Forest Research

Extension Note

Coast Forest Region
2100 Labieux Road, Nanaimo, BC, Canada, V9T 6E9, 250-751-7001

EN-021 Hydrology March 2006

Road construction and hauling in basaltic and granitic terrain: effects on sediment yield at Russell and Catherine Creeks, Tsitika River Watershed

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KEYWORDS:
Water management, streams, sediment, turbidity, forest road construction, basaltic terrain.

CITATION:
Hudson, R. 2006. Road construction and hauling in basaltic and granitic terrain: effects on sediment yield at Russell and Catherine Creeks, Tsitika Watershed. Research Section, Coast Forest Region, BCMOF, Nanaimo, BC. Extension Note EN-021.

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1. INTRODUCTION

The effects of forest roads on sediment production have been well documented in the literature. Studies have looked at various aspects of roads as sediment sources, including the effects of vehicular traffic on running surfaces (Reid and Dunne, 1984, Coker et al., 1993, Nistor and Rood, 1999), the role of cut and fill slopes on sediment budgets (Hudson, 2001b), and the role of road deactivation and the effects of road construction on sediment budgets (Beschta, 1978, Anderson and Potts, 1988, Megahan et al., 1986). What has not been well documented is the effect of building roads on basaltic terrain and hauling timber on those roads immediately following construction.

An analysis of sediment production and transport characteristics of basaltic and granitic terrain in Russell and Catherine Creeks revealed that, in the fall of 1997, newly constructed road used to access timber in Catherine Creek resulted in an order of magnitude increase in sediment yield that was closely related to timber hauling (Hudson, 2001c). A similar effect was observed at Russell Creek in the fall of 2004, when an impending change in land tenure led to an increased rate of cut to allow completion of the forest licensee's five-year development plan.

2. STUDY AREA

Russell and Catherine Creeks have been described in detail elsewhere (Hudson, 2001c, Hudson and Anderson, 2006). Both creeks are tributaries of the Tsitika River. Catherine Creek drains an area of 46 km^2, and is underlain entirely by the basaltic Karmutsen Formation. Slopes are unstable, steep, and directly connected to stream channels, resulting in a high and variable background level of sediment transport. Russell Creek drains an area of 31 km^2; about two-thirds of the area is underlain by the granitic Island Intrusive formation, with the upper third of the watershed area dominated by the Karmutsen formation. This results in very steep headwater areas dominated by sheer basaltic cliffs that serve as a continuous source of sediment, while the lower slopes are more gently sloped and disconnected from the mainstem channel by valley flat deposits.

3. METHODS

At both Catherine and Russell Creeks, continuous monitoring of streamflow and turbidity began in 1991 at stream gauge sites near the outlet of each watershed. Streamflow was measured as stage and converted to discharge using stage-discharge (rating) curves derived from standard flow measurements. Continuous records of suspended sediment

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ACKNOWLEDGEMENTS

This research was funded by the Forest Science Program. I am as always grateful for the technical assistance of John Fraser for keeping everything running and the data flowing, and also for review comments.

concentration (*SSC*) were calculated from turbidity, using relationships between turbidity and *SSC* measured in water samples collected automatically at each gauging site. In both cases the suspended sediment yield (*SSY*) was evaluated on a storm-by-storm basis using continuous *SSC* and streamflow from the main stream gauge in each watershed. *SSY* is simply the product of *SSC* and discharge.

Relationships between turbidity and *SSC* are very complex and require knowledge of sediment transport processes as well as turbidity probe behaviour (Hudson, 2001a). At both creeks there are several sediment transport modes that represent different stages in the regular cycle of sediment supply and exhaustion. For example, at Russell Creek four distinct modes have been identified (Figure 1) that represent the changes in grain size distribution of the wash load that occur during storms as the stream rises and falls. There is a similar set of characteristic sediment curves for Catherine Creek. These curves were used together with measured *SSC* from water samples to determine continuous *SSC* and total storm-based *SSY* for each creek.

Relationships between *SSY* and storm peak flow (Q_p) were established for each site, including base relationships for periods when there was no active hauling or road construction and relationships for the period affected by road activity. For each of the base relationships a 90% prediction interval was calculated. For the period of road activity, if the *SSY* for a given storm plotted above the upper prediction limit, it was deemed to have been affected by the activity. The excess sediment that was produced as a result of the activity was determined as the difference between the measured *SSY* and the *SSY* predicted for the storm using the base relationship (Table 1).

4. RESULTS

Turbidity (*T*) and measured *SSC* data collected in the fall of 2004 at Russell Creek indicate that during periods of road construction and hauling activity, the sediment load is mostly dominated by a finer grain size distribution than during times of inactivity (Figure 1). This is consistent with the known effect on sediment production of driving heavy trucks over forest roads (Reid and Dunne, 1984). During those periods, the turbidity for a given sized storm was higher than normal, but the *SSC* was lower than would be expected from historic *SSC* vs. *T* relationships that apply to periods with no road activity. The road activity disturbs sediment sources, resulting in an increased production of fine sediment, specifically in the clay range. The result is that the sediment transport modes shifted down one level as shown in Figure 2, such that the *SSC* vs. *T* relationships are in the "very fine" to "normal" range during road activity due

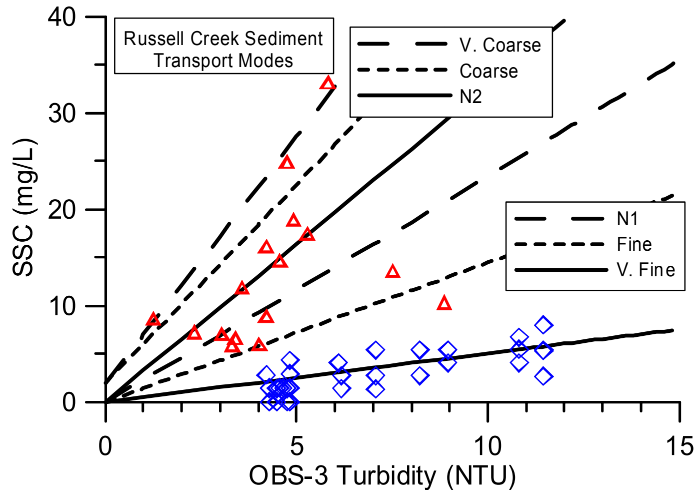

Figure 1. Characteristic *SSC* vs. *T* relationships for Russell Creek, with 2004 data superimposed. (The curves have been established over more than a decade of sampling and measurement, and describe different sediment transport modes according to streamflow and cycles of sediment supply and transport. The superimposed 2004 data points show that more than 60% of the samples were in the "very fine" mode [diamonds]. The remaining points [triangles] follow the usual distribution with respect to sediment transport modes.)

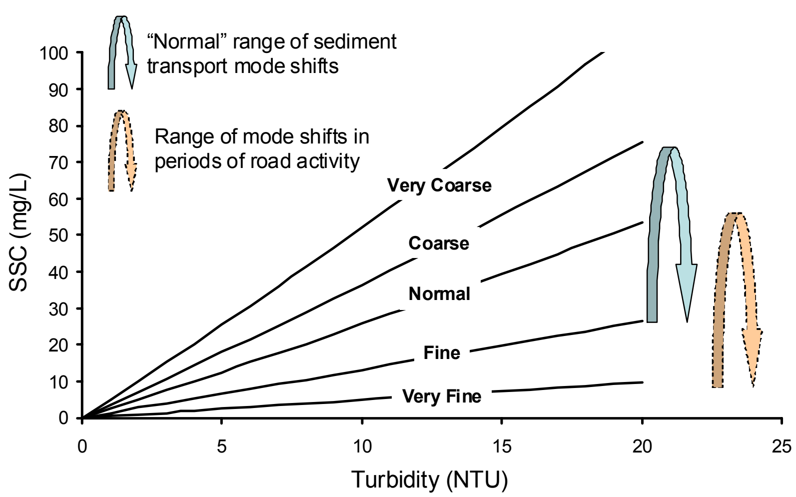

Figure 2. Sediment transport modes and progression of shifts, Russell Creek. (The change in grain size distribution of suspended sediment due to road activity results in a general downward shift in sediment transport mode progression during affected storms. Sediment transport modes shift from "fine" to "coarse" normally, but during periods of road activity they tend to shift from "very fine" to "normal". This change in the pattern reflects the fact that road use produces fine sediments while other processes produce sediment in a wider range of grain sizes.)

to the increased production of clay sized sediment.

The base relationships between *SSY* and peak flow at Russell and Catherine Creeks were derived from periods during which there were either no roads in the watershed area, or the existing road network was not in active use (Figures 3 and 4). These base relationships can be described by power functions as follows:

$$SSY = 1.474\left(Q_p^{\ 3.19}\right) \quad (1)$$

for Russell Creek, and

$$SSY = 1.740\left(Q_p^{\ 3.18}\right) \quad (2)$$

for Catherine Creek. These equations are not significantly different from each other. That is, they are collinear, and therefore by combining the two data sets we can derive a common equation for the base relationship of the total storm sediment load for both creeks:

$$SSY = 1.397\left(Q_p^{\ 3.23}\right) \quad (3)$$

The effect of road construction and hauling activity on sediment yield patterns is striking. In both cases, there is a general

Table 1. Comparison of *SSY* due to road use with historic relationships at Russell and Catherine Creeks.

Date	Peak Flow (m^3/s)	Measured *SSY* (Kg)	*SSY* calculated from Base Relationship (Kg)	Excess *SSY* Significantly Greater than Base (Kg)
Russell Creek 2004				
8/22/2004	1.803	1263	10	1253
8/25/2004	1.834	1502	10	1492
8/29/2004	1.865	1489	11	1478
8/30/2004	2.351	3647	23	3624
9/11/2004	10.875	18341	2983	15358
9/15/2004	10.118	30695	2370	28324
10/8/2004	17.143	99224	12743	86481
10/30/2004	8.938	12388	1596	10792
11/6/2004	15.677	33994	9581	NA
11/7/2004	14.993	31267	8310	NA
11/8/2004	17.047	63609	12515	NA
11/15/2004	52.820	440961	461563	NA
11/24/2004	12.106	22301	4201	NA
12/3/2004	4.463	4268	174	4093
12/9/2004	3.365	2689	71	2618
12/10/2004	29.520	305478	72141	NA
12/16/2004	7.450	2557	893	NA
Average/Totals	12.492	1073115	588301	155515
Catherine Creek 1997				
9/17/1997	8.848	11112	2071	9041
9/26/1997	17.072	147466	15608	131858
9/28/1997	16.115	86278	13073	73206
9/30/1997	20.653	153564	28021	125543
10/1/1997	23.762	574348	43115	531233
10/3/1997	21.440	87774	31434	56340
10/8/1997	8.020	53126	1531	31809
10/15/1997	44.945	1055392	305654	749738
10/26/1997	23.919	10056	43996	NA
10/28/1997	35.874	520339	152890	367449
11/2/1997	41.324	715469	236118	NA
11/5/1997	33.174	357888	120213	NA
11/26/1997	24.509	12036	47417	NA
12/14/1997	30.735	226887	95069	NA
12/16/1997	26.950	32458	63482	NA
Average/Totals	25.156	3761699	991653	2067175

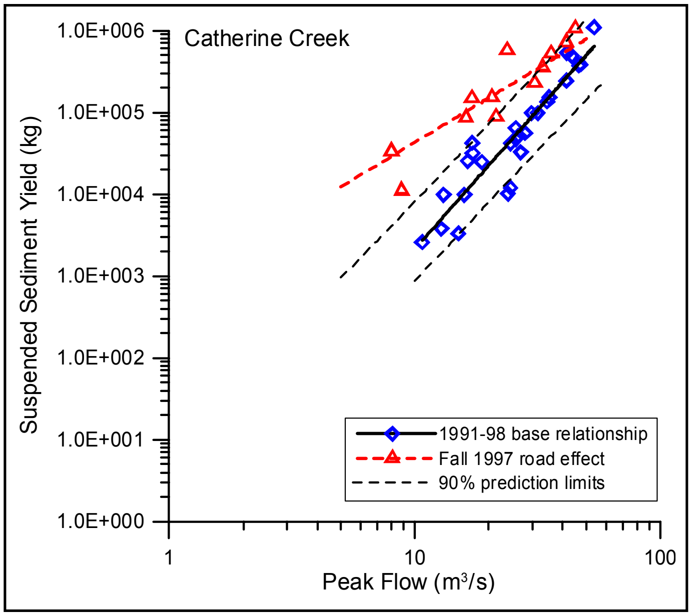

Figure 3. Effect of road construction and use, Catherine Creek, 1997.

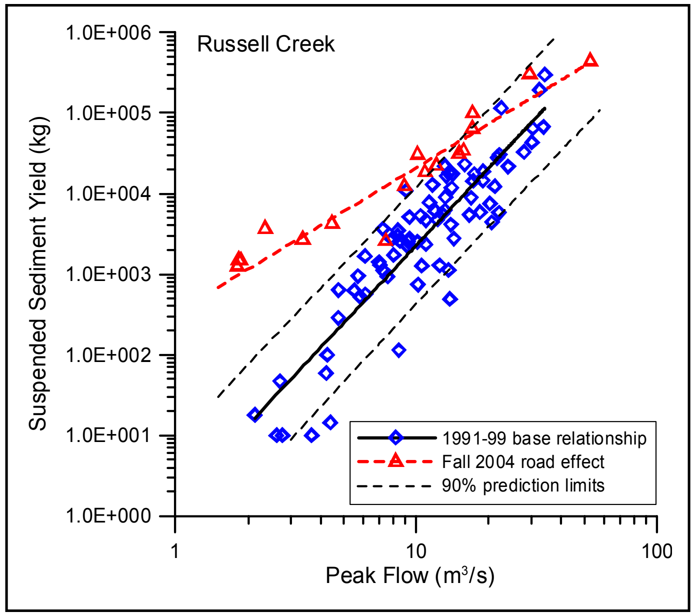

Figure 4. Effect of road construction and use, Russell Creek, 2004.

convergence between the base and affected relationships towards the higher flows. The sediment yield increase due to road construction and use at Russell Creek affected 10 out of 17 (59%) events measured between August and December 2004. At Catherine Creek in the fall of 1997, nine out of 15 events (60%) were affected by road activity. At Russell Creek, the highest flow during the affected period (52.82 m^3/s) occurred on November 5, 2004. This is also the highest flow measured at that site since inception of the study in 1991.

For the period of the road affect at each creek, there is a relationship described by a power function. These relationships are parallel in linear form; that is, they have common slopes and different intercepts as follows:

$$\ln(SSY) = 5.797 + 0.71D + 1.806(Q_p) \qquad (4)$$

where D is a classification variable, such that at Russell Creek D=0, and at Catherine Creek D=1. The exponential form of this equation is:

$$SSY = 329.31e^{0.71D}Q_p^{\ 1.806} \qquad (5)$$

Thus while the base relationships of *SSY* vs. Q_p at Russell and Catherine Creeks are collinear, the road effect at Catherine Creek is just over twice that of Russell Creek for a given peak flow. The main result of this is that while *SSY's* associated with large events at Russell Creek are unaffected by road construction and use, at Catherine Creek the *SSY* associated with some of the large events is significantly higher than the base relationship. Since *SSY* is high for these larger events, the total excess sediment yield at Catherine Creek is about 10 times that at Russell Creek.

5. DISCUSSION

The fact that the base relationships of total storm *SSY* over Q_p are the same for both creeks suggests that both are governed by the same sediment transport process. The sediment transport regime at the watershed scale for both creeks is dominated by predictable fluvial processes as opposed to episodic debris flow processes. At smaller scales we would find that sediment transport becomes less predictable and more episodic as we go upstream and closer to individual sediment sources. The co-linearity between the two base relationships suggests that the basaltic lithology dominates sediment production at Russell Creek. However, despite the similarity in the base relationships, there are differences between the two watersheds that are responsible for the road effect being twice as intense at Catherine Creek.

At Catherine Creek, the road effect was due to 10 km of road, either newly constructed or reactivated. At Russell Creek it is estimated that in the fall of 2004 about 6 km of new road was constructed, 4.8 km of existing branch road reactivated, and 4.8 km of mainline road used for hauling (Table 2). About 3.9 km of the road at Russell Creek was on basaltic terrain, which

Table 2. Road construction and use (km of road) during road effect periods.

Watershed:	Russell		Catherine
Terrain:	Basaltic	Granitic	Basaltic
New road	3.0	4.0	2.0
Reactivated road	1.8	3.0	8.0
Mainline road		4.8	
Total	3.9	11.8	10.0
Effective Length	59.8		99.8

Table 3. Summary of study results.

	Effective Road Length (km)	Total Measured *SSY* (tonnes)	Total Base *SSY* (tonnes)	Significant Excess *SSY* (tonnes)	Absolute Excess *SSY* (tonnes)
Russell 2004	59.8	1073	588	156	485
Catherine 1997	99.8	3762	992	2067	2770
	Watershed Area (km^2)	Sept. – Dec. Rainfall (mm)	Duration (Storm Days)	Normalized *SSY* (g/day/mm/km)	
				Significant	Absolute
Russell 2004	31	987	62	42.5	132.5
Catherine 1997	46	1204	92	187.0	250.6

Note: In an effort to compare results from Catherine and Russell Creeks, the results were normalized by dividing the excess sediment by time, rainfall and effective road length (g/d/mm/km). The significant excess yield includes only those storms for which the measured *SSY* was outside the prediction interval of the base relationship whereas the "absolute excess *SSY*" is simply the total measured *SSY* minus the total base *SSY*.

is both steeper and more directly connected to the stream network than the granitic terrain. In recognition of the differences between lithologies it seemed reasonable to derive an effective road length index in which the roads on basaltic lithology are weighted more heavily than roads on granitic terrain. Based on observation and measurement the basaltic roads were assigned a weight of 10 and the granitic roads, a weight of 1.

The changes in sediment yield due to road construction and use at Catherine and Russell Creeks are not directly comparable; primarily, conditions were wetter in the fall of 1997 than in 2004 despite the extreme event of November 5, and this resulted in overall higher flows and hence, higher sediment yields. To normalize the sediment yields and thereby account for differences in moisture, timing, and extent of roads, the excess yield due to road activity at each creek was divided by the September – December rainfall, the total duration of storms during which the sediment was produced and transported, and effective road length (Table 3). There are two quantities: significant excess *SSY* (the total *SSY* from all events where measured *SSY* was significantly greater than base *SSY*), and absolute excess, which is simply the total measured minus the total base *SSY*. The ratio of normalized absolute excess *SSY* of Catherine Creek over Russell Creek is 1.9. Recall that equation 5 predicts that excess *SSY* from Catherine Creek is 2.03 times that of Russell Creek. Since these ratios are comparable, this suggests that the difference in intensity in the road effect is attributable to the mixed terrain at Russell Creek compared with the entirely basaltic terrain at Catherine Creek.

Because the flow and sediment record at Russell Creek is more complete than at Catherine Creek, the Russell Creek data cover a greater range of flows. The road effect results in sediment yield that is two orders of magnitude higher than the base relationship at low flow (peak flows around 2 – 3 m^3/s). At low flow and for small storms, sediment transport is dominated by fines under inactive road conditions, and thus the effect of the road activity is maximized. Under high flow conditions and for large storms, sediment transport tends to be dominated increasingly by sand, which masks the effect of the fine sediment produced by roads. The road effect at Russell Creek is not significantly different than the base relationship for storms with peak flow greater than around 20 m^3/s (about one year return interval).

Order of magnitude increases in sediment yield following road construction have been documented elsewhere (e.g., Anderson and Potts, 1988) but this is perhaps the first time that 100-fold increases in sediment yield have been documented following road construction and use. This seems to be a feature of basaltic terrain.

6. CONCLUSIONS

Road construction followed by immediate use has a large effect on the sediment yield of small storms, particularly when the roads are located on steep basaltic terrain. At Russell Creek the excess sediment contribution from newly constructed road magnified the sediment yield of low return interval (i.e., less than 0.5-year) storms up to 100-fold. The sediment yield of the 0.5- to 1.0-year events was magnified 10-fold and the sediment yield of larger events was not different from the base relationship. This increased yield presents a chronic problem whereby the fine sediment is introduced to the stream channel under low flow conditions and is therefore likely to go into channel storage until larger events occur to transport the sediment to lower stream reaches. The implications of this are as follows:

1. Accelerated rate of cut with newly constructed road is likely to result in increased turbidity among low return interval storm events, and
2. The excess sediment produced from these roads is likely to result in infilling of the gravel substrate in stream channels, at least temporarily.
3. These implications are important for their potential effect on fisheries habitat.

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