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Storm-Based Sediment Budgets in a Partially Harvested Watershed in Coastal British Columbia

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Cover photo: Russell Creek is a sub-basin of the Tsitika River watershed on northeastern Vancouver Island, British Columbia.

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ABSTRACT

A program of sediment-budget research commenced in 1994 at Russell Creek, a sub-basin of the Tsitika River watershed on Northeastern Vancouver Island, British Columbia. Part of the program aimed to determine the relative contribution of different types of sediment sources to the sediment load of mainstem channel sites in Russell Creek and its main tributary, Stephanie Creek, which are two typical Coastal British Columbia streams.

The report describes a sediment-budget model that predicts the sediment yield from gullies, forestry-road-related sources, and landslides based on attributes of the sediment sources and storm rainfall characteristics. The sediment-budget model will help forest managers assess the effects of forestry activities on sediment production in streams, and the related implications for fish habitat. The model will also be useful to forestry-road-deactivation planners in predicting the effectiveness of road-deactivation scenarios.

KEYWORDS

forestry, forest management, hydrology, streams, sediment, sediment budget, sediment production, sediment yield, fish habitat, forestry roads, road deactivation, Vancouver Forest Region, British Columbia

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INTRODUCTION

Sediment production in creeks and rivers in Coastal British Columbia is a natural process, and the subject of ongoing research in the Vancouver Forest Region and elsewhere in the province. One of the most important issues related to this research is the effects of forest harvesting and related activities on the sediment budgets of creeks.

A program of sediment-budget research commenced in 1994 at Russell Creek, a sub-basin of the Tsitika River watershed on Northeastern Vancouver Island, British Columbia. Part of the program aimed to determine the relative contribution of different types of sediment sources to the sediment load of mainstem channel sites in Russell Creek and its main tributary, Stephanie Creek, which are typical Coastal British Columbia streams. This report describes a sediment-budget model that predicts the sediment yield from gullies, forestry-road-related sources, and landslides based on attributes of the sediment sources and storm rainfall characteristics. The sediment-budget model will help forest managers assess the effects of forestry activities on sediment production in streams, and the related implications for fish habitat. The model will also be useful to forestry-road-deactivation planners in predicting the effectiveness of road-deactivation scenarios.

BACKGROUND

Interest in sediment-production research began in the 1960s because of concern for the potential effects of increased sedimentation in forest streams on fish habitat and health.

Research on the effects of road construction and harvesting and silvicultural practices on suspended sediment loads in streams was undertaken in watersheds with unstable soils in the Oregon Cascades, and on more stable granitic soils in Idaho. Harvesting without roads or without slash burning had minimal effects on suspended sediment concentration (SSC). However, slash burning relatively immediately after harvesting resulted in large increases in SSC in the short-term; these increases diminished over time and as the harvested sites became re-vegetated (Frederiksen 1970; Brown and Krygier 1971). Similar results were obtained in the Idaho study, except that SSC levels before harvesting were less than in the Oregon studies and the effects of the burning on SSC were less severe (Megahan et al. 1995). Similar large increases in SSC were noted immediately after road construction; peak SSC increased up to 250 times immediately after harvesting in the Oregon study, but in the Idaho study, watershed sediment yield increased 5 times during the road-construction phase (Megahan et al. 1986). While the effects of road construction on sediment yield are fairly immediate and rather severe, they subside after construction is complete; nevertheless, SSC levels in roaded watersheds remain at elevated levels due to a combination of road-surface erosion and road-related landslides (Brown and Krygier 1971; Reid and Dunne 1984; Beschta 1978).

From the above, it is clear that watershed lithology plays a big role in how forestry activities affect SSC levels and sediment yield. In an earlier study of storm-based sediment yield in the Tsitika River watershed, Hudson and Sterling (1998) found that Catherine Creek yielded about 5.5 times as much sediment as Russell Creek over the same time period. Catherine Creek was undeveloped at the time, and 25% of Russell Creek was roaded and harvested. The difference was attributed to the dominant bedrock lithology. Basaltic bedrock areas in the Tsitika River watershed produced over 6 times more debris torrents per unit area than did the granitic bedrock areas (Sterling 1997).

In the absence of slash burning, forest roads remain the primary harvesting-related source of fine sediments in streams. Efforts have been made to quantify the relative importance of road components. Reid et al. (1981) found that 60% of road-related sediment production was derived from landslides, and 20% was derived from running surfaces. Sediment yield from road surfaces is related to road use, with active haul roads yielding one and two orders of magnitude more sediment than moderately used and abandoned roads, respectively (Reid and Dunne 1984). Nistor and Rood (1999) found that sediment yield from roads was related to road gradient, with over 90% of road-related sediment produced by the running surface.

The effects of road-related sediment yield on the sediment budget of fish-bearing streams has also been studied, because most sediment produced by roads enters small ephemeral streams. Silt and clay-sized fractions were transported efficiently even at low flows, whereas sand-sized and coarser particles were stored in ephemeral stream channels such that up to 45% of the sediment was actually delivered to the receiving stream (Duncan et al. 1987). Distance of sediment travel in headwater channels was related to attributes of the channels, including catchment area, channel gradient, the presence of log jams, area of sediment sources and length of roads draining into the site (Megahan and Ketcheson 1996).

Earlier sediment-budget studies relied on developing relationships between SSC of point samples and stream discharge in order to calculate SSC and sediment yield during storms. Several authors have alluded to the difficulty of this approach, because different relationships exist for rising and falling stages, and from storm to storm (Brown and Krygier 1971; Beschta 1978). Other investigators have used bulk methods—such as settling basins (e.g., Megahan et al. 1995)—of determining sediment yield; the drawbacks are that long time periods are required to conduct the measurement, and that channel cannot be assessed because it is cut off from the source.

As early as the 1970s, in-stream turbidity meters were tested to overcome the problems associated with the hysteretic behaviour of suspended sediment in relation to streamflow (Walling and Webb 1982). The advent of optical backscatter (OBS) technology (Downing 1983; Downing and Beach 1989; Ludwig and Hanes 1990) has since resulted in much greater precision in monitoring SSC for sediment budget studies (Hudson and Sterling 1998; Jordan and Commandeur 1998; Hudson 2001).

Sediment-Budget Research in the Tsitika River Watershed

In an effort to understand sediment-production processes, the Tsitika River Sediment Monitoring Program was initiated in 1991. This program as originally implemented consisted of two components:

1. Continuous monitoring of streamflow, turbidity, suspended-sediment concentration, and grain-size distribution at three sites: the mainstem of Tsitika River, and at the mouths of Russell and Catherine Creeks, two sub-basins of the Tsitika River.

2. Manual measurement of discharge and sampling of water for the determination of suspended-sediment concentration at several pre-selected sites during storms; these sites were supposed to represent the individual sediment sources that would supply sediment to the main creeks, and were dispersed throughout the Tsitika River watershed.

The purpose of having the two components was to determine the relative contributions of different types of sediment sources to the overall sediment production in the main creeks during storms. Storm sampling was carried out for three years in conjunction with automatic monitoring. The early stage of the program met with some success, but it became apparent that the scale of the project was too large. Because the Tsitika River watershed is 370 km^2 in area, it was not possible to sample in sufficient detail, either temporally or spatially, to construct a reproducible sediment budget at that scale. It was concluded that a sub-basin of the Tsitika River would be a more appropriate scale for this type of research. Russell Creek was selected for sediment-budget investigations for the following reasons:

1. It was already gauged.
2. It has a history of harvesting, as well as ongoing forestry activities, including active harvesting and a mainline haul road.
3. It contains both granitic and basaltic bedrock types, as well as tributary creeks with contrasting watershed morphologies that were thought to influence sediment-production processes.

Nistor (1996) studied fine sediment transfer in gullies in Russell Creek. The study focussed on fluvial sediment transfer as opposed to episodic sediment production due to debris flows and/or landslides. Thus, Nistor's results are highly relevant to the current study. His findings include the following:

- Sediment transfer in gullies occurred almost entirely during large rainfall and snowmelt events.

- Sediment was entrained from sediment sources on the channel margins above a flow threshold that is characteristic to each gully.

- Fluvial sediment transfer in gullies occurred as a series of discrete sediment pulses, as opposed to a steady background rate. These pulses occurred on the rising limb of the storm hydrographs, and were brief compared to the duration of the runoff event. Thus the normal fluvial sediment production is in itself episodic in nature.

Based on these results, Nistor recommends that for the determination of sediment budgets, high frequency sampling, beginning at the onset of runoff events, is essential.

The sediment-budget research program in Russell Creek as it currently exists is based on five automatic stream-monitoring sites where stage and turbidity are measured continuously, and ten representative sediment source sites where manual sampling and flow measurements are carried out during storms. The purpose of this paper is to report on the results of sediment-budget investigations during storms, based on an analysis of sediment yields at the manual and automatic sites. The sediment budget includes an analysis of the relative importance of natural and man-made sediment sources. Sediment yield is defined as the total mass of sediment carried past a point by a stream over specified time interval. This study focuses on the suspended sediment yield, which is the total mass of sediment carried in the water column, as opposed to bed yield, which is transported along the channel bed by rolling or saltation.

In principle, the sediment-budget approach is an accounting procedure in which sediment yield during storms is measured in one or more mainstem stream channels, and also at selected sediment source sites. The mainstem sites are monitored automatically, whereas the individual sources are monitored manually.

The sediment source sites that are selected for monitoring represent specific types of sediment sources, such as gullies, road sources, and landslides. The most significant elements of forest roads are those that are directly connected to the stream channel network. These road elements are associated with stream crossings. The sediment yield from connected road elements can be measured by collecting water samples in gullies above and below the road crossings. The sediment yield derived from the crossings can be separated from the yield derived from the gullies, by subtracting the sediment yield above the crossings from that below.

This sampling strategy directly measures the sediment yield from the crossings but does not provide a breakdown of the yield according to the components that make up the crossing; these include the cut slopes, fill slopes, ditches, and running surface.

The measured source yields are used to develop relationships between sediment-production characteristics and measured attributes of the sediment sources. These relationships are then used to reconstruct the sediment budget during the storm; the source yields are added up and the result is compared to the measured sediment yield at the mainstem stream that drains the watershed area that contains those sediment sources. If the total yield from sediment sources is close to the measured stream yield, then the relative contributions of the different types of sediment sources to the sediment budget can be determined.

The sediment-budget approach has been successfully applied to four storms of varying magnitudes in Russell Creek. The purpose of this paper is report on the results of those investigations.

STUDY AREA

Physical Characteristics

Russell Creek (Figure 1) drains an area of 30.9 km^2. A large batholith of granitic Island Intrusions underlies the lower two-thirds of the watershed. The upper one-third of the watershed is underlain by the extrusive or basaltic Karmutsen Formation. These basaltic rocks are typically weak and easily erodible, and the igneous rocks are typically hard and resistant. There is a band across the middle of the watershed where surficial material derived from the Karmutsen formation is draped over the igneous bedrock. The lower watershed is relatively gently sloped, the basin is bowl shaped and has two bowl-shaped, third-order tributaries. There is a broad valley flat that buffers the middle reaches of the channel from coarse sediments generated by debris flows and landslides. Thus, sediment sources in the middle part of the watershed are not directly connected to the main channel. In contrast, the upper part of the watershed that is underlain by the Karmutsen formation tends to be steep with exposed basaltic bluffs and incised stream channels. In the Karmutsen areas the sediment sources tend to be directly connected to the channel system.

Automatic Gauging Sites

Morphological characteristics of Russell Creek and its sub-basins are given in Table 1. The watershed is divided into sub-basins by the automatic stream gauge sites (Figure 1). Stream gauges are located at Russell Creek mainstem at the bridge (Figure 2), Stephanie Creek at the bridge (Figure 3), upper Stephanie Creek, Russell Creek above Stephanie confluence ("the Confluence", Figure 4), and upper Russell at TS120. This network of gauging sites creates a nested set of sub-basins of decreasing size. Sediment-budget investigations are carried out within areas as defined by the gauging sites.

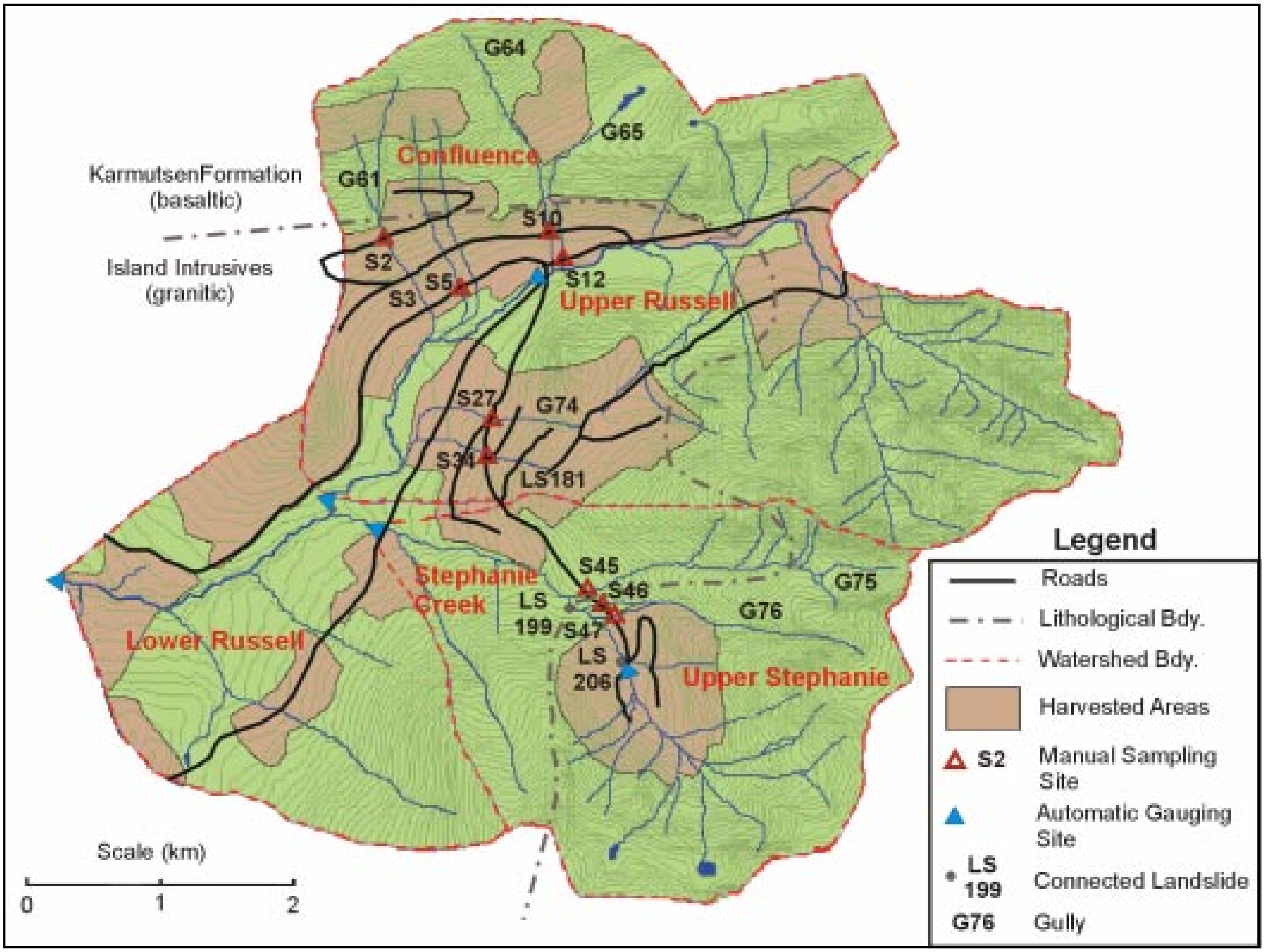

Figure 1. Map of Russell Creek: for readability, only the features discussed in the text are plotted on the map.

Table 1. Morphological factors of Russell Creek and sub-basins.

Factors	Stephanie	Russell above the Confluence	Russell Main
Area (km^2)	8.61	16.03	30.88
Elev. range (m)	470-1680	420-1715	265-1715
Drainage density	2.28	2.26	2.23
Birfurcation ratio	4.58	3.41	2.88
Mean channel gradient, lower channel above gauge (%)	15.0	3.1	5.0
Channel profile at gauge (%)	8.5	3.6	3.1
Channel type	Cascade-pool, incised below upper Stephanie	Riffle-pool gravel bed buffered by valley flat	Riffle-pool gravel bed, lower reaches incised
Avg. land slope	0.53	0.52	0.47
Area-elevation curve	Convex	Concave	Concave
Form factor	0.56	0.34	0.55

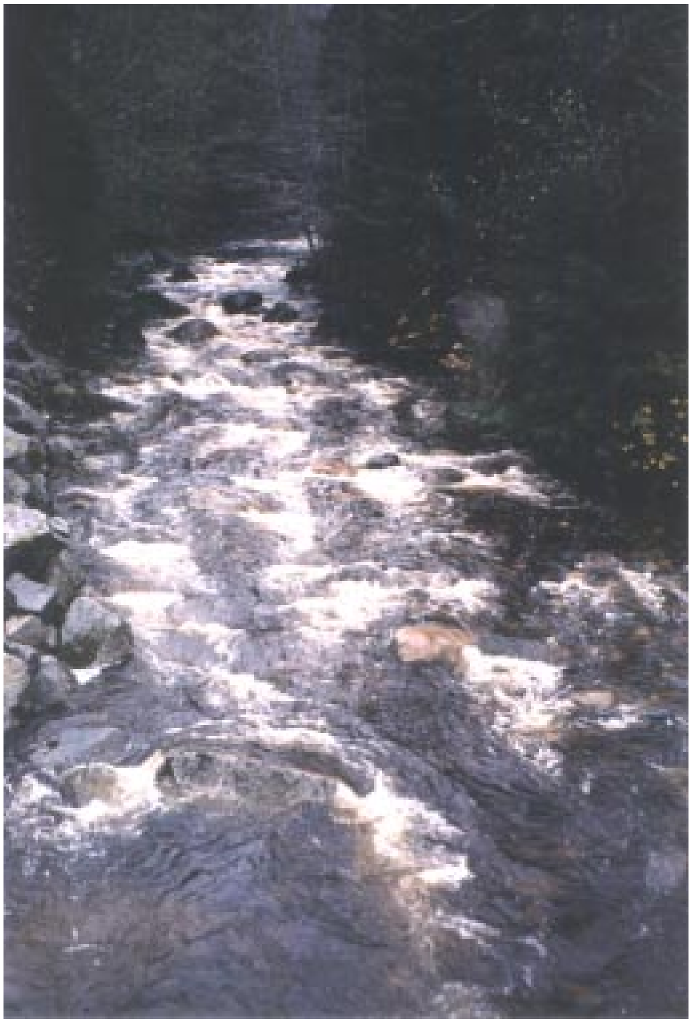

Figure 2. Russell Main channel.

Sediment Source Inventory and the Selection of Sampling Sites

Maynard (1991) carried out a complete inventory of sediment sources in Russell Creek and elsewhere in the Tsitika River Watershed. In the summer of 1996, the inventory was updated and ground-truthed (Paulig 1996). All sediment sources in Russell Creek were documented and described by a set of qualitative and quantitative attributes. Qualitative attributes consisted primarily of the type, erosional activity and connectivity of the feature, as well as the geological formation and whether or not the feature was harvested. The main features of interest were the ones that could potentially be directly connected to the channel system, including landslides, gullies, road crossings, and eroding ditches. A sediment source feature was considered significant if it was actively eroding and connected to a gully, tributary, or mainstem channel. Quantitative attributes included area of exposed sediment sources in the case of landslides and road crossings; channel gradients, gully catchment areas; lengths of eroding ditch; and some semi-quantitative descriptors of gully

Figure 3. Stephanie Creek.

Figure 4. The Confluence.

stability, degree of revegetation, etc. The significant sediment sources are described in Appendix A (Table A1). The sources are organized by type and by the sub-basin in which they fall. To conserve space, only the directly connected and active sediment sources are listed.

A subset of the sediment sources was selected for manual sampling. The purpose of the manual sampling was to collect data upon which to build the sediment-budget model. Therefore, the sample sites should be representative of sediment production in Russell Creek. To achieve this, cluster analysis was done on the sediment inventory attributes (Paulig 1996; Hudson 1999). This analysis was done on gullies, road crossings, and ditch sites separately. Representative crossings and ditches were paired with representative gullies. The cluster analysis resulted in the selection of ten manual sampling sites (in Figure 1, Site 48 is not shown because it is very close to the upper Stephanie gauge). The relevant attributes of those sites are summarized in Table 2. The manual sites were grouped into two areas within Russell Creek, so the sampling could be done efficiently during storms by two operators, each following a continuous loop.

METHODS

Instrumentation

The Russell Main stream gauging site was installed in November 1991, and operated by Water Survey of Canada. In 1996 the original equipment was upgraded to fully digital operation. Stage was measured and recorded using a nitrogen bubbling system connected to a Water-log H-350 transducer, and recorded by a high-resolution Unidata 7000 series "Macro" data logger. Discharge was measured using the standard current metering technique, and rating curves were established to convert the measured stages into streamflow. Turbidity was measured using a D&A Instruments optical backscatter (OBS) probe calibrated in the range of 0-500 NTU and monitored by the data logger. An ISCO 3700C automatic sampler was used to collect water samples. The turbidity probe was installed in an ABS housing, which was installed on a steel mounting plate along with the sampler intake tube such that the sensor and intake were at a height of 20 cm above the base of the plate. In this way, the OBS probe "sees" the same water volume from which the sample is withdrawn. This assembly was placed in a pool in the stream channel. The sampler, data logger, stage recorder, power supplies, etc. were housed in a shelter on the stream bank. Identical instrumentation was used at the other sites, except that stage was measured with a Keller 210-S submersible transducer, and discharge was measured with a combination of current metering and salt dilution gauging. The data loggers were programmed to monitor mean stage, and minimum, mean, and maximum turbidity on a 5-min log interval. At upper Stephanie Creek, two ISCO samplers were used simultaneously above and below the landslide (Site 206) to characterize the sediment production from a landslide connected to the channel. The water samples were collected from the ISCO samplers regularly and analyzed for sediment concentration.

At the manual measurement sites, stream water was collected manually with a DH-48 sampler. Staff gauges were installed and were read each time samples were collected. Stream discharge at these sites was measured using salt dilution, and rating curves were developed. In the summer of 1998, additional automatic monitoring sites, consisting of stage and rainfall only, were installed at Sites 3 and 27 (Figure 1). These sites were used to derive a continuous record of streamflow at the other manual sites for storms that occurred after that time, based on the manual readings. Rainfall and total precipitation were measured at sites near Russell Main, upper Russell, and upper Stephanie. Rainfall was measured with tipping-bucket rain gauges, and total precipitation was measured with 16-inch (40-cm diameter) PVC standpipe gauges, monitored continuously.

Data Interpretation

The process of sediment production in high-energy coastal streams is extremely complex. Consequently, interpretation of suspended sediment and turbidity data is also very complex, and has been described in detail by Hudson (2001). Relationships between turbidity and suspended sediment depend on

Table 2a. Attributes of road-crossing sites selected for monitoring.

Source no.	Crossing type	Sub-basin [a]	Associated gully	Gully gradient at crossing (%)	Length of connected road (m)	Length of connected ditch (m)	Stability of crossing S [b]	Sediment source areas: Crossing fill slope (m^2)	Crossing cut slope (m^2)	Ditch cut slope (m^2)	Site elev. (m)
2	log	CN	G 61	30	360	135	4	294	300	450	660
5	pipe	CN	G 62	15	200	50	1	0	32	0	500
27	log	CS	G74	30	80	20	3	35	96	40	560
34	pipe	CS	LS181	50	500	140	2	15	0	420	600
10	pipe	UR	G 64	27	85	55	3	564	0	32	540
12	log	UR	G 65	15	75	10	1	3	20	0	510
45	log	S	G 75	25	120	120	4	291	0	960	760
46	washout	S	G 76	25	100	100	5	0	0	800	760
47	log	S	G 76	25	400	200	2	16	48	600	760

[a] CN = Confluence, north slope. CS = Confluence, south slope. UR = Upper Russell, above TS120. S = Stephanie. [b] S is a qualitative measure of the overall stability of the crossing cut-and-fill slopes, where 1 = most stable (low gradient, no evidence of erosion) and 5 = most unstable (evidence of total failure of the crossing). Categories 1 to 4 have degrees of erosion, including rill erosion, in and around the crossing.

Table 2b. Attributes of gullies selected for monitoring.

Gully no.	Road crossings	Sub-basin	Bed stability S1 [a]	Bank stability S2 [a]	Torrented vs untorrented T [a]	Length (m)	Total area (km^2)	Gauged area (km^2)	Gradient (%)	Geologic formation G [b]	Harvested vs unharvested H [c]
61 (upper)	2,3,4	CN	1	0	0	1200	0.584	0.532	57	1	1
61 (lower)		CN	1	1	1	800			20	1	1
62	5,6	CN	0	0	0	1400	0.260	0.236	47	1	1
64	9,10	CN	0	0	0	2000	0.780	0.764	53	1	1
65	11,12	CN	0	1	0	1700	1.024	1.014	21	1	1
74	26,27, 29,30	CS	1	1	1	1000	0.528	0.216	45	0	2
75	45	S	0	0	0	2500	1.300	1.272	25	0	0
76	46,47	S	1	1	1	2200	0.959	0.940	35	1	0

[a] The variables S1, S2, and T are category variables to describe gully stability, where 0 = stable and 1= unstable. [b] 0 = granitic and 1 = basaltic or basaltic surficial material draped over granitic bedrock. [c] 0 = unharvested. 1 = partially harvested. 2 = completely harvested.

grain-size distribution. The grain-size distribution of the suspended sediment in streams depends on sediment supply and hydrologic conditions. Consequently at any given site there is more than one relationship between turbidity and suspended sediment. This results in various suspended-sediment regimes.

A sediment-production regime is defined as a specific range of conditions that controls the relationship between SSC and turbidity at a point on a stream. The relationship that is usually in effect is called the normal regime (Figure 5). The relationships are curves because, as in-stream flow conditions and turbidity change, the grain-size distribution of the suspended sediment also changes. At low turbidity the normal regime consists entirely of fines (i.e., silt and clay). At higher flows (and hence, at higher turbidity) the stream is capable of carrying sand as well as fines, and the proportion of sand in the suspended load increases with increasing turbidity. During a large storm, sediment production will switch to a coarser regime. At Russell Creek this transition occurs in response to a specific rainfall intensity threshold. Under the coarse regime, the stream carries either a coarser grade or a higher proportion of sand for a given turbidity, resulting in a steeper SSC vs turbidity curve. After large storms, the sediment production switches to a finer regime that consists entirely of fines. This transition occurs because the supply of transportable sand is more limited than the supply of fines, and large storms have a tendency to flush most of the available sand from the watershed. Subsequent to this, the finer regime will remain in effect until erosional processes have made available a fresh supply of transportable sand, and there are storms capable of transporting it.

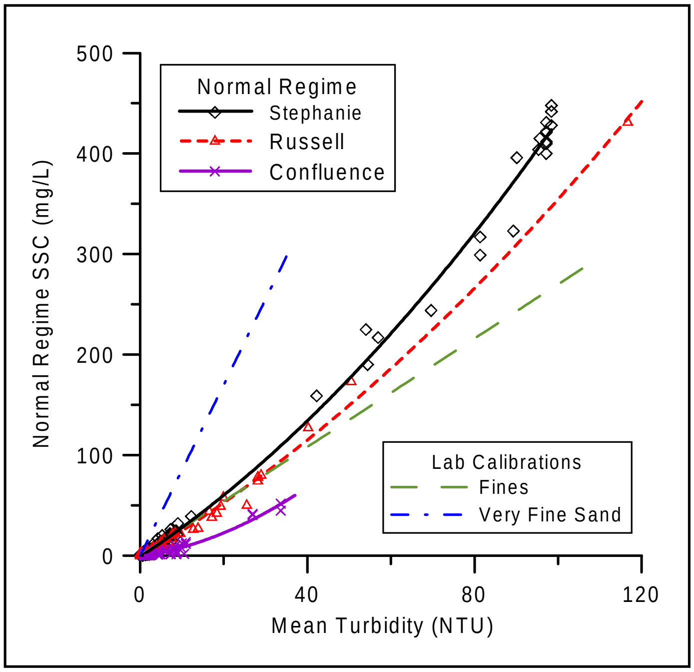

Figure 5. Comparison of normal regime SSC vs turbidity relationships at Russell Main, Stephanie, and the Confluence.

At Russell and Stephanie Creeks these regime transitions can be predicted from rainfall intensity and flow conditions. SSC vs turbidity relationships can be used to determine the relative proportion of sand and fines in the suspended load (Hudson 2001). These methods are integral to the calculation of SSC and sediment yield at the mainstem gauging sites.

For each storm, suspended sediment yield was calculated for each site that was monitored. Sediment yield is calculated as the product of the suspended sediment concentration (SSC) and streamflow or discharge (Q), as follows:

$$Yield(kg) = \frac{SSC \cdot Q \cdot L.I.}{1000} \qquad (1)$$

where

SSC is in mg/L,

Q is in m^3/s, and

L.I. is the log interval in seconds.

This gives the total mass of suspended sediment transported over a single log interval. In most cases, the interval is 5 minutes. Summing the 5-min yields over the duration of a storm gives the total storm sediment yield.

For the automatic gauging sites, SSC was calculated using the detailed methods described by Hudson (2001). For the manually sampled sediment source sites, streamflow and SSC hydrographs had to be reconstructed from point data. The streamflow records were reconstructed by developing relationships between the staff gauge readings and continuous stage records from a nearby reference site (either a mainstem site, or Sites 3 or 27). The reference site was chosen based on maximum correlation among the sites for which data were available, recognizing that there may be different relationships for rising and falling stage. This synthesized stage data were then converted to discharge using the appropriate rating curve. As an independent check on the synthesized flow data, flow volume ratios were plotted against catchment area ratios between the manual sites and the reference sites on which the synthesis was based. An example of the development of a storm hydrograph from point data and a summary of volume ratios appears in Appendix B.

The SSC data for the manual sites were reconstructed using methods similar to the reconstruction of the flow data. In this case, for a given site, relationships were developed between the SSC derived from sample data and either streamflow at the same site, or turbidity at a reference site, whichever produced the better results. Again, different relationships were developed for rising and falling SSC.

RESULTS

The grain-size distribution of suspended sediment in streamflow at mainstem sites is highly site-specific. A comparison of normal regime SSC vs turbidity relationships at Russell Main, the Confluence, and Stephanie Creek demonstrates the effects of channel characteristics on grain-size distribution (Figure 5).

Factors that affect grain-size distribution of the suspended sediment load include channel gradient and connectivity of sediment sources. A key feature of the graph is the slopes of the field calibrations relative to the lab calibration lines. The slope of the normal regime curve for the Confluence is less than that of the lab calibration for fines throughout its range. This indicates that the normal regime's suspended sediment load at the Confluence is composed entirely of silt and clay. This is partly due to the channel gradient, and also due to the fact that the channel above the Confluence is buffered by a long section of valley flat. The reduced gradient encountered by the gullies as they reach the valley flat causes the sand fraction carried in suspension to be deposited before reaching the main channel of Russell Creek. In contrast, the normal regime's sediment transport at Russell and Stephanie Creeks includes increasing sand content as turbidity rises. At Stephanie Creek, the normal regime includes a proportion of sand that varies from 0% at 10 NTU turbidity to 45% at 100 NTU; at Russell Creek, the proportion of sand varies from 0% at 40 NTU turbidity to 37% at 100 NTU, peaking at 70% at 800 NTU (Hudson 2001). The lower reaches of Russell Creek are incised, and are affected by a series of small sidewall failures. Russell Creek is also affected by inflows from Stephanie Creek, which has a higher channel gradient and contains sediment sources with a high degree of connectivity. These facts all have a significant bearing on sediment-budget accounting. The fact that the automatic gauging sites break up the system into smaller measurement reaches is very useful for calculating the sediment budget within each section.

It proved very difficult to obtain complete data upon which to base a sediment budget. One cause of the difficulty was the timing of events. Even the largest sediment-production events at Russell Creek have a time base of less than 24 h (Hudson and Sterling 1998). Other factors included difficulty of access due to snow, equipment malfunction, and inability to predict large events with any accuracy. In addition, many events occur over night, making it impractical and dangerous to do the sediment source sampling. However, to date, complete information has been collected for two large events on 01 October 1997 and 12 November 1998, as well as smaller events on 24 January 1998, 14 November 1998 and 20 November 1998. In addition to this, Gullies G75 and G76 were monitored automatically at Sites 45 and 46 during a storm in April 1996 that provided important information on sediment production during extreme conditions. Meteorological characteristics of the storms are summarized in Table 3.

Sediment-Production Characteristics of Selected Sources in Russell Creek

The suspended-sediment yields measured during the storms at mainstem and sediment source sites are summarized in Table 4.

The storm that occurred on 12–13 November 1998 resulted in a peak flow of 17.1 m^3/s on Russell Creek, with a peak SSC of over 50 mg/L (Figure 6). SSC derived from turbidity readings is in very close agreement with observed SSC. This is not a large event—the peak flow has been exceeded an average of 4.5 times/y since monitoring began in the fall of 1991, giving it a return period of <0.25 y. It therefore represents conditions that occur frequently at Russell Creek.

At Site 2, on the north slope of the Confluence, a large pulse of sediment was generated from the road crossing, whereas SSC levels generated by the gully above the crossing were relatively low (Figure 7a). Site 2 is the upper crossing of gully G61, of which the lower part is torrented (Figure 7b). The gully above Site 2 has an unstable bed, but is scoured of fine sediment (i.e., sediment that is capable of being transported in suspension).

Table 3. Characteristics of storms for which sediment budgets are calculated.

	Russell Main rain gauge (elev. 275 m)			Stephanie Cr. meteorological site (elev. 830 m)				
		Maximum storm intensities				Maximum storm intensities		
Storm start date	**Storm rainfall R_s (mm)**	**12-hour R_{12} (mm/12 h)**	**24-hour R_{24} (mm/24 h)**	**Storm rainfall R_s (mm)**	**Daily snow (mm)**	**12-hour R_{12} (mm/12 h)**	**24-hour R_{24} (mm/24 h)**	**Comments**
04 Apr 96	138	60	117	192	54.3	54	106	Snow, rain on snow
01 Oct 97	44	27	43	54	8.5	38	55	
12 Nov 98	68	54	68	58	0	58	59	
14 Nov 98	57	15	27	59	0	15	21	Rain on snow, 3-day event
20 Nov 98	28	27	41	63	5.5	42	56	Freezing level 740 m

Table 4. Measured storm sediment yields at gauging sites and sediment source sites. [a]

	4-6 April 1996			01 October 1997			12 November 1998		
Site	**Total (kg)**	**Above feature (kg)**	**Feature yield (kg)**	**Total (kg)**	**Above feature (kg)**	**Feature yield (kg)**	**Total (kg)**	**Above feature (kg)**	**Feature yield (kg)**
Russell Main	297 236.1	n.a.	n.a.	11 330.9	n.a.	n.a.	18 460.1	n.a.	n.a.
Confluence	*22 149.9*	n.a.	n.a.	1 866.6	n.a.	n.a.	2621.0	n.a.	n.a.
Upper Russell	n.m.	n.a.	n.a.	n.m.	n.a.	n.a.	909.0	n.a.	n.a.
Stephanie	171 279.7	n.a.	n.a.	8 724.8	n.a.	n.a.	12 888.4	n.a.	n.a.
Upper Steph./LS206	*16 291.0*	*12 311.7*	*3 979.3*	524.6	326.0	198.6	1 234.0	1531.7	297.7
G61 / Site 2	n.m.	n.m.	n.m.	81.8	26.5	55.3	239.0	39.7	199.3
G62 / Site 5	n.m.	n.m.	n.m.	13.7	10.8	2.8	18.5	11.5	7.0
G64 / Site 10	n.m.	n.m.	n.m.	279.3	59.4	219.9	408.6	57.9	350.7
G65 / Site 12	n.m.	n.m.	n.m.	211.0	177.9	33.1	463.9	384.3	79.6
G74 / Site 27	n.m.	n.m.	n.m.	n.m.	n.m.	n.m.	428.3	364.0	64.3
LS181 / Site 34	n.m.	n.m.	n.m.	29.9	15.0	14.9	28.6	40.7	-12.1
G75 / Site 45	8 799.5	1 747.5	7052.0	166.8	143.7	23.1	181.5	123.9	57.6
G76 / Site 46	23 883.8	23 883.8	0.0	2 822.1	2 735.9	86.2	2 680.8	2 690.5	-9.7
G76b / Site 47	*374.9*	*86.7*	*288.2*	15.2	3.5	11.7	69.1	16.7	52.4
	14 November 1998			**20 November 1998**			**24/25 January 1998**		
Russell Main	2 806.3	n.a.	n.a.	4 863.5	n.a.	n.a.			
Confluence	1 247.8	n.a.	n.a.	992.0	n.a.	n.a.			
Upper Russell	276.0	n.a.	n.a.	554.2	n.a.	n.a.			
Stephanie	915.7	n.a.	n.a.	2 841.6	n.a.	n.a.			
Upper Steph./LS206	24.3	0.00	24.3	2.8	0.0	2.8			
G61 / Site 2	n.m.	n.m.	n.m.	8.4	0.0	8.4			
G62 / Site 5	n.m.	n.m.	n.m.	2.0	1.1	0.9			
G64 / Site 10	n.m.	n.m.	n.m.	23.7	0.0	23.7	12.0	0.0	12.0
G65 / Site 12	n.m.	n.m.	n.m.	126.4	127.2	-0.8	44.3	8.6	35.7
G74 / Site 27	5.4	5.4	0.0	n.m.	n.m.	n.m.			
LS181 / Site 34	0.0	0.0	0.0	0.0	snow conditions				
G75 / Site 45	0.0	0.0	0.0	0.0	Min T <0	0.0			
G76 / Site 46	22.8	22.8	0.0	0.0	Min T <0	0.0			
G76b / Site 47	0.0	0.0	0.0	0.0	Min T <0	0.0			

[a] Values in italics are estimated. n.m. = not measured. n.a. = not applicable.

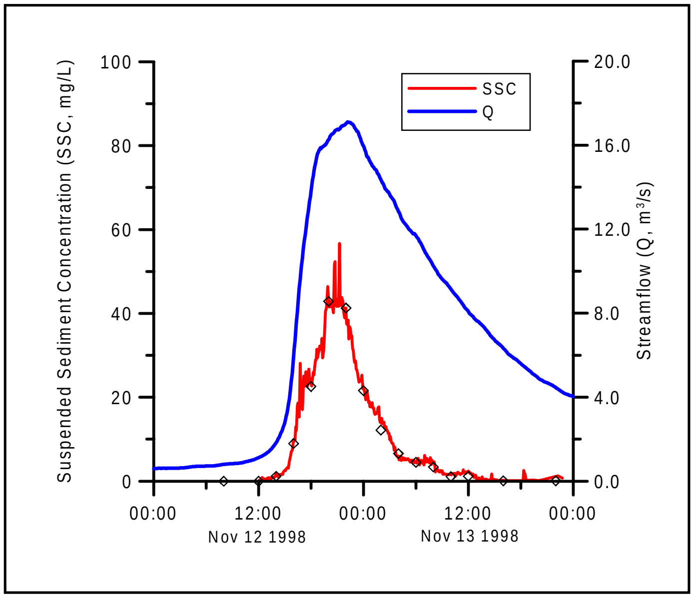

Figure 6. Streamflow and SSC, Russell Creek, 12 November 1998. The blue line is streamflow, the red line is SSC calculated from turbidity, and the black diamonds are observed SSC from samples.

In contrast, at Site 12 in gully G65 (Figure 1), sediment production from the gully is higher, but the crossing produces almost no sediment (Figure 8a). This is evident from the SSC concentrations above and below the crossing, which are very close together. This gully has a stable bed, and unstable sides (Figure 8b).

On the south slope of the Confluence, there are two prominent features that were selected for sampling (Figure 9a); gully G74, the unstable gully on the left side of the slope, and the landslide scar (LS181) to the right of gully G74. The photograph was taken in the summer of 1994. Gully G74 experienced a debris flow in October 1994. Photographs taken in the spring of 2000 show evidence of ongoing instability in gully G74, while the landslide scar is more difficult to pick out because of re-growth of vegetation (Figure 9b). At Site 27 on gully G74, most of the sediment is derived from the gully itself, with a minor contribution from the crossing (Figure 10). At Site 34, at the base of landslide LS181, sediment-production levels are relatively low (Figure 11), with the crossing actually accumulating sediment (i.e., the SSC above the crossing has a higher peak than that below). This occurs because there is a small sump at the upstream end of the culvert. Water ponds in the sump before flowing through the culvert, allowing the sand to settle out. Because water samples were collected in the ditch

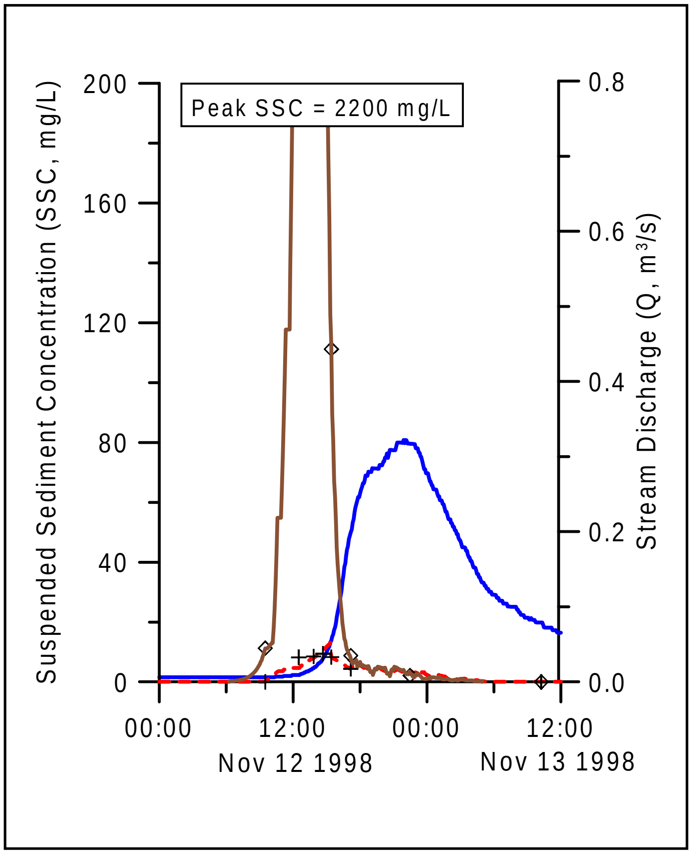

Figure 7a. Streamflow and SSC at Site 2 above (red dashed line) and below (brown solid line) the crossing. The diamonds and plus signs represent SSC from samples.

Figure 7b. Gully G61. Site 2 is the upper crossing.

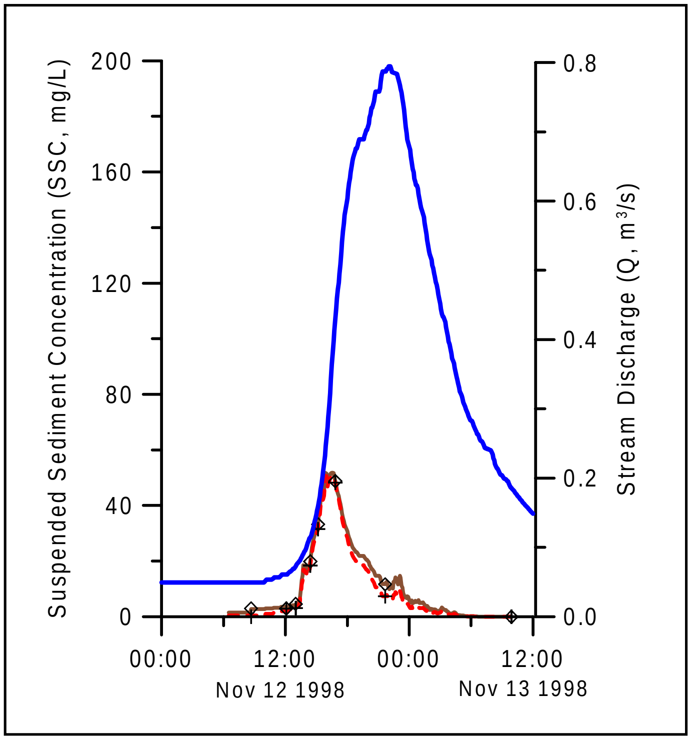

Figure 8a. Streamflow and SSC at Site 12 above (red dashed line) and below (brown solid line) the crossing. The diamonds and plus signs represent SSC from samples.

Figure 8b. Gully G65 looking upstream from Site 12. Most of the sediment is derived from the gully, due to its unstable sides.

Figure 9a. Russell Confluence, north slope, as of summer 1994, prior to debris flow in gully G74 (on left of slope). The landslide scar LS181 (center of photo) is also clearly visible, and was identified as a potential sediment source.

Figure 9b. Russell Confluence, north slope, as of spring 2000. Note ongoing instability in gully G74, whereas the landslide scar LS181 is becoming re-vegetated, and is hard to see.

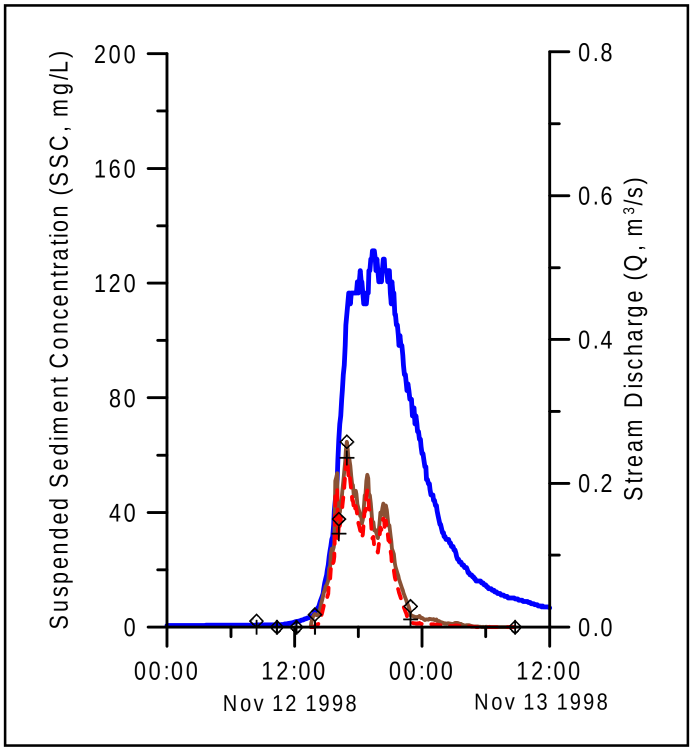

Figure 10. Streamflow and SSC at Site 27 above (red dashed line) and below (brown solid line) the crossing. The diamonds and plus signs represent SSC from samples.

above the crossing, those samples contained the sand, silt, and clay that had eroded from the ditch and other sources, whereas the water sampled below the culvert likely contained only silt and clay.

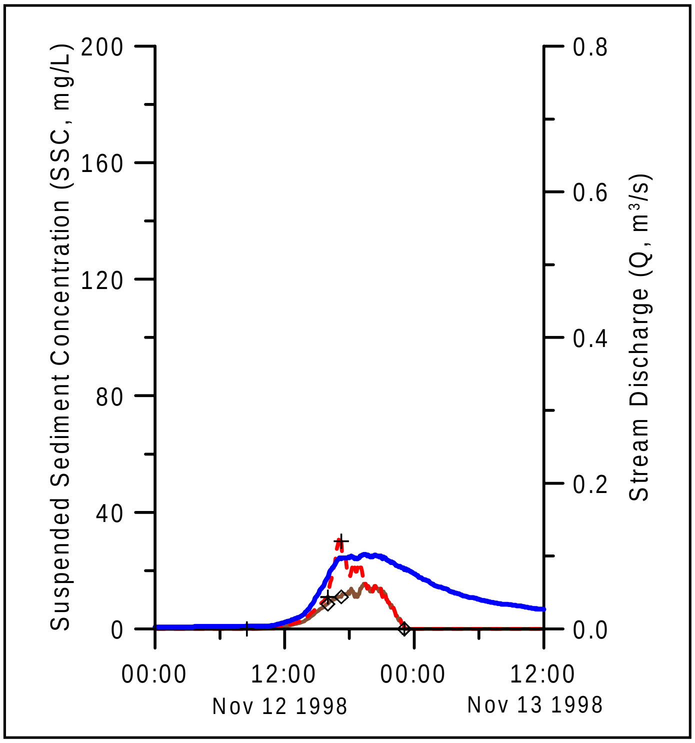

Figure 11. Streamflow and SSC at Site 34 above (red dashed line) and below (brown solid line) the crossing. The diamonds and plus signs represent SSC from samples.

In Stephanie Creek, the two large gullies (gullies G75 and G76) show markedly different sediment-production behaviour (Figure 12a). Gully G75 is a stable underlain by granitic bedrock and produces very little sediment despite its size, whereas gully G76 lies within the Karmutsen formation and experiences frequent debris flows. Consequently, it is one of the largest sediment producers in Russell Creek. Sediment is entrained from the debris flow levees that line the gully sides whenever flow rises in response to storms (Figure 12b).

At upper Stephanie Creek, the sediment yield from a small landslide (LS206, Figure 13a) was measured by subtracting the sediment yield derived from the automatic gauging site at upper Stephanie from the yield derived from manual sampling above the landslide (Figure 13b). In this case, the continuous record for upper Stephanie above landslide LS206 was based on a relationship between sampled SSC and turbidity as measured at the gauging site. Directly connected landslides on the sidewalls of incised channels constitute an important type of sediment source in Stephanie and lower Russell Creeks. Landslide LS206 is the uppermost feature of this type in Stephanie Creek. Sediment production above that point is derived from gullies and road sources. For the 12 November storm, the yield from landslide LS206 was relatively small compared to the yield from upper Stephanie. However, the variability in SSC below the feature compared to that above is a direct result of the proximity of the sampler to the feature, and of the process by which the landslide delivers sediment to the channel. The rapid fluctuations in SSC below landslide LS206 (Figure 13b, brown line) indicate that sediment produced from the landslide scar is delivered to the channel by means of a series of small slumps. The sediment production from sources above landslide LS206

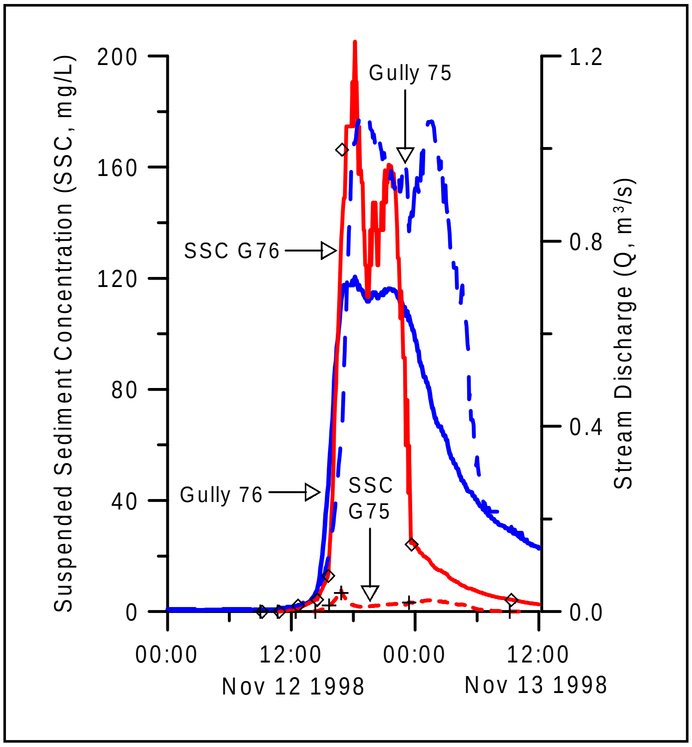

Figure 12a. Streamflow and SSC in gullies G75 (blue and red dashed lines) and G76 (solid blue and red lines). In both cases, the SSC is from above the crossing.

is integrated over time by the flow, because those sources are dispersed throughout the upper watershed, resulting in a relatively smooth SSC hydrograph (Figure 13b, red dashed line).

The sediment yield data from Site 45 are a special case. In November 1995, a debris flow occurred in gully G76. The culvert was plugged, which caused the flow to run down the road grade to enter gully G75 above the crossing. The washout caused a large amount of erosion to both the road surface and the ditch where it flows into the gully on the upstream side of Site 45 (Figure 14a). During the storm of 4–6 April 1996, ongoing road and ditch erosion likely contributed most of the high sediment yield derived from the crossing (Figure 14b, Table 4). In the summer of 1996, the road was deactivated and the crossing at Site 46 was restored. The deactivation resulted in reduced sediment production from the crossing during subsequent storm events.

These measured yields were used to build the sediment-budget model. That model consists of three components: a road-crossing model, a gully model, and a landslide model.

Road-Crossing Model

To develop a model of sediment yield from road crossings, stepwise regression analysis was used to select the best set of predictors (Draper and Smith 1981). All the attributes listed in Table 2a were considered. For a given storm, the best predictor of sediment yield was the total area of cut-and-fill slopes adjacent to the crossing and connected to the stream channel (Figure 15). There is clearly an interaction with storm rainfall, because the slope of the yield vs area relationship is greater for the larger storm. Therefore, to build a general model of sediment yield from crossings, total storm rainfall and the maximum 12-h and 24-h intensity parameters were introduced into the analysis, as well as interaction variables between the rainfall variables and the crossing attributes. Stepwise regression analysis was applied to the lumped data set. Data from Site 45 had to be excluded because “unusual” yields from that site—both in the post-washout and post-deactivation phases—influenced the regression analysis. The analysis identified a model consisting of the total area of cut-and-fill slopes adjacent to the crossing and connected to the stream channel (A, m^2) and the interaction between A and storm rainfall (R_S, mm). The model of total storm sediment yield from crossings (Y_C, kg) is:

$$Y_C = 0.0137 R_S \cdot A - 0.29A \tag{2}$$

($R^2 = 93.4\%$, s.e. = 29.75)

Figure 12b. Gully G76 looking upstream from Site 46. The gully is lined with debris flow deposits such as these along its whole length.

If sediment yield data from Site 45 are re-introduced into the analysis, then the resulting equation for storm sediment yield from crossings becomes:

$$Y_C = 0.131 R_S \cdot A - 5.82A \qquad \text{(2a)}$$

(R^2 = 98.2%, s.e. = 621.3)

Figure 13a. Site 206, the landslide at upper Stephanie monitored for sediment yield.

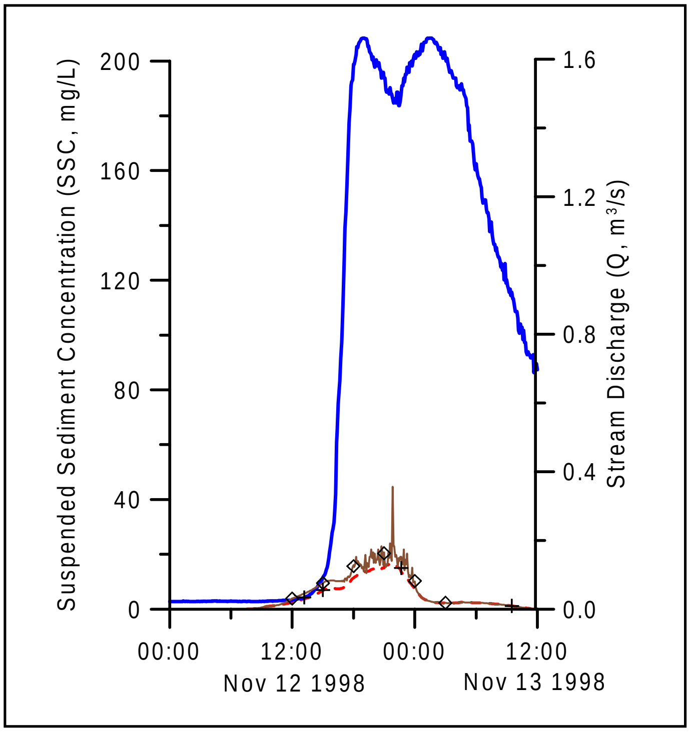

Figure 13b. Streamflow and SSC at upper Stephanie above and below Site 206, 12 November. Note the variability of the SSC below the landslide (solid brown line) as compared to that above (red dashed line).

Because the model coefficients of Equation 2a are an order of magnitude greater than those of Equation 2, the resultant calculated yields would be an order of magnitude greater than the chronic sediment yield that occurs from crossings under normal conditions. This equation might represent unusual post-failure sediment production, however it is based on data from one storm event at one site.

Measured and calculated yields are given in Table 5, along with storm rainfall. Note that R_S is calculated according to the elevation of the site, using rainfall – elevation relationships that are specific to each storm.

Figure 14a. Ditch above Site 45 after the washout of November 1995 and prior to road deactivation.

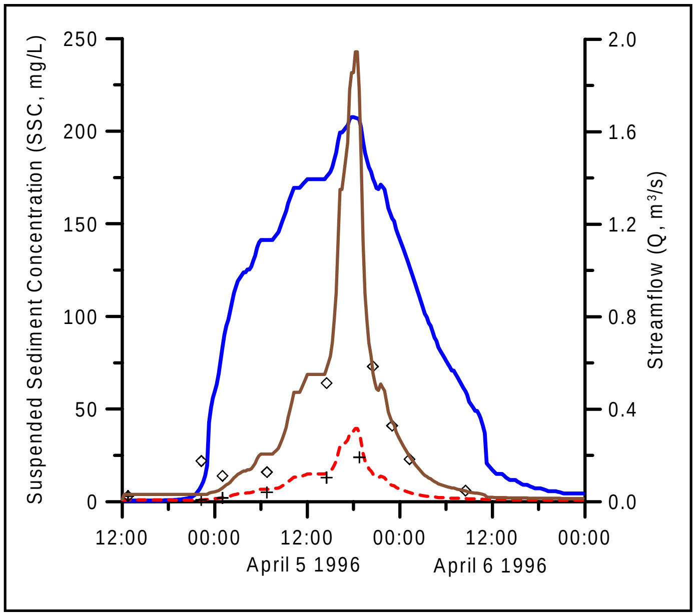

Figure 14b. Streamflow in gully G75, and SSC above (red dashed line) and below (solid brown line) Site 45 in its post-washout state, April 1996 storm.

There is a bias in the model that becomes apparent if measured yield is plotted against calculated yield (Figure 16). The bias occurs because ditch length and area of ditch cut slopes are not significant terms in the model. However, it is known that ditch erosion contributes sediment to stream crossings, and that the sediment eroded off road surfaces is also delivered to crossings by way of ditches (e.g., Reid and Dunne 1984). For this reason, the model is likely to underestimate sediment yield. Therefore, a one-tailed test can be used to account for road surface and ditch erosion (Table 5, Figure 16). In Figure 16, the solid line represents a relationship between measured and calculated yield. The dashed line is equal to the solid line minus 2 s.e.[1] All the data points that fall within that band represent erosion from only the cut-and-fill slopes adjacent to the crossing. Thus, any data points that lie above the dashed line represent sediment production from the crossing, and also include ditch and/or road surface erosion. In Table 5, these values are calculated and divided by the length of connected ditch emptying into the crossing, resulting in a logarithmic model of road erosion as a function of storm rainfall:

$$E_B = 0.83 \cdot \ln(R_S) - 3.18 \qquad (3)$$

(R^2 = 98.2%, s.e. = 0.059)

$$E_M = 6.18 \cdot \ln(R_S) - 19.8 \qquad (4)$$

(R^2 = 75.4%, s.e. = 1.509)

where

E_B and E_M are branch road and mainline road erosion respectively, in kg/m of ditch connected to the stream channel at the crossing.

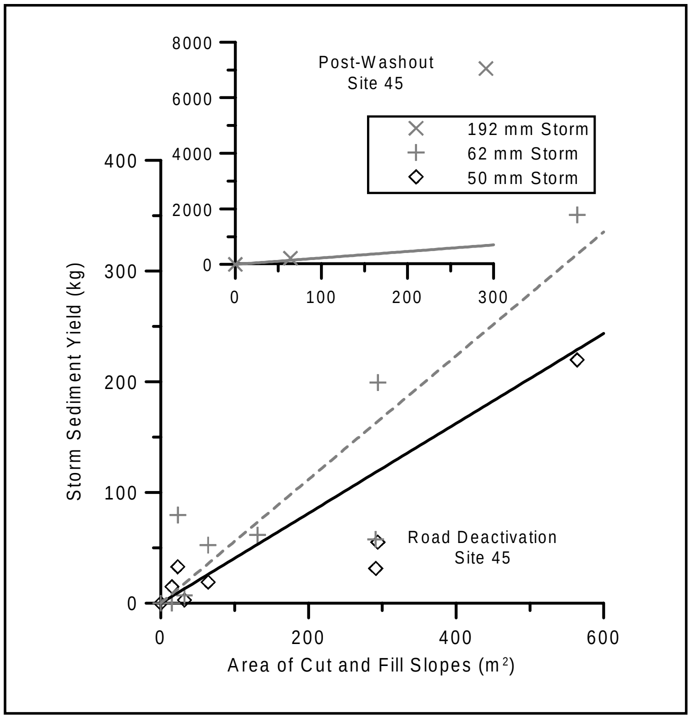

Figure 15. Sediment yield at road crossings vs area of cut-and-fill slopes for selected storms.

Branch road erosion consists primarily of ditch erosion, whereas mainline erosion also includes contributions of fine sediment from the road running surface.

There is a threshold of 25 mm of storm rainfall required before mainline road surface will occur. For branch erosion, the threshold is higher, at about 42 mm (Figure 17). The reason for the difference in the threshold is that on mainline haul roads, fine sediment is continually being created by truck traffic. This sediment is more easily eroded than ditch sediments or sediment on the running surfaces of occasional-use roads. This model describes chronic sediment production from road surfaces. Like the road-crossing model, it does not account for episodic sediment production such as the April 1996 event at Site 45, where the sediment produced by ditch erosion was over 50 times the erosion rate that would be predicted by the model for normal branch roads (Figure 17).

The running surfaces of mainline roads are known to be the largest producer of fine sediments (Reid and Dunne 1984). Frequent-use mainline road surfaces produce one order of magnitude more sediment than moderate use or temporarily unused mainline roads. Reid et al. (1981) broke down sediment yield from mainline road erosion into categories according to road use. Annual yield during one measurement year was reported as 73 kg/y/m of road length during heavy use periods and 9.75 kg/y/m during temporary non-use periods. These results were derived from reconstructing unit hydrographs and SSC rating curves for culvert flows, from rainfall records. Measured rainfall for the year for which the yield was calculated was 3468 mm. Mainline roads were reported as sustaining heavy use 48% of the time. Temporary non-use periods included weekends and overnight during the week. This results in a weighted average yield of 160.4 kg/m/y, and includes sediment yield from road surfaces, cut slopes, and ditches.

While the methods used by Reid were different from the methods described in this report, both methods are based on storm rainfall. Therefore, Reid's results can be used to verify Equation 3. This is important because Equation 3 is based on data from only one site with 10 m of connected ditch, and therefore a small error in measuring any of the quantities can lead to a large error in applying the equation.

A total of 310 measured storm runoff events have been identified for Russell Creek between November 1991 and July 1999,

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[1] Normally, in a two-tailed test the regression line would be drawn with a ±1 s.e. band, creating an error band of 2 s.e. in width on either side of the regression line. Because this is a one-tailed test, all the error is loaded onto the negative side of the regression line. In this way, we are treating overprediction as due to random error, and underprediction as due to a systematic error, resulting from the fact that road surfaces and ditches are not represented in the crossing yield model.

Table 5. Measured and calculated crossing yields. [a]

Site	Area (m^2)	Rain (mm)	Measured yield, Y (kg)	Calculated yield, Ycalc (kg)	Road erosion (kg)	Road erosion/m ditch	
						Branch, E_B (kg/m)	Main, E_M (kg/m)
Site 2	294	51.3	55.3	121.4	0.0		
Site 5	32	47.9	2.8	11.7	0.0		
Site 10	564	48.7	219.9	212.8	7.1	0.128	
Site 12	23	48.1	33.1	8.5	24.6		2.460
Site 34	15	50.0	14.9	5.9	9.0	0.060	
Site 45	291	53.5	47.6	128.8	0.0		
Site 46	0	53.5	0.0	0.0	0.0		
Site 47	64	53.9	19.2	28.7	0.0		
Site 2	294	76.0	199.3	212.6	0.0		
Site 5	32	60.3	7.0	8.9	0.0		
Site 10	564	65.4	350.7	333.8	16.9	0.307	
Site 12	23	61.6	79.6	4.4	75.2		7.516
Site 27	131	59.0	64.3	59.6	4.7	0.235	
Site 34	15	59.0	40.7	-0.5	41.2	0.294	
Site 45	291	59.0	57.6	142.5	0.0		
Site 46	0	59.0	-9.7	-8.3	0.0		
Site 47	64	59.0	52.4	24.9	27.5	0.138	
Site 2	294	35.5	8.4	57.7	0.0		
Site 5	32	31.0	0.9	4.3	0.0		
Site 10	564	32.1	23.7	84.7	0.0		
Site 12	23	31.3	-0.8	3.2	0.0		
Site 10	564	24.6	12.0	26.4	0.0		
Site 12	23	22.0	0.0	0.0	0.0		0.000
Site 12	23	44.0	35.7	7.2	28.5		2.851
Site 45	291	192.2	7052.0	681.9	6370.2		
Site 46	0	192.2	0.0	0.0	0.0		
Site 47	64	192.2	288.2	150.0	138.2	1.223	

[a] Road and ditch erosion are determined using a one-tailed test, by assuming road erosion to be any yield in excess of a lower 1 s.e. band.

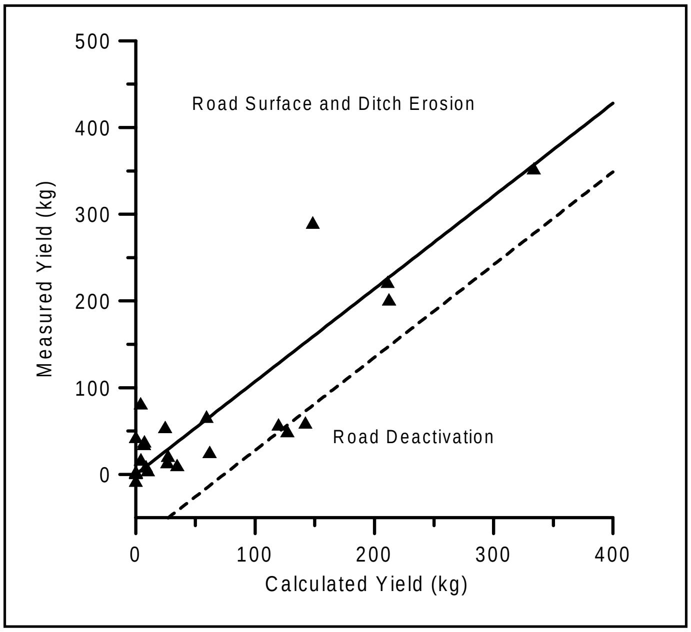

Figure 16. Measured vs calculated sediment yield from crossings (solid line). A one-tailed test suggests that the data points within the -2 s.e. band (dashed line) represent yield from cut-and-fill slopes, whereas points above the solid line include ditch and road erosion.

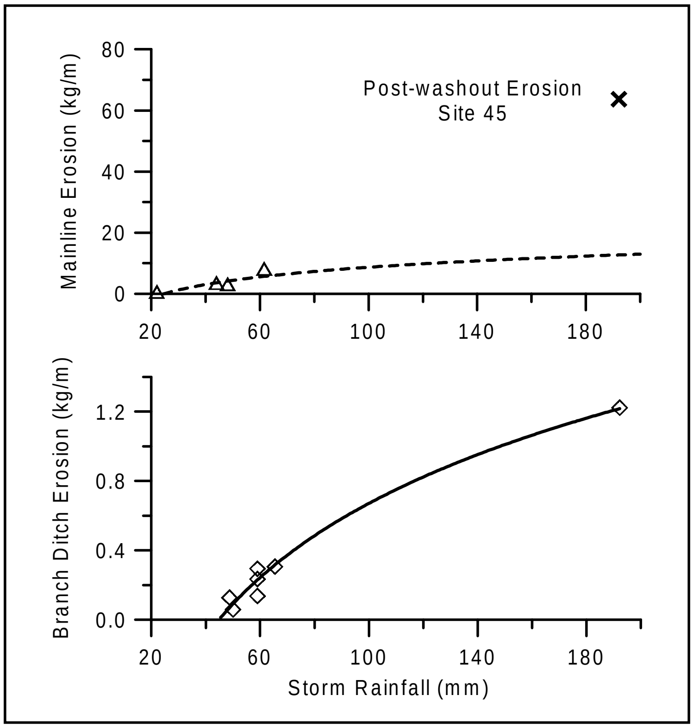

Figure 17. A model of sediment yield under "normal" conditions from ditches and from running surfaces of mainline roads. Note that the ditch yield from Site 45 in post-washout phase is about an order of magnitude greater than the model predicts.

of which 122 were over the threshold of 25 mm of rainfall. Storm rainfall contributing sediment from mainline roads ranged from 25 to 133 mm, and averaged 49 mm. Total annual rainfall for the period averaged 1826 mm. Application of Equation 3 to the storm record resulted in a mean annual yield from mainline roads of 54.6 kg/m of connected ditch. If the storm rainfall for the 310 events is multiplied by a factor of 1.9 to match the total annual rainfall for Reid's study, application of Equation 3 to this amplified storm data set results in an average annual yield of 156.7 kg/m. This matches Reid's results for average mainline road use.

Gully Model

Many of the gullies that were monitored have crossings above the monitoring site; therefore, the first step in developing the gully model was to remove the sediment produced by those additional crossings from the measured gully yields. This resulted in a data set that is summarized in Table 6.

For each gully, it was found that there is a relationship between storm sediment yield and storm rainfall (R_S) that takes the form

$$Y_G = b_0 + b_2 R_S{}^2 \qquad (5)$$

where

Y_G is the gully yield in kg, and

b_0 and b_2 are coefficients (Figure 18).

Note that this is a second order polynomial without the linear term. The coefficients of this equation are given in Table 6 for each gully. Note also that the April 1996 storm is an important data point in this relationship that was measured directly only on gullies G75 and G76. The regressions of yield vs rainfall were first performed on the data for all gullies excluding the April 1996 storm. Then the regressions were re-done for gullies G75 and G76 with the April 1996 yields included. Based on a linear relationship between the two sets of coefficients for gullies G75 and G76, yields from the other gullies for the April 1996 storm were estimated.

A general model of gully yield was developed to predict the coefficients of Equation 5 from gully attributes listed in Table 2b. Also included were interaction variables. As with the crossing model, the gully yield model predictors were identified using stepwise regression, resulting in the following equations:

$$b_2 = 0.0407 \cdot A_G - 0.134 \cdot T + 0.773 \cdot TA_G - 0.0062 \cdot S1 + 0.0737 \cdot S2 \qquad (6)$$

$$b_0 = 1243 \cdot b_2 T - 1302 \cdot b_2 - 85.7 \cdot T - 16.4 \cdot S1 + 84.3 \cdot S2 \qquad (7)$$

The relationship between the coefficients and gully attributes (gully stability S1, S2, and T, and area A_G, m^2) is shown in Figure 19. The terms S1, S2, and T are category variables that represent the stability of the channel bed (S1) and channel banks

Table 6. Gully yield data set for modeling. [a]

Gully no.	Stability classification variables			Gauged area	Y vs R coefficients		Comment
	S1	S2	T	(km^2)	b_0	b_2	
61	1	0	0	0.532	-36.6	0.0155	Scoured at Site 2, deposition lower
62	0	0	0	0.236	-1.61E-02	3.70E-06	Stable
64	0	0	0	0.764	-44.1	0.0330	Stable
65	0	1	0	1.014	-65.4	0.1150	Unstable banks
74	1	1	1	0.216	-24.3	0.1097	Torrented, active sediment sources
75	0	0	0	1.272	-67.5	0.0524	Stable
76	1	1	1	0.940	-59.0	0.6990	Torrented, active sediment sources

Gully no.	Storm rain (mm)	Storm yield (kg)	Storm rain (mm)	Storm yield (kg)	Storm rain (mm)	Storm yield (kg)	Storm rain (mm)	Storm yield (kg)
61	175.6	450.0	51.3	26.5	80.9	18.6	35.5	0.0
62	160.0	0.102	47.9	0.0	60.3	0.0	31.0	0.0
64	163.9	844.6	48.7	59.4	65.4	57.9	32.1	0.0
65	161.0	2918.0	48.1	178.8	61.6	301.9	31.3	127.2
74	165.9	2993.9			59.0	359.7	17.0	5.4
75	185.4	1747.5	53.5	143.7	59.0	123.9	17.0	0.0
76	185.4	23 970.5	53.5	2 739.4	59.0	2 707.2	17.0	22.8

[a] Includes only the significant gully attributes. Road-related contribution is subtracted.

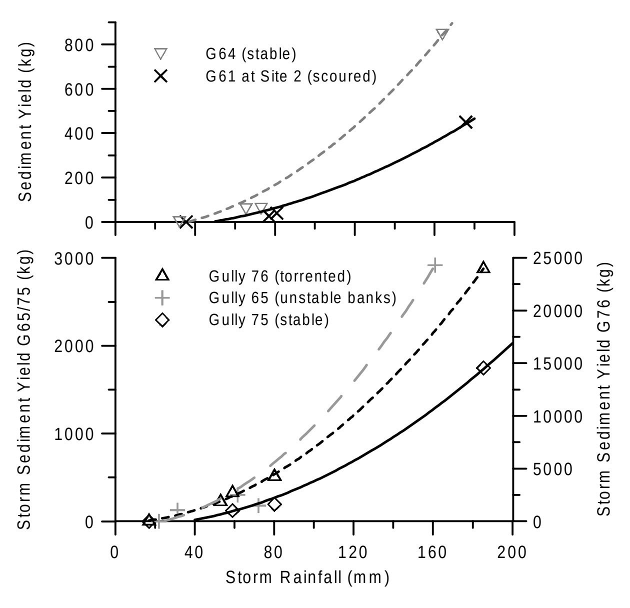

Figure 18. Gully yield as a function of storm rainfall.

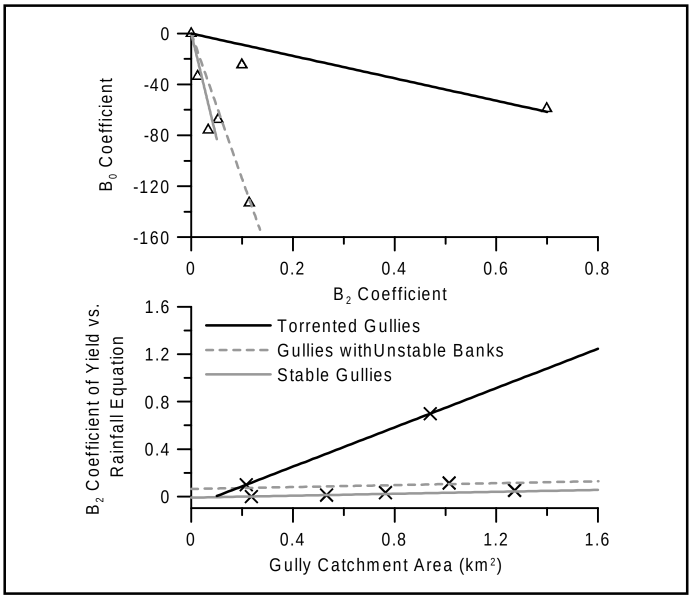

Figure 19. The gully yield model consists of a method of predicting the equation coefficients of the curves in Figure 18, based on gully attributes.

(S2) of the gully in question, and whether or not the gully is torrented. Each term is 1 if unstable and 0 if stable; together they form a single parameter to describe gully stability. Thus, Equations 5–7 form a 3-parameter model built on 27 data points. The overall R^2 is 99.9% with a weighted RMS error of 4.8%.

Landslide Model

To determine the chronic sediment yield from landslides, it was assumed that a landslide would deliver a volume of sediment to the channel that is proportional to its surface area, and to rainfall intensity (Rood 1984). The landslide model is based on the measured yields from landslide LS206 (Table 7, Figure 20), with the exception of the April 1996 event, for which landslide yield was not measured directly, and 20 November 1998, during which landslide LS206 was under snow. As an alternate method, the yield from lower Russell (below the Confluence) was divided by the total landslide area in lower Russell (2330 m^2) to estimate landslide yield for those storms. The yield from lower Russell is estimated as the yields from Russell Creek, minus the sum of yields from the Confluence, Stephanie Creek, and additional yields from two gullies in lower Russell. Because the Confluence gauging site was not operating at that time, a method was needed to estimate the yield at the Confluence for the April 1996 event. If all measured storm yields from the Confluence are plotted against those of Russell Creek (Figure 21), the resulting linear relationship has an R^2 of 95.0% and a s.e. of 506 kg. This uncertainty in the Confluence yield leads to an error in the estimated landslide yield of ± 0.2 kg/m^2.

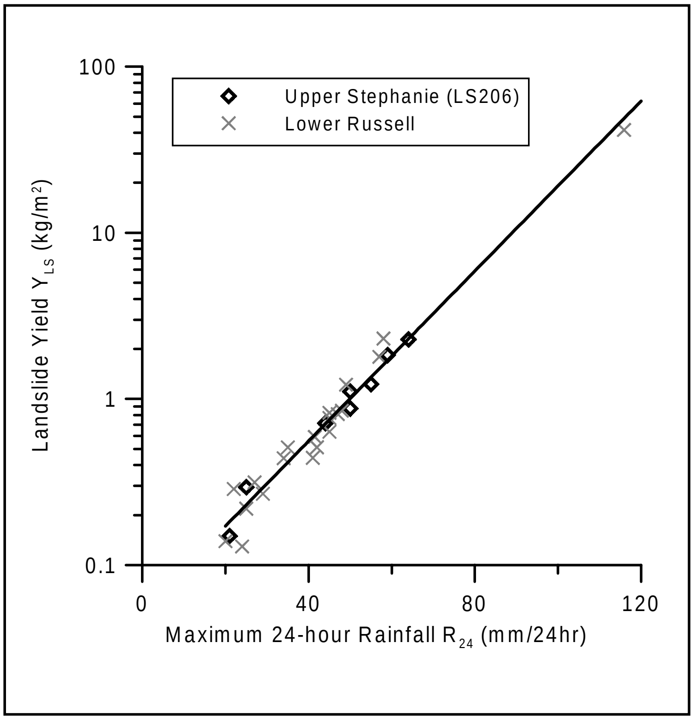

Figure 20. Landslide yield per unit area, as a function of the maximum 24-h storm rainfall intensity. The graph includes yields calculated from LS 206 (upper Stephanie) and from lower Russell landslides.

Table 7. Table of measured landslide yields and storm rainfall characteristics.

Date	R_s (mm)	R_{24} (mm)	Reference site	Upper Stephanie yield Above 206 (kg)	Upper Stephanie yield Below 206 (kg)	Landslide yield (kg/m^2)
04 Apr 96	133	116	R1			41.60
30 Sep 97	42	43	Steph	630.7	838.3	1.28
01 Oct 97	55	55	Steph	326.0	524.6	1.23
15 Oct 97	40	50	Steph	191.0	333.2	0.88
16 Oct 97	20	50	Steph	365.1	545.0	1.11
30 Oct 97	103	64	Steph	272.2	642.5	2.29
02 Nov 97	57	42	Steph	1476.3	1666.4	1.17
05 Nov 97	50	44	Steph	624.9	740.9	0.72
12 Nov 98	58	59	Steph	1234.0	1531.7	1.84
14 Nov 98	44	21	Steph	0.0	24.3	0.15
20 Nov 98	28	42	R1			0.59

The best predictor of landslide yield was the 24-h maximum rainfall intensity (R_{24}), for an exponential relationship as follows:

$$Y_{LS} = 0.0567e^{0.0572 \cdot R_{24}} \qquad (8)$$

($R^2 = 99.2\%$)

where

Y_{LS} is landslide yield in units of kg/m^2 of landslide surface area.

Application of the Sediment-Budget Model

As discussed above, the sediment-budget model is an accounting procedure in which the yields from all significant sediment sources in a sub-basin of Russell Creek are added up and compared to the measured mainstem yield for that sub-basin. Measured source yields were used where available, and all other yields are calculated using the yield models described above. This results in a sediment-budget model that is essentially rainfall based. Sediment budgets were calculated for the 1 October 1997 storm and for three storms in November 1998; as well, a "tentative" budget was calculated for the April 1996 storm.[2]

The sediment budget is applied to sub-basins of Russell Creek: Russell Creek above the Confluence, Stephanie Creek, and lower Russell. For the Confluence, the budget applies to the area between the Confluence gauging site and the upper Russell gauging site. Similarly, at Stephanie Creek, upper Stephanie is considered as one unit and the budget applied to the area that drains to the channel below the upper Stephanie gauge (Figure 1). Because upper Russell began operation in the middle of October, suspended sediment yield had to be estimated for the storm of 1 October 1997. A relationship was developed between the measured sediment yields at upper Russell and the Confluence (Figure 21). The resulting linear relationship has an R^2 of 90.0% and a s.e. of 141 kg.

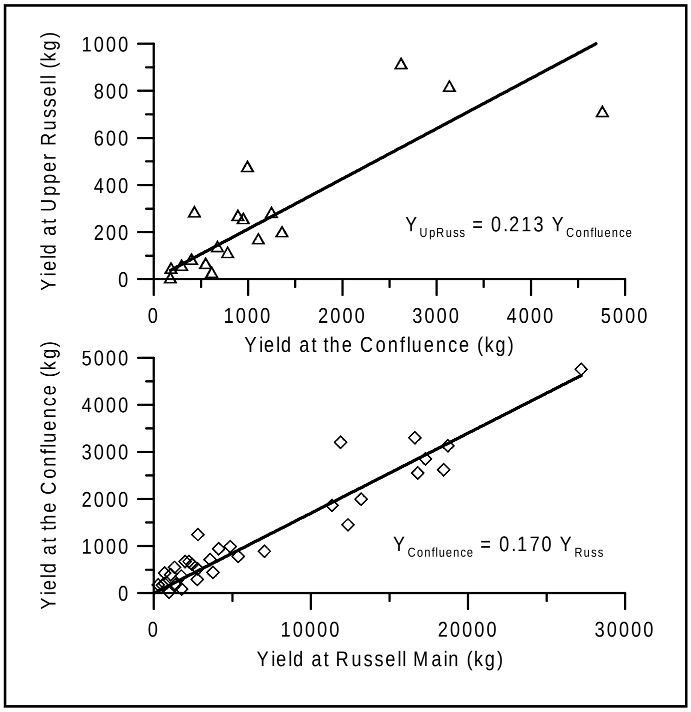

Figure 21. Relationships between storm yields at Russell Main, the Confluence, and upper Russell.

The sediment-budgeting procedure for Stephanie Creek and lower Russell is relatively straightforward, because the sediment sources in those sub-basins are directly connected to the channel network. However, this is not the case for the Confluence, because the valley flat absorbs the sand component of the suspended load before it reaches the main channel. Therefore, it was necessary to multiply the source yields by the proportion of fines found in the sediment sources.

The mean grain-size distribution of different source types was reported by Maynard (1991) and later verified by Paulig (1996) by performing sieve analysis on samples collected from selected sources (Table 8). Because only the sand and silt fractions are transportable in suspension, the proportion of fines (Pf_T) in the transportable load is equal to:

$$Pf_T = \frac{\%\,fines}{\%sand + \%\,fines} \qquad (9)$$

Thus for the Confluence, the yields from road crossings and ditches, mainline road surfaces, and landslides are multiplied by 0.16, 0.22, and 0.24 respectively. To derive a multiplier for gully yield is somewhat more complex, because the proportion of sand transported by channels is related to hydrologic conditions and channel gradient (Hudson 2001).

The proportion of sand in the suspended load is in part related to sediment supply; however, an examination of selected events where supply is not a limiting factor shows there are logarith-

Table 8. Mean grain-size distribution of sediment sources, by type.

Source type	% Sand	% Fines	% Fines in transportable fraction
Cut-and-fill slope, ditches	42	8	16.0
Road grade	35	10	22.2
Slope failure	45	13	22.4
Debris flow	35	3.5	9.1

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[2] Details available on request. Sediment-budget calculations are summarized in Table 10.

mic relationships between the proportion of sand in the sediment yield and the channel gradient (Table 9a, Figure 22a). The coefficients of the relationships are related to the logarithm of storm rainfall (Figure 22b and 22c). This allows the proportion of sand transported by a channel to be calculated, based on the channel gradient and the storm rainfall. The mean gradient of gullies in the Confluence is 41%; thus there is a relationship between the proportion of sand (hence the proportion of fines) in the sediment load carried by gullies, and storm rainfall (Table 9b, Figure 22d). An equation to calculate the proportion of the gully load transported to the main channel in the Confluence is:

$$P_{fines} = 1.89 - 0.334 \cdot \ln\left(R_S\right) \qquad (11)$$

or, Equation 11 can be expressed as a percentage by multiplying the coefficients by 100.

The sediment-budget model was very successful (Table 10). For the November 1998 storms, error in the budget was within 10% for sub-basins and for Russell Creek as a whole. Error was somewhat higher for the 1 October 1997 storm, at between 9 and 13.5% for Russell Creek and sub-basins. The reason for the higher error during these storms was probably

Table 9a. Calculated proportion of sand in sediment yield for selected storms at Stephanie and Russell Creeks. An equation to predict the proportion of sand as a function of channel gradient for a given storm is given as:

$$P_{sand} = C \cdot \ln(Gradient) + I \qquad (10)$$

(e.g., Figure 22a). The gradients of Russell Main, Russell at the Confluence, and Stephanie Creek are 5%, 3.1%, and 15% respectively. The equation coefficients C and I are related to storm rainfall.

	Stephanie		**Russell**			**P sand vs In(Channel Gradient)**	
Storm date	**SS yield (kg)**	**P sand (%)**	**SS yield (kg)**	**P sand (%)**	**Rain (R_s) at Russell Main (mm)**	**C**	**I**
04 Apr 96	171 279.7	42.0	297 236.1	23.0	133	25.014	-23.766
07 Apr 96	46 107.7	14.0	22 097.7	16.0	Stephanie supply limited relative to Russell		
30 Sep 97	13 721.1	29.0	16 787.6	16.0	55	17.253	-16.336
01 Oct 97	8 963.4	8.0	11 331.0	13.0	Stephanie supply limited relative to Russell		
03 Oct 97	4 792.1	4.0	782.9	0.0	24	2.729	-3.6233
15 Oct 97	5 467.0	17.0	5151.5	13.0	43	10.016	-9.1911
26 Oct 97	2 084.7	10.0	3 760.2	8.0	34	5.556	-4.092

Table 9b. Calculation of proportion of sediment production transported by gullies across the valley flat. The coefficients of Equation 10 given in Table 9a are related to storm rainfall, also given in Table 9a (Figure 22b, c). These relationships can be used to predict coefficients C and I from storm rainfall for the storm for which one wants to know the proportion of sand or fines in the sediment load of a channel with a known gradient. Given that the mean gradient of Confluence gullies is 41.4%, Equation 10 can then be used to calculate the proportion of sand for the storms given below. This allows Equation 11 to be derived, which is used to determine the proportion of fines transported by Confluence gullies for a given storm (Figure 22d).

Storm date	**RS basin average**	**C**	**I**	**Mean gully gradient (%)**	**Psand (%)**	**Pfines (%)**
04 Apr 96	157.0	29.027	-27.9902	41.42	80.10	19.9
01 Oct 97	51.5	15.649	-15.4468	41.42	42.83	57.2
12 Nov 98	66.5	18.717	-18.3233	41.42	51.37	48.6
20 Nov 98	32.4	10.086	-10.2318	41.42	27.33	72.7

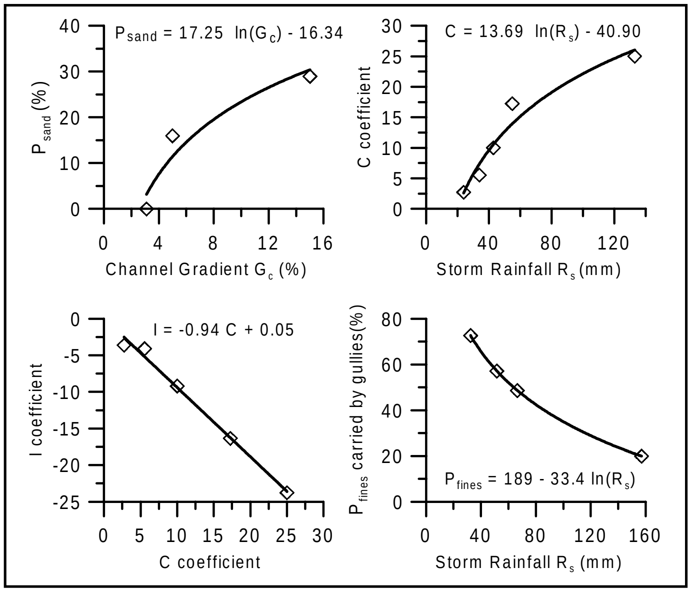

Figure 22. Determination of Equation 11. 22a, top left: determination of Equation 10, example given for 9/30/97 storm. 22b and c, top right and bottom left: prediction of the coefficients of Equation 10 based on storm rainfall. 22d, bottom right: a relationship to determine the proportion of fines in the total suspended sediment yield carried by Confluence gullies as a function of storm rainfall.

that SSC at the main gauging sites was derived entirely from SSC vs turbidity relationships. Calculations could not be verified because the automatic samplers were not working during that event.

DISCUSSION

Results show that landslides directly connected to the mainstem channels are the biggest contributors of suspended sediment. In the four storms analyzed, the contribution from landslides was between 50 and 90% of the sediment yield. Gullies were generally less important than landslides as sediment sources, with the exception of gully G76. For example, in the 12 November 1998 storm, gully G76 accounted for 63% of the total yield from gullies. The biggest producer in Russell Creek is landslide LS199 (Figure 23), which happens to be in the unharvested part of Stephanie Creek. During the 12 November storm, gully G76 and landslide LS199 together accounted for 44% of the total yield from Stephanie Creek and 35% of the yield from Russell Creek as a whole. Both these features are unharvested. On the average, Stephanie Creek accounts for about 60% of the sediment yield of Russell Creek[3], even though it accounts for only 28% of the area. The dominance of Stephanie Creek, and in particular, gully G76 and landslide LS199, over the sedi-

Table 10. Summary of sediment-budget results for four storms. All sediment yields are in kg of suspended sediment per storm. Total sediment budget for Russell Creek includes all sources from Stephanie, Russell above the Confluence, and lower Russell sub-basins.

	1 Oct 1997 Basin avg. rainfall: 50.2 mm				
Sub-basin	Total (kg)	Upper (kg)	Gullies (kg)	Roads (kg)	Landslides (kg)
Stephanie					
Measured yield	8 725	326			
Harvested			19	433	231
Unharvested			3 179	n.a.	5 708
Total			3 198	433	5 939
Total sources			9 896		
Error (%)			13.4		
Confluence					
Measured yield	1 867	392			
Harvested			925	276	14
Unharvested			n.a.	n.a.	23
Total			925	276	37
Total sources			1 630		
Error (%)			-12.7		
Total budget, Russell Creek					
Measured yield	11 330.9				
Harvested			944	709	1 199
Unharvested			3 179	n.a.	6 356
Total			4 123	709	7 555
Total sources			12 387		
Error (%)			9.3		
Proportions					
Harvested			7.6		9.7
Unharvested			25.7		51.3
Total			33.3	5.7	61.0

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[3] This is based on an average of 24 events where yield at both Stephanie Creek and Russell Main were measured, but excludes 4 events where Stephanie Creek was under snow.

Table 10, continued:

Sub-basin	12 Nov 1998 Total (kg)	Basin avg. rainfall: 60.4 mm Upper (kg)	Gullies (kg)	Roads (kg)	Landslides (kg)
Stephanie					
Measured yield	12 888	1 234			
Harvested			26	639	992
Unharvested			2 888	n.a.	7 335
Total			2 914	639	8 328
Total sources			13 115		
Error (%)			1.8		
Confluence					
Measured yield	2 621	909			
Harvested			1 135	429	55
Unharvested			n.a.	n.a.	28
Total			1 135	429	83
Total sources			2 556		
Error (%)			-2.5		
Total budget, Russell Creek					
Measured yield	18 460.1				
Harvested			1 161	1 084	2 808
Unharvested			3 117	n.a.	8 524
Total			4 278	1 084	11 332
Total sources			16 694		
Error (%)			-9.6		
Proportions					
Harvested			7.0		16.8
Unharvested			18.7		51.1
Total			25.6	6.5	67.9

Table 10, continued:

Sub-basin	14 Nov 1998 Total (kg)	Basin avg. rainfall: 54.7 mm Upper (kg)	Gullies (kg)	Roads (kg)	Landslides (kg)
Stephanie					
Measured yield	916	0			
Harvested			10	0	58
Unharvested			81	n.a.	847
Total			91	0	905
Total sources			995		
Error (%)			8.7		
Confluence					
Measured yield	1 248	276			
Harvested			941	168	3
Unharvested			n.a.	n.a.	5
Total			941	168	8
Total sources			1394		
Error (%)			11.7		
Total budget, Russell Creek					
Measured yield	2 806				
Harvested			951	182	301
Unharvested			245	n.a.	1013
Total			1196	182	1313
Total sources			2691		
Error (%)			-4.1		
Proportions					
Harvested			35.3		11.2
Unharvested			9.1		37.6
Total			44.4	6.8	48.8

Table 10, continued:

	20 Nov 1998	Basin avg. rainfall: 40.5 mm			
Sub-basin	**Total (kg)**	**Upper (kg)**	**Gullies (kg)**	**Roads (kg)**	**Landslides (kg)**
Stephanie					
Measured yield	2 842	0			
Harvested			0	0	235
Unharvested			31	n.a.	2 519
Total			31	0	2 754
Total sources			2 785		
Error (%)			-2.0		
Confluence					
Measured yield	992	554			
Harvested			425	59	5
Unharvested			n.a.	n.a.	7
Total			425	59	12
Total sources			1 049		
Error (%)			5.7		
Total budget, Russell Creek					
Measured yield	4 863.5				
Harvested			425	63	1053
Unharvested			31	n.a.	3069
Total			456	63	4122
Total sources			4641		
Error (%)			-4.6		
Proportions					
Harvested			425	63	1053
Unharvested			31	n.a.	3069
Total			456	63	4122

Figure 23. Landslide LS 199, Stephanie Creek, produces more sediment than any other source in Russell Creek.

ment budget is undoubtedly due to the underlying lithology.

Unharvested sediment sources are more important than harvested sources to the sediment budget in Russell Creek. Harvested sources include the gullies and landslides that are in areas that have been harvested, and do not include road-related sources. The contribution from harvested sources is between 17 and 47% of the sediment budget, with an average of 30% (Table 11a). Because about 30% of the watershed area has been harvested, this might suggest that harvesting has had no effect on sediment production from gullies and landslides in this watershed. This is based on the assumption that sediment production is uniformly distributed across the landscape. However, because the sediment budget is dominated by two unharvested features, this assumption is questionable.

If the relative contribution of harvested and unharvested souces are recalculated with contributions from gully G75 and landslide LS199 excluded, the resultant contributions are perhaps less biased (Table 11b). In this case, the harvested contribution ranges from about 30–60%, with an average of 47%. In lower Russell, the sediment yield is almost entirely due to landslides, all of which are harvested. However, connected landslides tend to be concentrated in the incised channel reaches. Considering that all gullies in the Confluence (i.e., the area between Russell Creek above Stephanie confluence and Russell Creek at TS120) have been at least partly harvested, it is difficult to draw conclusions about the effect of harvesting on gully yield. The instability in gullies G61, G65, and G74 could be a result of harvesting. The Confluence area (between the Confluence and upper Russell stream gauges) is 19.5% of the area of Russell Creek. The average contribution from Confluence gullies to the total yield of Russell Creek is in the range of 14 to 23%, depending on whether buffering is considered and on whether or not the contributions from roads and from gully G76 and landslide LS199 are included (Table 11c). In any case, the percent contribution to Russell Creek yield from gullies in the Confluence is proportional to the area of the Confluence, ex-

Table 11a. Summary of relative contributions of harvested sources and roads to the overall sediment yield of Russell Creek, and the effect of the valley flat on those yields. Buffered refers to the sediment yield as delivered to channels, and unbuffered refers to sediment yield at the source; both are calculated excluding contributions from upper Russell and upper Stephanie.

		Total yield, all sources			Contribution from harvested area		Contribution from roads	
Date	**Basin avg., storm rain (mm)**	**Buffered (kg)**	**Unbuffered (kg)**	**% reduction by V.F.**	**Buffered (%)**	**Unbuffered (%)**	**Buffered (%)**	**Unbuffered (%)**
04 Apr 96	141.9	24 9015	365 389.3	31.8	n.a.	30.5	n.a.	23.0
01 Oct 97	50.2	12 387	15 133	18.1	17.3	22.4	5.7	15.0
12 Nov 98	60.5	16 694	22 150	24.6	23.8	33.8	6.5	15.5
14 Nov 98	54.7	2 691	4 323	37.8	46.5	53.7	6.8	22.4
20 Nov 98	40.5	4 641	5 306	12.5	31.8	34.7	1.4	7.4

Table 11b. As above, but excluding gully G76 and landslide LS191.

		Total yield, all sources			Contribution from harvested area		Contribution from roads	
Date	**Basin avg., storm rain (mm)**	**Buffered (kg)**	**Unbuffered (kg)**	**% reduction by V.F.**	**Buffered (%)**	**Unbuffered (%)**	**Buffered (%)**	**Unbuffered (%)**
04 Apr 96	141.9	181 002	297 376	39.1	n.a.	37.9	n.a.	28.7
01 Oct 97	50.2	7 461	10 207	26.9	28.7	33.2	9.5	21.7
12 Nov 98	60.5	10 882	16 338	33.4	53.6	33.8	10.0	21.0
14 Nov 98	54.7	2 331	3 963	41.2	53.7	58.5	7.8	24.4
20 Nov 98	40.5	2 896	3 561	18.7	51	51.8	2.2	11.1

Table 11c. Summary of contributions from Confluence gullies to the sediment yield of Russell Creek at Russell Main.[a]

	% of total yield	**% of yield, excluding contribution from roads**	**% of yield, excluding contribution of G76 & LS199**
Buffered	14	15	20
Unbuffered	16	17	23

[a] Numbers in the table are percent contributions averaged over 4 events.

pressed as a percentage of the total area of Russell Creek. Based on these figures, it is not possible to conclude that harvesting has increased sediment yield from gullies or from landslides. If there is an effect, it is minor compared to the dominant effect of lithology.

There is no relationship between the relative contribution from harvested sources and storm size. Likely, this is because the distribution of sediment production by source type is related to precipitation distribution, which is highly variable. Also, the presence of snow affects sediment production. However, there is a distinct relationship between the contribution from road sources and storm size (Table 11, Figure 24). The contribution from roads at the source varied from 7% for a small (40 mm rainfall) storm to 23% for a large (140 mm rainfall) storm. If

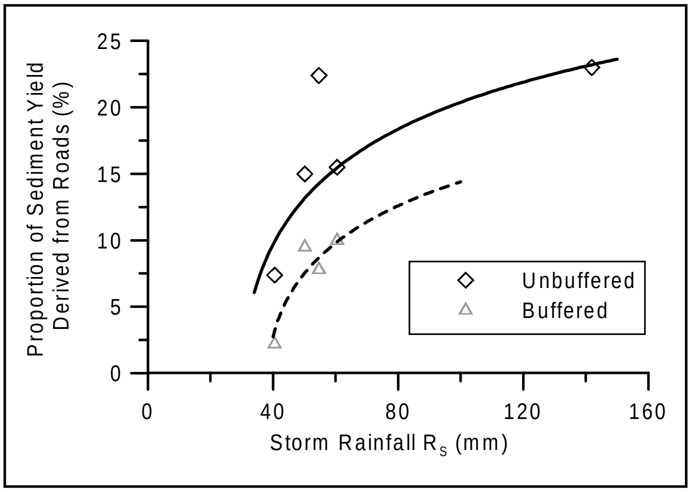

Figure 24. Contribution of road-related sources to the sediment budget of Russell Creek. The roads become more significant contributors as storm rainfall increases, but are less significant when the main channel is buffered by a valley flat.

the contribution from gully G75 and landslide LS199 is excluded, the proportions are increased to range from 11 to 29%.

The storm that occurred on 14–15 November 1998 was different from the other storms in that rainfall intensity was low (Table 3). Because of this, yield from landslides was less than from other sources. However, the rainfall that contributed to the storm was sustained over three days, such that the gullies produced sediment yields comparable to other events. In addition, upper Stephanie was under snow at the beginning of the event, which reduced the yield from gullies G75 and G76 (Table 4). Consequently, the Confluence produced more sediment than Stephanie Creek. This resulted in an increase in the relative contribution from harvested and road-related sources for that event.

Connectivity of sediment sources has a major effect on sediment yield. As discussed above, Stephanie Creek usually contributes about 60% of the suspended sediment load of Russell Creek, except for events such as the 14 November event, where Stephanie Creek was under snow and lower parts of the watershed were snow-free. On the average, 25% of the total yield of Russell Creek is derived from landslides in the incised lower reaches of Russell Creek below Stephanie confluence.[4] The area of lower Russell is 6.24 km^2, or 20% of the total watershed area. Stephanie Creek is dominated by the Karmutsen formation, whereas lower Russell is underlain by the granitic Island Intrusive formation. Because the areas of Stephanie Creek and lower Russell are comparable, this demonstrates the importance of lithology compared to connectivity as factors controlling the sediment budget.

The effects of the valley flat in the Confluence on sediment delivery are analyzed by comparing sediment yield at the source to that delivered to the channel (Table 11). The valley flat reduces the overall sediment yield to Russell Creek as measured at Russell Main by a factor that ranges from 12% to about 40% (Table 11a), depending on storm size and whether or not the contributions from G75 and landslide LS191 are included (Table 11b). Generally, the larger the storm, the greater the effect of the buffering: this is because larger storms are capable of entraining more sand, all of which is absorbed by the valley flat. The valley flat also reduces the contribution from road-related sources to a maximum of 10%, because most sources of that type are concentrated in the Confluence.

If the effect of the valley flat is analyzed for the Confluence alone, then the buffering capacity is 50% for storms in the range of 50–60 mm rainfall. An interesting effect of the buffering involves gully G61 as it crosses the mainline road. The lower part of the gully is torrented and unstable (Table 2), thus a large sediment yield from that feature is expected. A debris flow occurred in that gully in the fall of 1995, but the deposition ran out on the mainline road. Because the gully is scoured at Sites 2 and 3, the gully is usually flowing at those sites. At low to medium flow, the flow becomes sub-surface through the debris flow deposit. There is a culvert at the road crossing, but a rainfall event of at least 30 mm is needed to induce flow through the culvert. This results in a reduction in effective rainfall at that site, with a subsequent reduction in sediment yield in the sediment-budget calculations.

Forest Management Implications

The results of these investigations suggest that watershed morphology has a greater influence on the sediment budget of Russell Creek than forest-harvesting activities. The buffering capacity of the valley flat is sufficient to absorb an amount of sediment equivalent to the contribution from road-related sources as measured at the source (Table 11). The sediment budget of Stephanie Creek, which is not buffered by a valley flat, is dominated by two large sediment sources that are in the unharvested area. Even in the case of the April 1996 storm in the aftermath of the road washout at Site 45, road-related sources contributed only 6.9% of the suspended sediment in Stephanie Creek. In the Confluence, the sediment is mostly derived from harvesting-related sources because all of the gullies in that part of the watershed have been harvested, at least partially. Sediment-yield data suggest that harvesting may have caused a slight increase in yield from harvested sources, but this is not conclusive. Furthermore, an earlier analysis of sediment yields at Russell and Catherine Creeks revealed that basin lithology was a more important factor in controlling sediment yield than forest development (Hudson and Sterling 1998). Taken together, these results suggest that forest management activities have had only minor effects on the sediment budget of Russell Creek.

Given the above conclusion, deactivation may have little effect on sediment production from roads, particularly in the Confluence, because the buffering capacity of the valley flat is

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[4] Averaged over 27 storm events with yield data from Russell Main, Stephanie Creek, and the Confluence.

sufficient to absorb about half of the sediment that is produced. However, this may not always be the case: in watersheds that lack that buffering capacity, road deactivation might reduce sediment yield substantially. The sediment budget can also be used to show the effect of road-related sources on sediment yield in watersheds that are not buffered by a valley flat and to predict the potential effects of deactivation on road crossings, and of harvesting-induced debris flows in gullies.

In the Confluence, the most significant crossings in terms of sediment production are the large ones such as those at Site 2 (Figure 25) and Site 10. At those sites, the primary mechanism responsible for sediment production seems to be rill erosion on the fill slopes. Rilling also occurred at Site 45; however, the deactivation of the road appears to have succeeded in reducing sediment production from that crossing by diverting water away from the fill slope (Figure 26 and Figure 15). Thus, two possible solutions for reducing sediment yield from crossings are: either the effective crossing area can be reduced (i.e., reduce the area of exposed sediment in the cut-and-fill slopes), or water can be diverted away from the crossing. This can be achieved by cross ditching on inactive roads, or by spacing culverts so as to divert water onto the forest floor. These solutions can be used only if water is not diverted onto potentially unstable slopes.

To learn more about the effectiveness of these options, several scenarios were investigated using the sediment-budget model for the Confluence, for the 12 November 1998 storm (Table 12). The sediment budget for the storm as it occurred indicates that 48% of the sediment at the source was derived from roads; as delivered to channels, that contribution was reduced to 26% by the valley flat. The reduction of connected ditch length to a maximum of 10 m was more effective at reducing sediment yield from roads than reduction of the effective area of the sediment sources. However, if a combination of water management and reduction of source areas to a maximum of 30 m^2/crossing are applied, then the sediment-budget model indicates that the relative contribution from road sources is reduced to 17% at the source, or 7% if buffered by a valley flat. Source area reduction would likely take the form of armouring the larger fill slopes and vegetative stabilization of the cut slopes in crossings that have large areas of exposed sediment. Water manage-

Figure 25. Evidence of rill erosion on the fill slope at Site 2.

Figure 26. Site 45 after road deactivation. There is evidence of past rill erosion, but the deactivation has diverted water away from the crossing.

Table 12. Potential effects of several deactivation/water management scenarios on the contribution of road sources to the sediment budget at the Confluence, based on the 12 November 1998 storm. The unbuffered yields are the total yields from road-related sources as measured at the source; the buffered yields are the total mass of road-derived sediment delivered to the channel.

Confluence, 12 Nov 98 scenario	**Unbuffered**		**Buffered**	
	Yield (kg)	**%**	**Yield (kg)**	**%**
Existing configuration	2366	48	438	26
1. Reduce sediment source area per crossing to max. of 50 m^2	1557	39	311	20
2. Reduce sediment source area per crossing to max. of 30 m^2	1426	37	287	19
3. Reduce ditch length per crossing to max. of 10 m	1332	36	236	16
4. 2 and 3 together	449	17	85	7

ment would involve additional culvert placement or cross ditching to reduce delivery of road surface and/or ditch-derived sediment to the crossings.

CONCLUSIONS

A program of sediment-budget research commenced in 1994 at Russell Creek, a sub-basin of the Tsitika River watershed on Northeastern Vancouver Island, British Columbia. Part of the program aimed to determine the relative contribution of different types of sediment sources to the sediment load of mainstem channel sites in Russell Creek and its main tributary, Stephanie Creek, which are two typical Coastal British Columbia streams.

This report presents a rainfall-based, sediment-budget model that predicts the sediment yield of Russell Creek and its sub-basins to within ±10% for four storms with a range of storm rainfall volumes and intensities. The model is based on the attributes of measured sediment sources, including landslides, gullies, and road-related sources. The model did an excellent job of determining the relative contributions of the different types of sediment sources to the overall sediment yield from the watershed, and also explains the effect of basin morphology on the sediment budget. The main factors controlling the sediment budget of Russell Creek, in order of importance, are lithology and basin morphology, with forest management activities playing a minor role.

The model can be used to forecast the effectiveness of forestry-road-deactivation scenarios on the relative contribution of sediment from forestry roads, and to assess the effect of existing sediment sources on the sediment budget of creeks. As such, it is a very valuable management tool, but it requires further research to verify and/or refine it for a broader range of storm conditions, and to extend it to other watersheds with different morphological characteristics.

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APPENDIX A: SEDIMENT SOURCE INVENTORY

Table A1. Gullies.

Gully no.	Bed stability S1 [a]	Bank stability S2 [a]	Length (m)	Total area (km^2)	Gauged area (km^2)	Gradient (%)	Geologic formation G [b]	Harvested vs unharvested H [c]	Torrented vs untorr. T [a]	Road crossings	Sub-basin [d]
61 (upper)	1	0	1200	0.584	0.532	57	1	1	0	2,3,4	C
61 (lower)	1	1	800	n.a.	not gauged	20	1	1	1	none	C
62	0	0	1400	0.260	0.236	47	1	1	0	5,6,6u	C
63	0	0	1500	0.304	0.276	47	1	1	0	7,8,8u	C
additional	0	0	n.a.	0.540	n.a.	n.a.	1	1	0	none	C
64	0	0	2000	0.780	0.764	53	1	1	0	9,10	C
65	0	1	1700	1.024	1.014	21	1	1	0	11,12	C
66	0	0	620	0.169	n.a.	61	1	1	0	13	UR
67	0	0	1340	0.610	n.a.	39	1	0	0	14	UR
68	0	0	800	0.291	n.a.	10	1	2	0	15	UR
69	1	1	840	0.306	n.a.	64	1	1	1	18	UR
70	0	0	1140	0.519	n.a.	40	1	1	0	21	UR
71	0	0	1680	0.612	n.a.	65	1	0	0	23	UR
72	0	0	740	0.101	n.a.	38	1	0	0	24	UR
73	0	0	740	0.101	n.a.	43	1	2	0	25	UR
74	1	1	1000	0.528	0.216	45	0	2	1	26-30,39,40	C
additional	1	0	n.a.	0.650	n.a.	n.a.	0	2	0	31-36	C
75	0	0	2500	1.300	1.272	25	0	0	0	45	S
76	1	1	2200	0.959	0.940	35	1	0	1	46,47	S
77	0	0	540	0.104	0.104	48	1	2	0	56,57	S
78	0	0	1000	0.182	n.a.	54	1	1	0	55	US
79	0	0	1200	0.218	n.a.	43	1	0	0	54	US
80	0	0	360	0.066	n.a.	55	1	1	0	58	US
81	0	0	740	0.202	n.a.	54	1	1	0	51,50	US
82	0	0	740	0.202	n.a.	51	1	1	0	52	US
83	0	0	600	0.164	n.a.	53	1	1	0	53,49	US
84	0	0	2200	0.964	n.a.	65	0	0	0	none	LR
85	0	0	1280	0.380	n.a.	25	0	0	0	43	LR
86	0	0	2800	2.204	n.a.	29	0	0	0	44	LR
87	0	0	1100	0.200	n.a.	40	1	0	0	54	US

[a] 0 = stable. 1 = unstable. [b] 0 = granitic. 1 = basaltic or basaltic surficial material draped over granitic bedrock. [c] 0 = unharvested. 1 = partially harvested. 2 = completely harvested. [d] C = Confluence. UR = Upper Russell. LR = Lower Russell. S = Stephanie. US = Upper Stephanie.

Table A2. Crossing attributes.

Site no.	Crossing type [a]	Road gradient RG [b]	Stream gradient SG (%)	Length of assoc. road L (m)	Geologic formation G [c]	Stability crossing S [d]	Source areas		Ditch cut slope (m^2)	Ditch length (m)	Site elev. (m a.s.l.) [e]
							Fill slope (m^2)	Cut slope (m^2)			
1	1	1	6	600	0	1	bridge crossing		n.m.	n.m.	265
43	3	3	30	440	0	1	15	0	n.m.	132	
44	3	1	25	680	0	1	15	0	n.m.	157	
Confluence											
2	2	2	30	360	1	4	294	300	450	135	660
3	3	3	27	600	1	4	68	16	228	152	560
4	3	1	15	380	1	4	19	0	n.m.	110	500
5	3	1	15	200	1	1	0	32	0	50	500
6	3	1	27	120	1	1	120	42	0	64	560
6 upper	n.a.	n.a.	n.a.	n.a.	1	n.a.	22	35	400	100	660
7	3	1	15	120	1	1	32	24	0	10	500
8	3	1	27	40	1	1	108	166	n.m.	0	560
8 upper	n.a.	n.a.	n.a.	n.a.	1	n.a.	100	0	234	54	640
9	3	1	15	60	1	2	8	8	74	74	510
26	n.a.	1	54	n.a.	0	n.a.	n.m.	n.m.	n.m.	n.m.	
27	2	1	30	80	0	3	35	96	40	20	560
28	5	1	55	60	0	4	50	8	85	17	560
29	3	1	18	280	0	1	15	0	n.m.	106	510
30	3	1	18	400	0	1	15	0	n.m.	127	480
31	3	1	20	700	0	1	15	0	n.m.	159	480
32	3	1	20	220	0	1	15	0	n.m.	92	510
33	4	1	31	100	0	3	30	19	n.m.	46	560
34	3	4	50	500	0	3	15	0	n.m.	140	600
35	5	3	54	70	0	5	80	20	2630	26	Above 34
36	4	3	54	80	0	3	30	70	311	31	Above 34
37	4	3	54	80	0	3	30	70	174	17	Above 34
38	4	3	54	80	0	3	30	70	174	17	Above 27
39	4	3	54	80	0	3	30	70	174	17	Above 27
40	4	3	54	80	0	3	30	70	174	17	Above 27

continued

Table A2, continued:

Site no.	Crossing type [a]	Road gradient RG [b]	Stream gradient SG (%)	Length of assoc. road L (m)	Geologic formation G [c]	Stability crossing S [d]	Source areas		Ditch cut slope (m^2)	Ditch length (m)	Site elev. (m a.s.l.) [e]
							Fill slope (m^2)	Cut slope (m^2)			
Upper Russell [f]											
10	3	2	27	85	1	2	564	0	32	55	540
11	3	2	27	60	1	2	144	6	4	2	540
12	2	1	15	720	1	2	3	20	0	10	510
Stephanie											
41	5	4	20	200	0	4	108	166	n.m.	86	610
42	1	1	18	480	0	1	30	0	n.m.	137	
45	2	3	25	120	0	1	291	0	960	120	760
46	5	4	25	100	1	5	0	0	800	100	760
47	2	5	25	400	1	2	16	48	0	200	760
48	2	5	18	200	1	1	30	0	n.m.	86	US
49	4	1	18	40	1	3	30	0	n.m.	0	US
50	4	1	18	100	1	3	30	0	n.m.	46	US
51	4	3	18	60	1	3	30	0	n.m.	17	US
52	4	3	18	100	1	3	30	0	n.m.	46	US
53	4	3	18	300	1	3	30	0	n.m.	110	US
54	3	1	35	50	1	3	30	0	n.m.	6	US
55	4	1	34	100	1	3	30	0	n.m.	46	US
56	4	3	45	160	1	2	30	0	n.m.	74	900
57	4	4	45	520	1	2	30	0	n.m.	142	1000
58	5	5	18	120	1	5	30	0	n.m.	57	US

[a] 1 = bridge. 2 = log culvert. 3 = pipe culvert. 4 = cross ditch. 5 = washout. [b] 1 = 0-4.9%. 2 = 5-9.9%. 3 = 10-14.9%. 4 = 15-19.9%. 5 = 20%. [c] 0 = granitic. 1 = basaltic or basaltic surficial material draped over granitic bedrock. [d] S is a qualitative measure of the overall stability of the crossing cut-and-fill slopes, where 1 = most stable (low gradient, no evidence of erosion) and 5 = most unstable (evidence of total failure of the crossing). Categories 1 to 4 have degrees of erosion, including rill erosion, in and around the crossing. [e] Blank = not required. [f] Additional crossing in Upper Russell not listed.

Table A3. Landslides and other slope failures.

Source no. [a]	Type [b]	Activity [c]	Connect [d]	Length (m)	Width (m)	Area (m^2)	Gradient (%)	Geolologic formation G [e]	Harvested vs unharv. H [f]
Lower Russell									
113	L3	2	6	10	4	40	100	0	0
114	L3	2	6	10	4	40	100	0	0
115	L2	2	6	15	10	150	75	0	0
116	L1	2	6	10	10	100	70	0	0
118	L1	2	6	10	5	50	100	0	0
120	L2	2	6	30	8	240	75	0	0
183	L1	2	6	5	4	20	75	0	0
184	L1	2	6	10	5	50	75	0	0
214	L2	2	6	25	8	200	75	0	0
117	L3	1	6	200	5	1 000	150	0	0
119	L2	1	6	20	3	60	60	0	0
121	L2	1	6	10	5	50	80	0	0
215	L2	1	6	15	2	30	70	0	0
90	L1	2	7	15	4	60	100	0	1
91	L1	2	6	30	6	180	100	0	1
96	L1	2	6	10	10	100	100	0	1
97	L1	2	6	10	10	100	100	0	1
98	L2	2	6	10	15	150	100	0	1
101	L1	2	6	15	10	150	110	0	1
112	L2	2	6	100	7	700	100	0	1
104	L1	1	6	5	4	20	100	0	1
110	L1	1	6	15	4	60	60	0	1
100	L1	1	5	6	4	24	100	0	1
105	L3	1	5	60	5	300	110	0	1
122	L1	1	5	5	4	20	70	0	1
Total area connected and active (activity 2+)						2 330			
Not connected									
95	L1	2	4	25	10	250	100	0	1
106	L1	1	4	35	10	350	100	0	1
93	L1	1	1	5	7	35	75	0	1
94	L1	1	1	10	10	100	70	0	1
103	L1	1	1	10	3	30	100	0	1

continued

Table A3, continued:

Source no. [a]	Type [b]	Activity [c]	Connect [d]	Length (m)	Width (m)	Area (m^2)	Gradient (%)	Geolologic formation G [e]	Harvested vs unharv. H [f]
Stephanie									
187	L1	2	7	10	10	100	100	0	0
191	L2	3	7	200	1.5	300	50	1	0
192	L2	3	7	200	1.5	300	50	1	0
193	L2	3	7	200	1.5	300	50	1	0
194	L2	3	7	200	1.5	300	50	1	0
198	L1	2	7	20	15	300	100	1	0
199	L1	2	7	80	25	2 000	100	1	0
200	L1	2	7	10	4	40	100	1	0
201	L1	2	7	50	15	750	100	1	0
202	L1	2	6	20	8	160	75	1	0
203	L1	2	6	15	10	150	75	1	0
204	L1	2	6	20	6	120	75	1	1
205	L1	2	7	15	5	75	100	1	1
211	L1	2	5	10	25	250	75	0	1
206	L1	3	7	18	9	162	100	1	1
Not connected									
190	L3	2	1	7	2	14	75	0	1
209	L3	2	3	240	200	48 000	100	1	0
210	L3	2	1	300	60	18 000	100	1	0
212	L1	7	3	700	10	7 000	45	0	0
213	L3	1	1	600	140	84 000	50	1	1
Upper Russell									
172	L1	1	7	180	60	10 800	100	1	0
174	L3	1	7	120	160	19 200	100	1	0
137	L1	2	5	15	5	75	100	1	0
138	L1	2	5	25	7	175	100	1	0
157	L2	3	5	15	5	75	100	1	1
160	L1	1	5	5	4	20	70	1	1
179	L1	1	5	20	3	60	75	1	0

continued

Table A3, continued:

Source no. [a]	Type [b]	Activity [c]	Connect [d]	Length (m)	Width (m)	Area (m^2)	Gradient (%)	Geolologic formation G [e]	Harvested vs unharv. H [f]
Confluence									
131	C	1	5	45	3	135	100	1	1
132	L3	1	5	15	3	45	75	1	1
133	L3	1	5	10	2	20	75	1	1
141	L2	6	5	275	3	825	35	1	1
142	C	2	6	120	3	360	100	1	1
143	C	2	6	65	3	195	100	1	1
182	B1	9	6	15	2	30	5	0	0
Not connected									
171	L2	6	3	900	3	2 700	60	1	1
181	L1	7	2	440	20	8 800	54	1	1
165	L1	1	1	300	30	9 000	100	1	0
175	L1	1	1	220	20	4 400	100	1	0
176	L3	1	1	160	160	25 600	100	1	0
188	L3	2	1	10	13	130	75	0	1

[a] A sediment source must have a deliverablitiy of at least 5, and an activity level of at least 2, to be considered a significant source.

[b] L1 = debris slide. L2 = debris flow. L3 = raveling. C = cutbank. B1 = channel bank failure. [c] 1 = low raveling. 2 = moderate raveling. 3 = high degree of raveling. 5 = scour, 10-25 cm deep. 6 = scour, 25-50 cm deep. 7 = scour, >100 cm deep. 8 = depositional sink. 9 = lateral erosion. [d] 1 to 4 = deliverability onsite to floodplain (i.e., not connected to channel network). 5 to 7 = deliverability to gully, tributary, or main channel (i.e., connected). [e] 0 = granitic. 1 = basaltic or basaltic surficial material draped over granitic bedrock. [f] 0 = granitic. 1 = basaltic or basaltic surficial material draped over granitic bedrock.

APPENDIX B: FLOW RATING AND VERIFICATION

Flow rating was done by a combination of salt dilution gauging and current metering at mainstem gauging sites. At manually sampled sediment source sites, salt dilution was used, but the rating curves were extended at the high end by surveying the channel, and calculating flows using Manning's formula. Values for Manning's n were estimated from flow measurements at lower stages. The rating curves were used to derive streamflows from stage readings. For example, the rating curve for gully G75 at Site 45 is an exponential curve that is based on a combination of salt dilution gauging, supplemented with survey data at the upper end (Figure B1).

Flow records for each gully were reconstructed from point data, based on relationships with a reference site where stage was monitored continuously. For example, manually collected stage readings at Site 45 during the 12 November 12 1998 storm correlated best with continuous stage readings at Site 3, but were different for rising and falling stage at Site 3 (Figure B2). Stage was still rising at Site 45 while at Site 3, it was falling. There is potential for substantial error in the reconstruction of flow records using these methods. In particular, the exact value and time of the peak stage at Site 45 was not known. Calculation of suspended sediment yield depends on accurate SSC and flow data. Thus, an independent method of verifying the flow data was needed.

The rising and recession characteristics of gullies differ from those of the mainstem stream sites. Because gullies are steeper than mainstem sites, are of lower stream order, and have smaller areas, they tend to be more flashy mainstem channels. For these reasons, the ratio of instantaneous flow in a gully to that in the mainstem stream is constantly changing. However, the ratio of total flow volume in a gully to total flow in the mainstem stream should be related to the ratio of the area of the gully to the drainage area at the mainstem gauge.

For each storm, the total volume of flow at each site was calculated. For each gully, the ratio of the flow volume to the volume of flow at the reference site used to reconstruct flow record was then calculated (Table B1). The ratio of the gully area to the drainage area at the reference site was also calculated. In some cases, adjustments had to be made in order to produce consistent relationship between flow volume ratios and area ratios. Following the example from gully G75 at Site 45, adjustments were made to the timing and magnitude of peak flows around the transition between rising and falling stage (Figure B1) to bring the flow volume ratio in line with the flow ratio vs area ratio relationship (Figure B3).

The resultant relationship between flow volume ratios and area ratios is consistent from storm to storm, and from site to site (Figure B3). Variability in the relationship is likely due to variability in precipitation distribution.

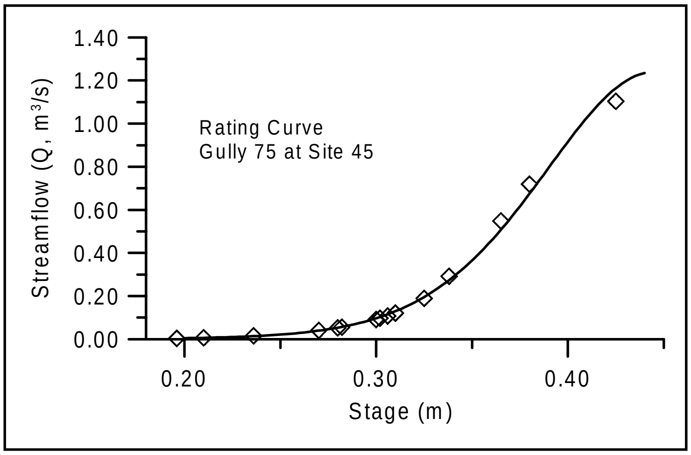

Figure B1. Exponential rating curve for gully G75 at Site 45.

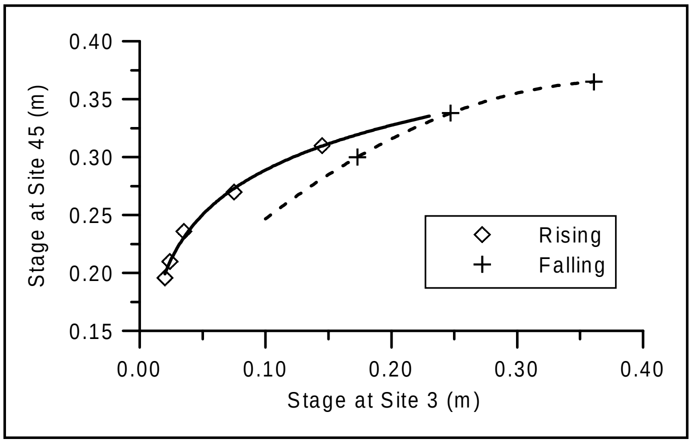

Figure B2. Relationships used to determine stage at Site 45 for the 12 November 1998 storm, based on continuously monitored stage at Site 3.

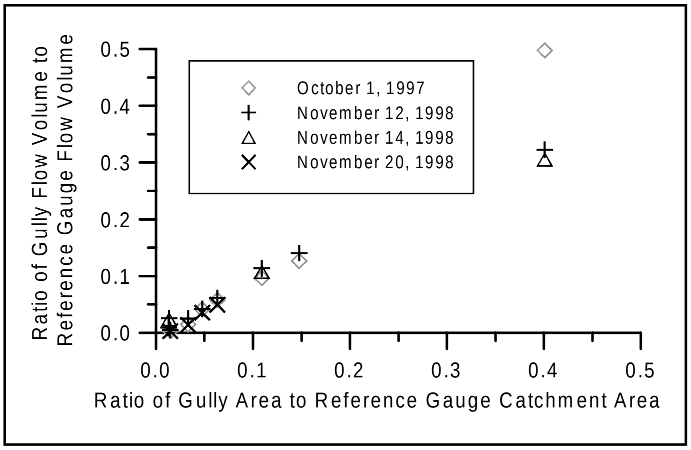

Figure B3. Storm flow volume ratios vs area ratios, for gullies compared to reference sites. The upper points are for upper Stephanie Creek. The fact that the relationship between flow ratios and area ratios is linear, and is consistent from storm to storm, indicates that the flow data are accurate.

Table B1. Calculation of flow volume and area ratios.

Storm date	Flow volume (m^3)	Gauged area (km^2)	Flow and area ratios				Reference gauge [a]
			Ratio of Russell Creek		Ratio of reference gauge		
			Flow	Area	Flow	Area	
01 Oct 1997							
Russell	1 028 415	30.880					
Confluence	734 907	16.028	0.715	0.519			
Stephanie	216 647.5	8.612	0.211	0.279			
Upper Stephanie	107 840	3.452	0.105	0.112	0.498	0.401	S
Site 2	11 012	0.532	0.011	0.017	0.015	0.033	C
Site 5	1 976	0.236	0.002	0.008	0.003	0.015	C
Site 10	30 538.5	0.764	0.030	0.025	0.042	0.048	C
Site12	42 588	1.014	0.041	0.033	0.058	0.063	C
Site 34		1.778					
Site 45	27 455.3	1.272	0.027	0.041	0.127	0.148	US
Site 46	20 907.5	0.940	0.020	0.030	0.097	0.109	US
12 Nov 98							
Russell	1 244 929.0	30.88					
Confluence	666 162.7	16.028	0.535	0.519	0.535	0.519	
Stephanie	369 758.0	8.612	0.297	0.279			
Upper Stephanie	119 192.4	3.452	0.096	0.112	0.322	0.401	S
Site 2	16 702.1	0.532	0.013	0.017	0.025	0.033	C
Site 5	3 416.6	0.236	0.003	0.008	0.005	0.015	C
Site 10	27 858.1	0.764	0.022	0.025	0.042	0.048	C
Site12	40 910.1	1.014	0.033	0.033	0.061	0.063	C
Gully B	17 040.7	0.216	0.014	0.007	0.026	0.013	C
Site 34	6 055.4	0.208			0.009	0.013	C
Site 45	51 905.8	1.272	0.042	0.041	0.140	0.148	S
Site 46	41 927.7	0.940	0.034	0.030	0.113	0.109	S
14 Nov 98							
Russell	563 486	30.88					
Confluence	333 868	16.028	0.593	0.519	0.593	0.519	
Stephanie	149 219.1	8.612	0.265	0.279			
Upper Stephanie	45 627.0	3.452	0.081	0.112	0.306	0.401	S
Gully B	3 576.6	0.216	0.006	0.007	0.024	0.013	C
Site 46	16 027.4	0.940	0.028	0.030	0.107	0.109	S
20 Nov 98							
Russell	155 1146	30.88					
Confluence	88 5488	16.028	0.571	0.519	0.571	0.519	
Site 2	12 205.1	0.532	0.008	0.017	0.014	0.033	C
Site 5	2 524.2	0.236	0.002	0.008	0.003	0.015	C
Site 10	31 407.4	0.764	0.020	0.025	0.035	0.048	C
Site12	43 695.3	1.014	0.028	0.033	0.049	0.063	C

[a] C = Confluence. S = Stephanie. US = Upper Stephanie.