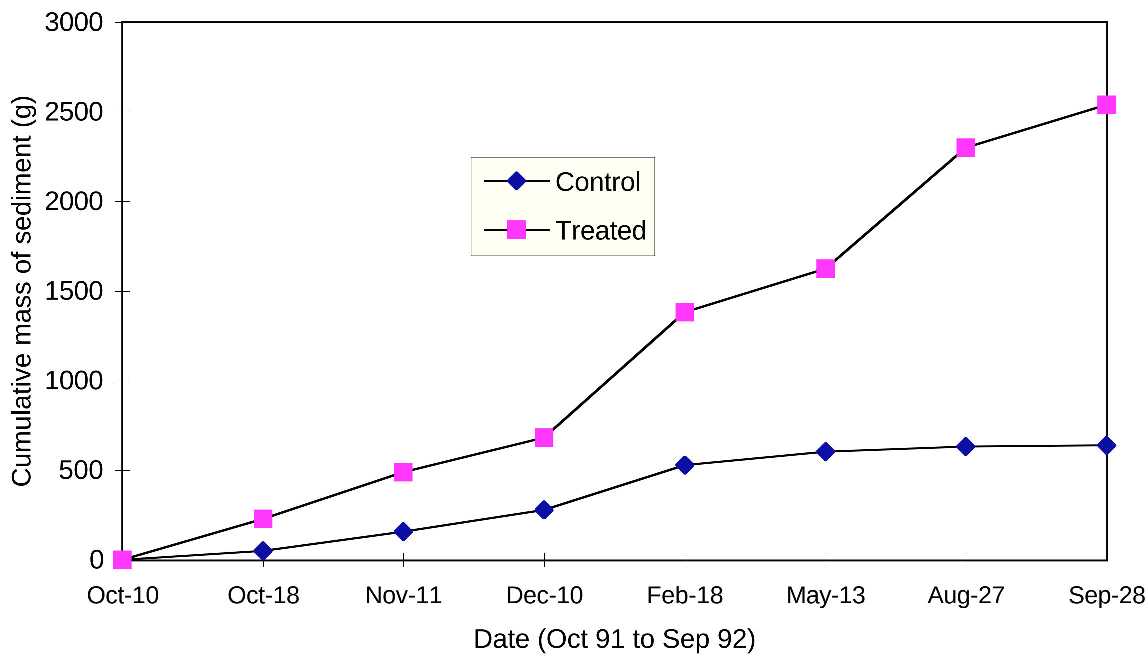


**Figure 10. Cumulative mass of sediment trapped in main road cutslope sediment traps (points are means of four samples).**

## Appendix 1. Procedure used to obtain period flows for calculation of suspended sediment yield.

The flow (Q) measurements taken during each field visit were calibrated against water level (stage, H) and flow equations were developed for each station (Table A1). The equations are based on a sample size of 18 for Control and 17 for Treated. For the time period October 18, 1991 to March 5, 1992, both equations compare very favourably with the standard equation for a 90° sharp-crested V-notch weir ($Q = 1.37\ H^{2.5}$). However, for the April 15 to December 1, 1992 period, the derived equations compare less favourably to the standard equation. Possible reasons for this include settling of the weir boxes over time, softening of the plywood crest causing a change in the nappe, and algal growth and sediment deposition in the box. These equations (for specific periods) were used to calculate total period discharge values for Treated using the electronic stage record. For Control, an indirect method of estimating total period discharge was used because the electronic record contained errors, and the backup water level charts were incomplete. A relationship between discharge at Control ($Q_C$) and discharge at Treated ($Q_T$) was obtained for the 16 flow measurements which were made at the same time:

$$Q_C = 0.00268 + 0.219\ Q_T \quad (r^2 = 0.57)$$

where Q is in $m^3/s$. The equation is considered to be reliable for Q between 0.0015 and 0.020 $m^3/s$ (1.5 to 20 L/s). The relationship indicates that $Q_C$ and $Q_T$ are similar at low flows (e.g., $Q_T$ = 4 L/s —> $Q_C$ = 3.6 L/s), but that $Q_T$ is significantly larger than $Q_C$ at higher flows (e.g., $Q_T$ = 20 L/s —> $Q_C$ = 7.1 L/s). Hourly $Q_C$ values were estimated using the above equation and summed to obtain total period discharge values (Table 2 in main text).

**Table A1. Stage-discharge equations developed for Control and Treated weirs**

| Time Period | Control | Treated |
|---|---|---|
| October 18, 1991 to March 5, 1992 | $Q = 1.399\ H^{2.5}$ (n=10) | $Q=1.366\ H^{2.5}$ (n=10) |
| April 15, 1992 to December 1, 1992 | $Q = 1.638\ H^{2.5}$ (n=8) | $Q = 1.610\ H^{2.5}$ (n=7) |
| Data combined | $Q = 1.457\ H^{2.5}$ | $Q = 1.488\ H^{2.5}$ |

**Appendix 2. Precipitation record at Ashlu Creek for the period September 1991 to December 1992, and climatic normals for Daisy Lake Dam (1951-80).**

| | Measured or Estimated Values for Ashlu Creek | Climatic Normals Daisy Lake Dam 1951-80 | |
|---|---|---|---|
| Time Period | Precipitation (mm) | Precipitation (mm) | Mean Air Temperature (°C) |
| 1991 | | | |
| Sept. 12-30 | 4 | ? | ? |
| October | 59[1] | 258 | 7.3 |
| November | 428[1] | 275 | 2.3 |
| December | 318[1] | 341 | -0.8 |
| 1992 | | | |
| January | 720 | 297 | -2.8 |
| February | 181 | 225 | 0.0 |
| March | 69 | 207 | 1.2 |
| April | 237 | 118 | 5.4 |
| May | 77 | 62 | 9.4 |
| June | 88 | 72 | 12.7 |
| July | 75 | 43 | 15.3 |
| August | 47 | 47 | 15.0 |
| September | 125 | 111 | 12.3 |
| October | 313[1] | 258 | 7.3 |
| November | 208 | 275 | 2.3 |
| December | 140[1] | 341 | -0.8 |
| Total | 2280 | 2054 | Mean = 6.4 |

[1] Predicted values are based on the Squamish STP station:
$Ashlu = (6.69 + 0.0356\ (S.\ STP))^2$  $r^2 = 0.974$  $n = 10$

The October 1, 1991 to September 30, 1992 water year total precipitation estimate at Ashlu Creek = 2,425 mm.

# APPENDIX 3. Channel Cross-Sectional Survey Data

Area and volume calculations for Control channel

| Cross section | Area Oct 91 ($m^2$) | Area Mar 92 ($m^2$) | Change in area ($m^2$) | Channel length represented by cross section (m) | Change in volume ($m^3$) |
|---|---|---|---|---|---|
| 1 | 1.52 | 1.45 | 0.07 | 4.95 | 0.35 |
| 2 | 4.28 | 4.45 | -0.17 | 8.45 | -1.44 |
| 3 | 2.31 | 2.16 | 0.15 | 4.70 | 0.71 |
| 4 | 7.02 | 5.13 | 1.89 | 3.33 | 6.29 |
| 5 | 3.44 | 3.18 | 0.26 | 2.90 | 0.75 |
| 6 | 2.49 | 2.90 | -0.41 | 2.93 | -1.20 |
| 7 | 0.88 | 0.74 | 0.14 | 3.65 | 0.51 |
| 8 | 2.32 | 2.78 | -0.46 | 3.00 | -1.38 |
| 9 | 9.03 | 8.26 | 0.77 | 2.53 | 1.95 |
| 10 | 0.76 | 0.66 | 0.10 | 2.23 | 0.22 |
| 11 | 0.49 | 0.41 | 0.08 | 3.28 | 0.26 |
| 12 | 1.81 | 1.36 | 0.45 | 2.65 | 1.19 |
| 13 | 0.38 | 0.30 | 0.08 | 1.40 | 0.11 |
| 14 | 0.42 | 0.40 | 0.02 | 1.68 | 0.03 |
| 15 | 0.58 | 0.62 | -0.04 | 1.10 | -0.04 |
| 16 | 1.09 | 0.62 | 0.47 | 2.75 | 1.29 |
| 17 | 0.52 | 0.45 | 0.07 | 3.30 | 0.23 |
| 18 | 5.13 | 5.15 | -0.02 | 2.15 | -0.04 |
| 19 | 0.70 | 0.75 | -0.05 | 2.05 | -0.10 |

Total change in volume (aggradation) = 9.69 $m^3$

Area and volume calculations for Treated channel

| Cross section | Area Oct 91 ($m^2$) | Area Mar 92 ($m^2$) | Change in area ($m^2$) | Channel length represented by cross section (m) | Change in volume ($m^3$) |
|---|---|---|---|---|---|
| 1 | 1.49 | 1.59 | -0.10 | 1.55 | -0.16 |
| 2 | 0.82 | 1.07 | -0.25 | 2.80 | -0.70 |
| 3 | 1.33 | 1.37 | -0.04 | 2.35 | -0.09 |
| 4 | 0.93 | 1.27 | -0.34 | 2.55 | -0.87 |
| 5 | 0.35 | 0.48 | -0.13 | 2.15 | -0.28 |
| 6 | 0.21 | 0.39 | -0.18 | 1.70 | -0.31 |
| 7 | 3.35 | 3.55 | -0.20 | 1.95 | -0.39 |
| 8 | 1.38 | 1.18 | 0.20 | 1.85 | 0.37 |
| 9 | 2.06 | 2.19 | -0.13 | 2.35 | -0.31 |
| 10 | 1.24 | 1.26 | -0.02 | 2.20 | -0.04 |
| 11 | 0.84 | 0.98 | -0.14 | 2.55 | -0.36 |
| 12 | 2.27 | 2.63 | -0.36 | 2.95 | -1.06 |
| 13 | 1.95 | 2.13 | -0.18 | 3.05 | -0.55 |
| 14 | 3.14 | 2.78 | 0.36 | 2.70 | 0.97 |
| 15 | 2.65 | 2.87 | -0.22 | 2.60 | -0.57 |
| 16 | 4.91 | 4.54 | 0.37 | 4.00 | 1.48 |
| 17 | 4.01 | 3.48 | 0.53 | 4.15 | 2.20 |
| 18 | 4.90 | 4.32 | 0.58 | 5.55 | 3.22 |

Total change in volume (aggradation) = 2.55 $m^3$

# Appendix 4. Particle size distribution of bedload samples obtained from weirs

| Date | Row | Depth | Edge | < 2 mm Soil Texture Clay | Sand | Silt | Particle Size >25 mm | 25-16 mm | 16-8 mm | 8-4 mm | 4-2 mm | < 2 mm | wood |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | | | | ——— % ——— | | | ——— % by weight ——— | | | | | | |
| **TREATED** | | | | | | | | | | | | | |
| Dec /91 | 120 | 30 | 60 | 3.1 | 91.2 | 5.7 | 32.5 | 10.2 | 10.2 | 8.3 | 10.6 | 28.1 | 0.0 |
| | 160 | 28 | 30 | 3.0 | 93.6 | 3.4 | 28.6 | 15.6 | 17.5 | 10.8 | 10.6 | 16.9 | 0.0 |
| | 160 | 25 | 60 | 1.3 | 93.6 | 5.1 | 8.5 | 18.3 | 20.1 | 15.4 | 13.4 | 24.3 | 0.0 |
| | 160 | 40 | 30 | 3.0 | 90.0 | 7.0 | 8.7 | 11.1 | 28.5 | 18.1 | 15.9 | 17.8 | 0.0 |
| | 190 | 25 | 60 | 0.7 | 94.6 | 4.7 | 3.3 | 20.0 | 17.0 | 14.9 | 15.7 | 29.2 | 0.0 |
| | 200 | 41 | 25 | 1.3 | 93.6 | 5.1 | 3.7 | 5.2 | 19.4 | 19.1 | 18.4 | 34.2 | 0.0 |
| Mar5/92 | 80 | - | 45 | 0.8 | 94.5 | 4.7 | 0.0 | 0.0 | 2.1 | 2.8 | 6.5 | 88.5 | 0.1 |
| | 100 | - | 20 | 1.6 | 92.6 | 5.8 | 7.8 | 7.8 | 20.1 | 18.6 | 18.5 | 27.1 | 0.1 |
| | 14 | - | 70 | 1.3 | 94.5 | 4.2 | 27.1 | 7.7 | 17.7 | 13.1 | 9.7 | 24.0 | 0.7 |
| Sep29/92 | org. surface layer | | | 2.5 | 60.2 | 37.3 | 0.0 | 0.0 | 0.0 | 0.0 | 0.3 | 81.1 | 18.6 |
| | box entrance | | | 0.7 | 90.8 | 8.5 | 0.0 | 14.9 | 18.5 | 16.3 | 14.9 | 33.9 | 1.5 |
| Average for Treated = | | | | 1.8 | 89.9 | 8.3 | 10.9 | 10.1 | 15.6 | 12.5 | 12.2 | 36.8 | 1.9 |
| **CONTROL** | | | | | | | | | | | | | |
| Feb6/92 | 110 | surface | | 2.1 | 94.2 | 3.7 | 0.0 | 0.0 | 0.0 | 0.1 | 7.6 | 92.3 | 0.0 |
| | 90 | 51 | - | 0.7 | 95.6 | 3.7 | 0.0 | 0.0 | 0.0 | 0.4 | 14.0 | 85.6 | 0.0 |
| | 90 | 68 | - | 3.0 | 86.4 | 10.6 | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 | 65.3 | 34.7 |
| | 170 | 50 | - | 2.6 | 91.4 | 6.0 | 0.0 | 0.0 | 0.0 | 0.4 | 2.4 | 97.3 | 0.0 |
| Mar5/92 | 70 | - | 30 | 2.0 | 74.7 | 23.3 | 0.0 | 0.0 | 0.0 | 0.1 | 0.1 | 95.5 | 4.2 |
| | 180 | - | 20 | 2.5 | 64.3 | 33.2 | 0.0 | 0.0 | 0.0 | 2.1 | 2.9 | 93.0 | 2.0 |
| | 240 | - | 45 | 0.5 | 95.9 | 3.6 | 0.0 | 0.0 | 0.0 | 0.0 | 0.7 | 99.3 | 0.0 |
| Sep29/92 | - | - | - | 1.4 | 91.6 | 7.0 | 0.0 | 0.0 | 0.0 | 0.4 | 1.6 | 96.0 | 2.0 |
| | - | - | - | 2.4 | 63.1 | 34.5 | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 | 83.8 | 16.2 |
| Average for Control = | | | | 1.9 | 84.1 | 14.0 | 0.0 | 0.0 | 0.0 | 0.4 | 3.3 | 89.8 | 6.5 |

Row = distance from outflow end of box (cm).
Depth = distance from top of box (cm).
Edge = distance from right hand side of box when facing upstream (cm).
Dashes indicate missing information.