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Interpreting Turbidity and Suspended-Sediment Measurements in High-Energy Streams 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

An ongoing program of sediment-budget research commenced in 1991 at Russell Creek, a sub-basin of the Tsitika River watershed on Northeastern Vancouver Island, British Columbia. The research involved in-stream measurement of turbidity and suspended sediment concentration (SSC), and subsequent analysis of the data to identify relationships between them. For a given stream there is more than one relationship between turbidity and SSC, representing different sediment production regimes. The report describes methods for predicting changes in sediment production regime, and explains how to use those different relationships to predict the grain-size distribution of suspended sediment in streams. These methods will help hydrologists assess the effects of forestry activities on sediment production in streams and the related implications for fish habitat and drinking-water quality.

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KEYWORDS

Forestry, forest management, hydrology, streams, sediment, sediment production, suspended sediment concentration, sediment budget, turbidity, fish habitat, water quality, Vancouver Forest Region, British Columbia

INTRODUCTION

Because excessive sediment production in streams is detrimental to fish habitat and drinking-water quality, the effects of forestry activities on sediment production is currently the focus of much research in British Columbia. To a large extent, this research depends on in-stream measurement of suspended sediment concentration (SSC) and turbidity.

Turbidity is an optical measurement. The units of measure are Napier Turbidity Units (NTU). Turbidity is measured either by shining a light through a water sample and measuring the attenuation of the light beam by particles in the water, or by shining an infrared beam into a volume of water and measuring the intensity of the light that is reflected back to the sensor. The latter method, called "optical backscatterance" (OBS, Downing 1983), is most commonly used to measure turbidity in situ. SSC is defined as the mass of sediment per unit volume of water that is carried by that water in a suspended state. The most common unit of measurement is milligrams of sediment per litre of water (mg/L). The sediment must be entrained in the water column to be considered suspended, and is therefore distinguished from bed load, which generally consists of larger particles that move in a thin layer adjacent to the channel bed. Suspended sediment concentration is normally measured by first collecting a sample of the water for which the measurement is desired, and then analysing the sample in a laboratory. The most common analytical method is to pass the sample through a filter, and then weigh the sediment that the filter traps.

Turbidity is often used as a surrogate for direct measurement of SSC in streams. Turbidity can be measured continuously, and can therefore be used to provide a continuous estimate of SSC. However, in many streams, the relationship between turbidity and SSC is complex. It is influenced by grain-size distribution and by the colour and composition of the particles (Hudson 1996). In high-energy Coastal streams, suspended sediment quality can change rapidly due to rapidly changing flow conditions. In-stream turbidity measurement is also subject to various interferences, including bubbles, obstruction by large objects or aquatic organisms, and light penetration (Teti 1996; Downing and Asher 1997).

The technology for monitoring in-stream turbidity is relatively new (OBS probes have been commercially available for about 10 years), but nonetheless has received widespread use in British Columbia and in the United States. It is an essential component of sediment-budget research (Jordan 1996; Lewis 1996; Jordan and Commandeur 1998; Hudson and Sterling 1998; Hudson 1999) because it allows for a level of detail that previously could not be achieved.

The purpose of this paper is to describe methods of interpreting suspended sediment concentration and turbidity data that have been gathered at Russell Creek, a typical Coastal British Columbia stream, as part of the sediment-budget research underway there since 1991.

STUDY AREA

Russell Creek is a sub-basin of the Tsitika River watershed, on northeastern Vancouver Island. Ongoing sediment production research began there in 1991 in response to concern over the potential effects of forestry activities on killer whale habitat in the Robson Bight, and on fisheries habitat in the Tsitika River.

Russell Creek provided an excellent opportunity to study sediment production and transport for the following reasons:

1. It contains two contrasting lithologies that are common to Vancouver Island; the basaltic Karmutsen Formation, and the granitic Island Intrusives. These formations have widely different sediment-production characteristics.
2. Active timber harvesting is under way in the Russell Creek area, with a history dating back to the early 1980s.
3. It has a range of morphological characteristics that influence sediment production in different ways. In part of the watershed, a broad valley flat buffers the channel from hillside sediment sources, while in other parts, the channel is incised and sediment sources are directly connected to the channel system.

These factors combine to create a high degree of complexity in interpreting in-stream SSC and turbidity conditions. This complexity has led to the development of the methods described in this report.

METHODS

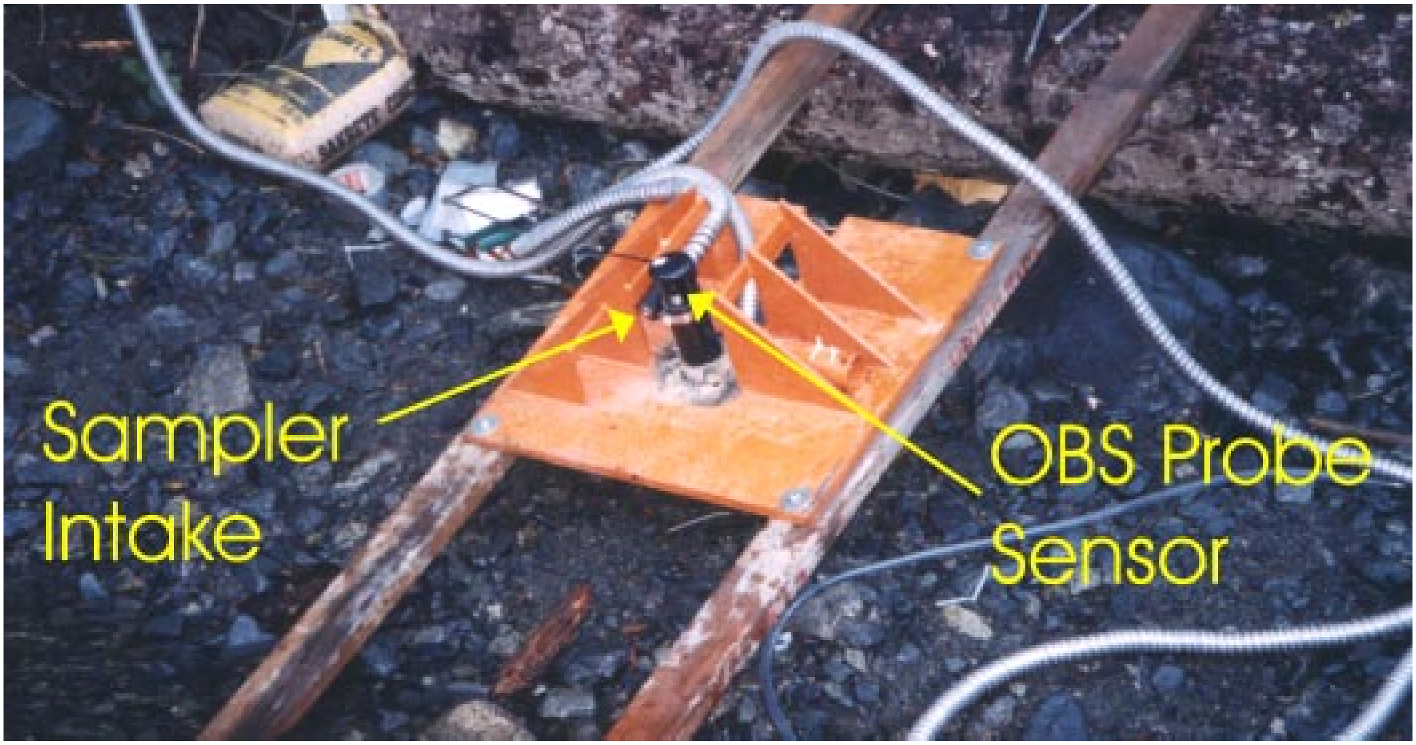
Turbidity, suspended sediment, and stage/discharge data were collected at five sites in Russell Creek (Table 1).

Turbidity was measured using a D&A Instruments optical back-scatter (OBS-3) probe that was calibrated in the range of 0–500 NTU. 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 20 cm above the base of the plate (Figure 1). This assembly was placed in a pool in the stream channel. Stage was measured using either a submersible transducer in the range of 0–5 p.s.i. (which is equivalent to a water depth range of 0–3.5 m) or a desktop transducer in the range of 0–15 p.s.i. (0–10.5 m), connected to a nitrogen bubbling system. Minimum, average, and maximum turbidity and average stage were recorded using a log interval of either 5 or 15 minutes. At each site, a Unidata, high-resolution, data logger collected the turbidity and stage data. An ISCO 3700C automatic

Table 1. Some characteristics of gauging sites in Russell Creek.

Characteristic	Russell	Confluence	Upper Russell	Stephanie	Upper Stephanie
Gauged area (km^2)	30.88	16.03	10.01	8.61	3.45
Channel gradient at site (%)	3.10	3.58	No measurment	8.49	7.65
Mean channel slope (%)	5.0	3.1	1.7	15.0	12.5
Channel type	Riffle-Pool (gravel)	Riffle-Pool (gravel)	Riffle-Pool (gravel)	Cascade-Pool	Cascade-Pool
Distance to nearest connected sediment source (m)	100	30	>1000	200	10

Figure 1. Steel-plate in-stream instrument mount; the OBS probe is mounted in the ABS pipe in the center of the plate. The sampler intake and the OBS sensor are 20 cm above the base of the plate. This assembly is placed in a stable pool in the channel. The plate must be placed on a stable bed with no large void spaces underneath, and weighed down with rocks to avoid being flipped by turbulent high-flow conditions.



sampler was used to collect water samples. The ISCO sampler, data logger, power supplies, et cetera were housed in a shelter on the stream bank. Samples taken by the ISCO sampler were analyzed at the Water Survey of Canada sediment lab for total suspended sediment concentration and, if possible, for grain-size distribution. The analysis of grain-size distribution required a minimum of 180 mg/L in a 1-L sample, and was performed on 32 samples from Russell and Stephanie Creeks. Samples collected in the fall of 1998 were analyzed in-house using identical methods. The purpose of the ISCO sampler collection was to calibrate the turbidity readings, to verify whether they represented actual sediment production, and to assist in interpretation of the data. The data logger system allowed the ISCO sampler to be triggered on the basis of either stage or turbidity. At most sites, a predetermined, site-specific change in stage was found to be the best triggering criterion, because rapidly fluctuating turbidity levels often caused oversampling. At times, the ISCO samplers were set to collect samples every two hours during storms. This was done to provide evenly paced samples when the field crew was conducting manual sampling at other sites. The simultaneous sampling and turbidity measurement allowed a field calibration to be developed by relating SSC derived from the ISCO samples to turbidity readings recorded at the same time as the samples were collected.

The turbidity probes were calibrated in the lab using a calibration column. The purpose of the lab calibration was to determine the effect of grain size on the suspended sediment concentration vs. turbidity relationship under conditions that approximate in-stream conditions.

The clear-plastic column is 40 cm in diameter and has a flat bottom. To perform the calibration, samples of sediment were obtained from the channels and passed through sieves to produce sorted samples. Four sieves were used with mesh sizes of 63, 125, 250 and 500µ, yielding samples that represent fines (silt and clay) and very fine, fine and medium sand respectively. The turbidity probes were attached to the side of the column with the sensor 20 cm above the bottom. A known volume of water is added to the column, and the graded sediments were added in weighed increments so that the concentration of sediment in the water can be calculated at each increment. The water in the column is circulated with a high-capacity submersible pump to ensure that the sediment is kept suspended. This is accomplished by manually swirling the pump outlet around the column while watching the bottom of the chamber to ensure that the sediment remains suspended. This is a somewhat simpler device than that used by Downing and Beach (1989), but the stability of the suspension is comparable (Figure 2). Short-term (5-s) variability in turbidity is less than that reported by Downing and Beach for a given concentration of sediment, while long-term variability (25-s) is greater, probably due to the manual operation of the pump to circulate the sediment. Variability of the signal also increases with increasing concentration, similar to the earlier study, and is greater for sand than for fines, presumably because it is more difficult to keep the sand suspended than the fines.

RESULTS

Grain-size distribution has a very substantial effect on the measured turbidity readings (Figure 3). The lab calibrations yielded linear relationships between suspended sediment concentration and mean turbidity for a given grain-size range (Figure 3), while the slope of the relationship rises with increasing grain size (Figure 4). This indicates that a given concentration of coarse grains (such as medium sand) will result in a lower turbidity than the

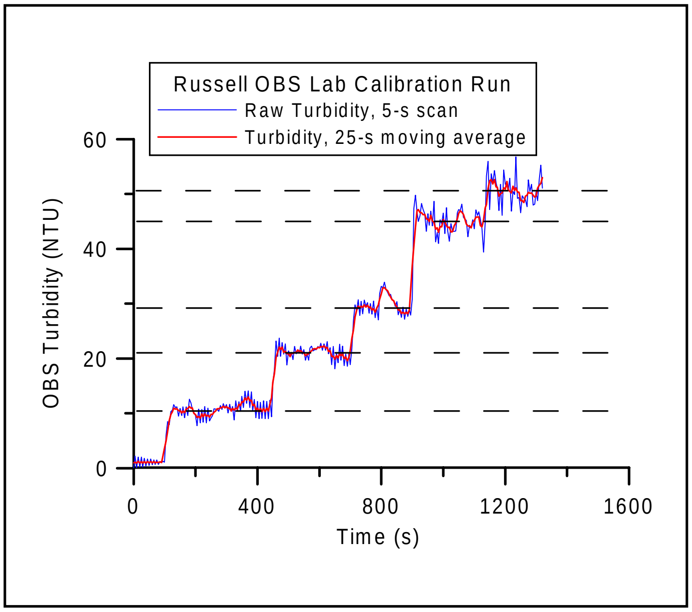


Figure 2. Example of a calibration run for the Russell Creek OBS probe.
The first two steps are the result of adding increments of fines; the last three steps are due to addition of fine sand to the calibration column. Note the increased variability resulting from sand, and from increased concentration. Calibration stability is acceptable.

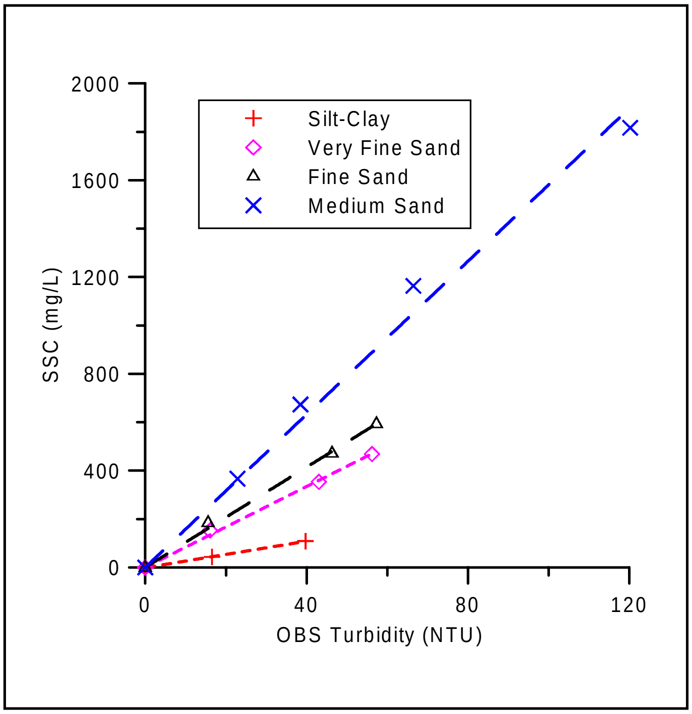


Figure 3. Lab calibration of Russell Creek turbidity probe. The calibration shows the effect of grain-size distribution on turbidity.

same concentration of fine grains (such as silt). Prior studies of the effects of grain size on the signal of OBS probes support these findings (Ludwig and Hanes 1990; Conner and DeVisser 1992) and can be explained by the ratio of surface area to mass being lower for coarser grain sizes. The OBS-3 turbidity probe operates by shining an infrared beam off the sediment, thus a given mass of coarse-grained sediment will reflect less light than the same mass of fine-grained sediment.

The in-stream apparatus described above observes only the portion of sediment which is carried in suspension. Bed-load transport, consisting of particles moving by rolling, sliding, or saltation at velocities less than the flow, is confined to a layer a few grain diameters in thickness above the bed. Thus, at a height of 20 cm the ISCO sampler and the OBS-3 probe are not affected by bed load. Suspended sediment is fine material that the channel is capable of transporting in the water column. This consists of silt/clay-sized sediment of grain diameter <64 microns and a variable quantity of sand that depends on the energy level of the channel.

In most cases, the suspended sediment concentration vs. turbidity relationships derived from field calibrations are non-linear, and are best described by second-order polynomials (Figure 5). The shape of the curve indicates that the grain-size distribution of the suspended load becomes coarser as turbidity increases. This occurs because suspended sediment concentration and turbidity generally increase with increasing streamflow, and higher flows are capable of entraining coarser sediment. There are two significant features of the field calibrations that require consideration in order to maximize the usefulness of the data. First, there is more than one relationship between suspended sediment concentration and turbidity at a given site, representing different sediment-production regimes, and there is a predictable shift between regimes during the course of storms. Second, the non-linear nature of the field calibration curves in relation to the lab calibrations allows the grain-size distribution of the suspended load to be predicted.

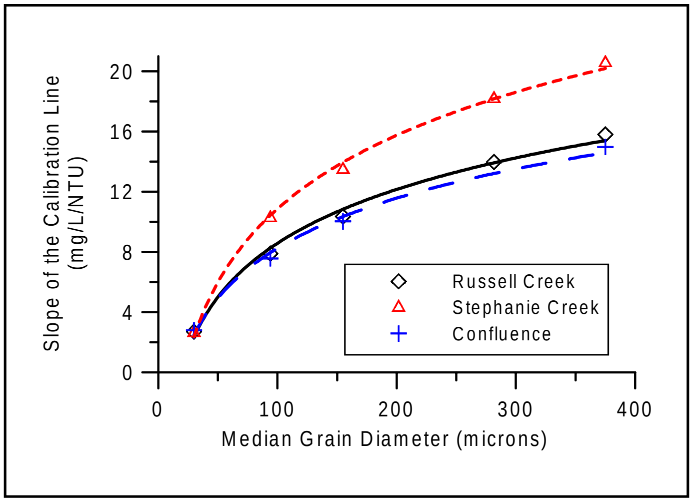


Figure 4. Effect of grain size on suspended sediment concentration vs. turbidity relationships: logarithmic relationship between the slope of the lab calibration and the median grain size.

Sediment-Production Regimes: Effects of Grain-Size Distribution on Field Calibration

At Russell Creek, three distinct sediment regimes have been identified (Figure 6, Table 2); at Stephanie Creek there are five distinct regimes (Figure 7, Table 2), and the relationship between SSC and turbidity changes between regimes in a predictable manner (Table 3). These regimes are termed “very fine” (VF), “fine” (F), “normal” (N), “coarse” (C), and “very coarse” (VC) because the relative slopes of the relationships suggest different grain-size distributions. Sediment production switches between regimes as a function of storm intensity, at a proportion of the peak flow. The timing of the storm in relation to other storms during a season is also a factor that determines the applicable regime during a specific storm and at any point during the storm.

These transitions in sediment-production regime reflect

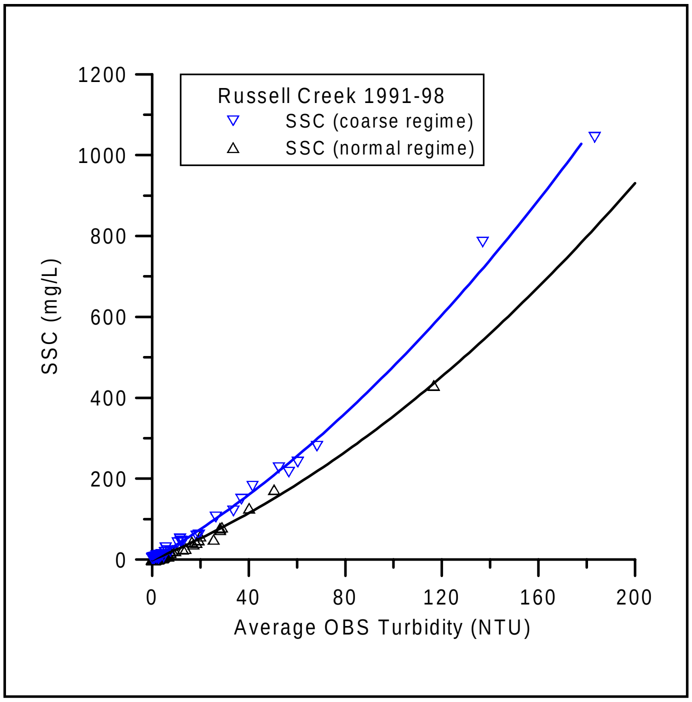


Figure 5. Field calibration of Russell Creek turbidity probe. The non-linear calibration shows that the grain-size distribution becomes more coarse as turbidity increases.

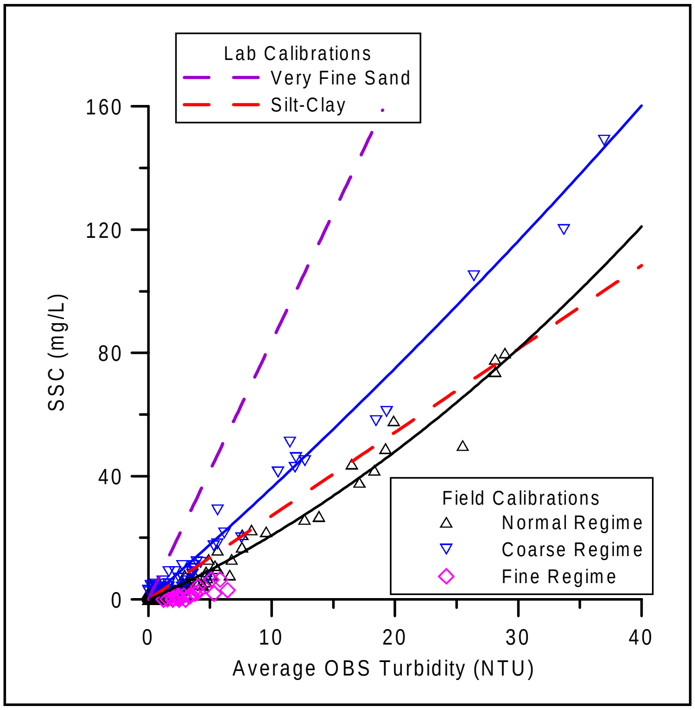


Figure 6. Field and lab calibration of Russell Creek turbidity probe for low range turbidity. In this and subsequent graphs, the red and purple dashed lines represent the lab calibrations for fines and very fine sand respectively.

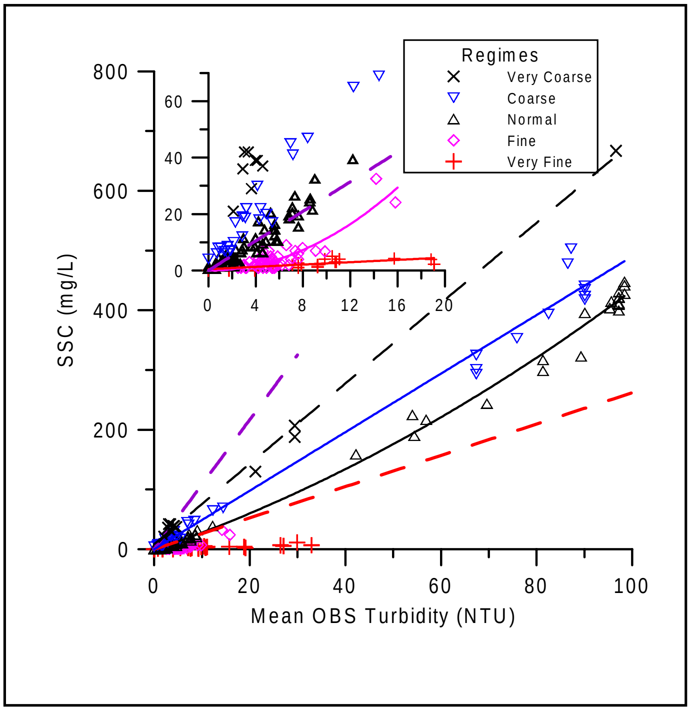


Figure 7. Field and lab calibrations of Stephanie Creek turbidity probe for full calibrated range and for low range (inset). Dashed red and purple lines represent the lab calibrations for fines and very fine sand.

Table 2. Coefficients, R², and standard error of equations describing sediment-production regimes for Russell and Stephanie Creeks. Equations are of the form $SSC = b_0 + b_1T + b_2T^2$ Low range for normal regime is T<40 NTU at Russell Creek, and T<100 NTU at Stephanie Creek.

	Grain size					
Site and regime	**Very fine**	**Fine**	**Normal (low range)**	**Normal (high range)**	**Coarse**	**Very coarse**
Russell Creek						
b_0	n.a.	0.00	0.00	-1.06	0.00	n.a.
b_1	n.a.	-0.10	1.68	2.46	3.49	n.a.
b_2	n.a.	0.1400	0.0358	0.0109	0.0129	n.a.
s.e.	n.a.	1.008	1.912	2.772	11.410	n.a.
R^2 (%)	n.a.	74.3	98.4	99.3	99.6	n.a.
Range (NTU)		0-10	0-40	40-200	0-200	
Stephanie Creek						
b_0	0.00	0.00	0.00	-63.20	6.63	15.10
b_1	0.26	-0.02	2.65	5.14	3.65	5.74
b_2	0.0000	0.1160	0.0169	0.0000	0.0140	0.0104
s.e.	1.276	2.364	9.298	26.060	17.970	8.764
R^2 (%)	90.0	88.6	99.7	93.1	98.5	99.8
Range (NTU)	0-20	0-16	0-100	100+	0-100	0-100

the fact that silt- and clay-sized fractions behave differently from sand-sized fractions in streams. The transport of sand in the stream is highly dependent on streamflow, since sand is transported as suspended load at high flows, and as bed load at lower flows. Sand is stored in the channel bed and transported during medium-to-high flow conditions, whereas silt- and clay-sized fractions tend to be transported out of the system during the same storm in which they are produced, because they are always carried in a suspended state. At turbidity levels below 20 NTU, normal regime sediment load is composed entirely of fines. As shown in Figures 4 and 5, the slope of the field calibration relationship below 20 NTU is less than that of the lab calibration for fines. Thus, at both Stephanie and Russell Creeks, the normal sediment-production regime will usually be in effect.

Criteria for the Occurrence of Regime Transitions

During a large storm, the regime will switch from normal to coarse. The threshold conditions for the transition appear to be related to rainfall intensity rather than to streamflow. In all cases, the rainfall intensity must exceed 4 mm/h for this transition to occur. Generally, minimum flow conditions for the transition are about 2 m^3/s at Stephanie Creek and about 10 m^3/s at Russell Creek. The transition does not occur at a flow threshold. Instead, once the rainfall intensity threshold is exceeded, the transition occurs on the average at about 82 and 80% of the difference between peak flow and base flow at Russell and Stephanie Creeks respectively, on the rising limb of the hydrograph. The proportion where the switch occurs is randomly distributed with respect to peak flow (Figure 8, top graph). It is also independent of time since the last storm. During the same storm, the regime will switch from coarse back to normal on the falling limb of the hydrograph, at the same proportion of the peak flow. These transitions reflect the fact that as streamflow increases, the stream has the ability to carry coarser-sized fractions. In addition to this there is also a very coarse regime at Stephanie Creek, which takes effect at peak flows in excess of 5.5 m^3/s.

After a series of such storms, or after the largest storm of the season, the sediment-production regime will then switch from normal to fine. This transition occurs on the falling limb of the hydrograph, at a proportion of the flow that is inversely proportional to the magnitude of the peak flow (Figure 8, bottom graph). This transition reflects the fact that large storms with high flow conditions tend to remove all transportable sand from the system. The sediment-production regime will then remain fine until the supply of transportable sand has been replenished, and flow conditions are high enough to carry

Table 3. Summary of measured regime transitions for Russell and Stephanie Creeks.

Transition type	Measured transitions (no.)	First quartile peak flow (m^3/s)	Proportion of peak flow	
			Mean	Std. deviation
Russell				
F - N or N - F	8	11.59	0.53	0.37
N - C or C - N	27	11.30	0.79	0.18
Stephanie				
F - VF or VF - F	6	2.53	0.85	0.07
F - N or N - F	12	1.80	0.80	0.18
N - C or C - N	16	2.30	0.75	0.27
C - VC or VC - C	3	5.63	0.69	0.38

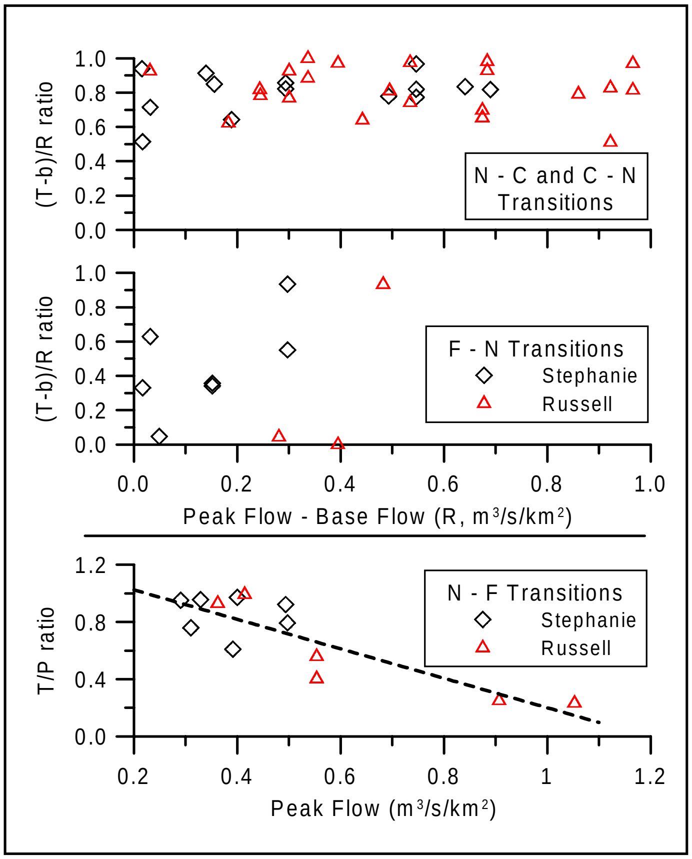


Figure 8. Occurrence of sediment-production regime transitions; these graphs show relationships between the flow at which the transitions occur, and peak flow. T-b is the transitional flow minus the base flow; P is the peak flow, and R is the peak flow minus the base flow.

it. After this occurs, the normal-to-coarse transitions will resume.

The fine-to-normal transition does not appear to be related to any threshold hydrologic conditions, but rather, to sediment supply. On the average, this transition occurs at about 45% of the difference between peak flow and base flow. The proportion at which the transition occurs appears to increase with increasing peak flow, but the relationship is weak and poorly defined (Figure 8, middle graph).

An example of this transition sequence occurred at Russell Creek between 12 November and 13 December , 1998 (Table 4, Figure 9). There were six storms during this period; the 12 November storm was the largest storm of the early part of the season, and the 12 December storm was the largest of the later part. This sequence of transitions represents the sediment-production and transport process discussed above, and is typical of Coastal watersheds. In the early part of the season there was a large supply of sand, most of which was removed by the 12 November storm. This caused a shift to F-N-F transitions for the next four events due to the lack of sand available for transport. During the following month, the supply of sand was presumably replenished, allowing the normal-to-coarse sediment-regime transitions to resume during the 12 December storm.

At other sites in Russell Creek, there are similar sediment-production regimes; for example, at Russell Creek, above the Stephanie confluence, the normal regime consists entirely of fine sediment due to the buffering influence of the valley flat (Figure 10). The coarse regime is poorly defined; in contrast to Russell and Stephanie Creeks, transitions between normal and coarse sediment-production regimes are not predictable. This is most likely due to the presence of a stream-bank failure immediately upstream from the gauging site. Regime transitions are governed by episodic inputs of sediment from the failure, and respond to rapidly changing sediment concentration and grain-size distribution. Similarly, at upper Stephanie Creek, the proximity of the gauging site to a large slope failure makes it very difficult to identify any sediment-production regimes due to rapidly fluctuating turbidity SSC levels. It appears that if the gauging site is too close to one or more sediment sources, the changes in grain-size distribution become unpredictable.

Use of Sediment-Production Regimes to Estimate Grain-Size Distribution

The grain-size distribution of the wash load can be inferred by comparing the field calibration curves to the slopes of the lab calibrations (Figures 6 and 7). At a given turbidity, if a tangent drawn to the curve representing any one of the sediment-production regimes has a slope that is less than or equal to the slope of the lab calibration for fines, this indicates that the wash load is entirely composed of silt and clay. Otherwise, the wash load will contain some proportion of very fine sand, depending on the slope of that tangent relative to the slope of the lab calibration for very fine sand. This suggests that, theoretically, the grain-size distribution of the wash load can be predicted for a given turbidity by taking the derivative of the equation, and interpolating the value of the derivative between the slopes of the lab calibrations.

For example, the equation for the normal regime suspended sediment concentration vs. turbidity curve at Stephanie Creek is:

$$SSC = 2.65T + 0.0169T^2 \qquad (1)$$

where

suspended sediment concentration is in mg/L, and

T is turbidity in NTU.

Differentiating Equation 1 gives the following:

$$S_T = 0.0338T + 2.65 \qquad (2)$$

where

S_T is the slope of a tangent to the curve for a given value of T.

The proportion of sand and fines in the wash load can then be estimated for a given turbidity by interpolating the value of S_T from the appropriate equation (representing the sediment-production regime that is in effect) between the slopes of the lab calibrations. Following the above example, for Stephanie Creek the equations of the lab calibrations for fines and very fine sand, respectively, are:

$$SSC = 2.62T \qquad (3) \text{ and}$$

$$SSC = 10.85T \qquad (4)$$

Recall that Equation 3 is for fines (i.e., silt and clay) only, and Equation 4 is for very fine sand only. Thus for normal sediment-production regime at Stephanie Creek, if the value of S_T is ≤ 2.62, then the wash load is entirely composed of fines. If the value of S_T is between 2.62 and 10.85, the wash load consists partly of fines and partly of very fine sand. Therefore, the proportion of sand in the wash load can be calculated as:

$$\frac{S_T - S_{fines}}{S_{vfs} - S_{fines}} \qquad (5)$$

Using the above method, grain-size distribution was estimated for the 32 samples collected from Stephanie and Russell Creeks on which grain-size distribution was mea-

Table 4. Characteristics of regime transitions for November–December 1998 storm sequence at Russell Creek.

Storm date	Peak 1-h rain intensity (mm/h)	Base flow (BF, m^3/s)	Peak flow (P, m^3/s)	Peak flow ($m^3/s/km^2$)	Transition type	Transition flows rising				Transition flows falling		
						F-N (m^3/s)	F-N % (P-BF)	N-C (m^3/s)	N-C % (P-BF)	C-N (m^3/s)	N-F (m^3/s)	N-F (% of P)
11/12/98	9	0.58	17.11	0.554	F-N-C-N-F	0.8	1	14	78	13.5	8.6	50
11/14/98	3	3.19	7.13	0.230	F (no trans.)	n.a.	n.a.	n.a.	n.a.	n.a.	n.a.	n.a.
11/15/98	3	6.77	8.61	0.278	F-N-F	7.1	18	n.a.	n.a.	n.a.	7.4	86
11/20/98	6	2.31	11.19	0.363	F-N-F	4.0	19	n.a.	n.a.	n.a.	8.5	76
11/25/98	8	5.81	10.44	0.337	F-N-F	9.4	78	n.a.	n.a.	n.a.	9.0	87
12/10/98	8	1.19	14.03	0.453	F-N-F	11.1	77	n.a.	n.a.	n.a.	12.1	86
12/12/98	5	3.42	18.71	0.606	F-N-C-N-F	13.3	65	16	81	16.0	9.1	49

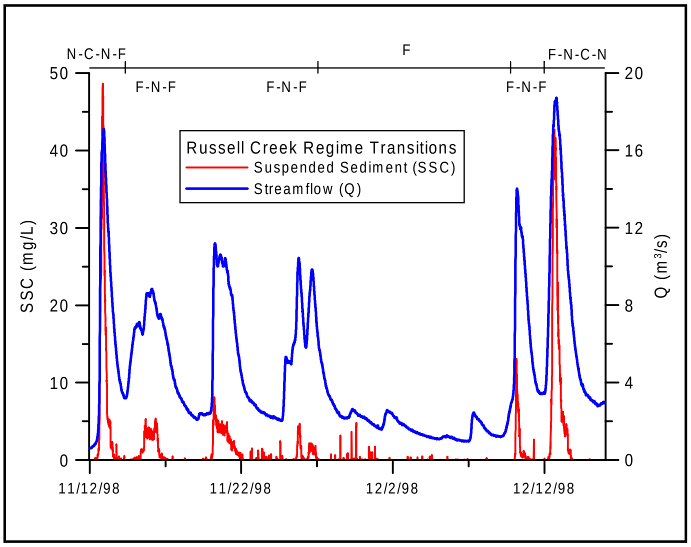


Figure 9. 12 November to 15 December storm sequence at Russell Creek showing sediment-production regime transitions.

sured (Table 5). The method provides a good estimation that is both accurate, and reasonably precise (Figure 11)

$$(P.Sand_{estimated} = 1.03(P.Sand_{observed}),\ R^2 = 93.5\%)\ .$$

An Example: Russell Creek, 12–13 November 1998

An example of the use of sediment-production regimes and the separation of suspended sediment into fine and sand fractions is given (Figure 12). During the 12 November, 1998 storm, there were discontinuities in the turbidity readings that occurred around the time when the transitions were expected to occur; these discontinuities indicated that the transition had occurred. For example, a large drop in turbidity on the rising of the hydrograph indicated that the regime had switched from the normal to coarse. Similarly, on the falling of the hydrograph there are points where the turbidity rises when it is expected to fall. The discontinuities also occur at around the expected transitions between coarse and normal and between normal and fine. The discontinuities are used to pinpoint the time at which the transition occurs.

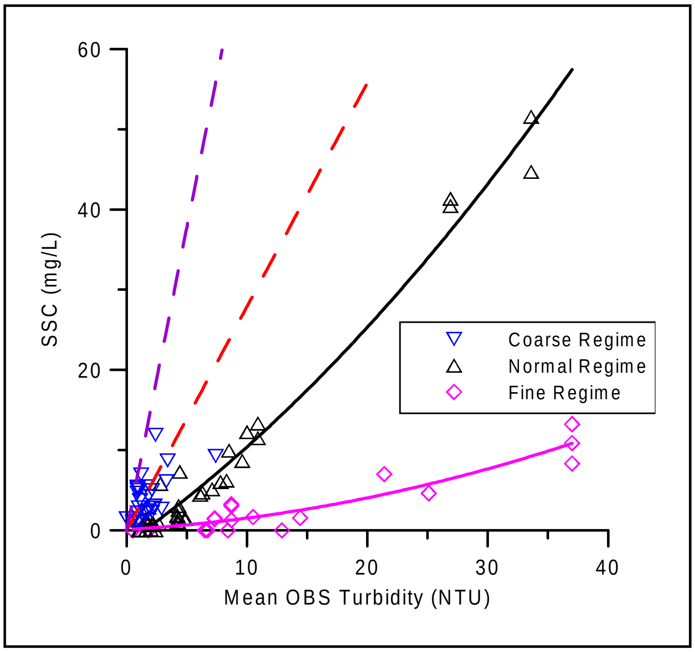


Figure 10. Sediment-production regimes at the confluence. Dashed red and purple lines represent the lab calibrations for fines and very fine sand. Note that the normal regime consists entirely of fines over the whole range.

The separation between fines and sand in the suspended sediment load is also done for the same storm (Figure

Table 5. Measured and calculated grain-size distribution for samples collected at Russell and Stephanie Creeks.

			Measured grain-size distribution						Lab calibrations		Estimated grain-size distribution	
Date & time of sample	**Turbidity T** (NTU)	**Observed SSC** (mg/L)	**Sand** (%)	**Silt** (%)	**Clay** (%)	**Regime**	**SSC from T** (mg/L)	**Tangent** (slope)	**Fines** (slope)	**Very fine sand** (slope)	**Sand** (%)	**Fines** (%)
Stephanie												
4/5/96 14:13	69.6	244	30	64	6	N	266.3	5.00	2.62	10.27	31.1	68.9
4/5/96 14:28	56.9	217	27	61	12	N	205.5	4.57	2.62	10.27	25.5	74.5
4/5/96 14:58	67.4	325	40	56	4	C	316.2	5.54	2.62	10.27	38.1	61.9
4/5/96 14:59	67.4	293	34	60	6	C	316.2	5.54	2.62	10.27	38.1	61.9
4/5/96 15:01	67.4	301	39	59	2	C	316.2	5.54	2.62	10.27	38.1	61.9
4/5/96 15:13	75.9	353	36	59	5	C	364.3	5.78	2.62	10.27	41.2	58.8
4/5/96 15:28	82.5	394	43	55	2	C	403.0	5.96	2.62	10.27	43.7	56.3
4/5/96 15:40	90.1	435	42	55	3	C	449.1	5.64	2.62	10.27	39.5	60.5
4/5/96 15:42	90.1	418	37	58	5	C	449.1	5.64	2.62	10.27	39.5	60.5
4/5/96 15:43	90.1	441	40	56	4	C	449.1	5.64	2.62	10.27	39.5	60.5
4/5/96 15:45	90.1	424	40	57	3	C	449.1	5.64	2.62	10.27	39.5	60.5
4/5/96 15:47	90.1	396	39	56	5	N	376.0	5.70	2.62	10.27	40.2	59.8
4/5/96 15:49	97.2	431	39	55	6	N	417.2	5.94	2.62	10.27	43.3	56.7
4/5/96 15:53	97.2	422	39	56	5	N	417.2	5.94	2.62	10.27	43.3	56.7
4/5/96 15:56	97.2	410	37	56	7	N	417.2	5.94	2.62	10.27	43.3	56.7
4/5/96 16:02	97.2	400	39	57	4	N	417.2	5.94	2.62	10.27	43.3	56.7
4/5/96 16:03	97.2	412	43	54	3	N	417.2	5.94	2.62	10.27	43.3	56.7
4/5/96 16:05	97.2	421	43	55	2	N	417.2	5.94	2.62	10.27	43.3	56.7
4/5/96 16:07	98.4	428	41	57	2	N	424.4	5.98	2.62	10.27	43.9	56.1
10/24/94 22:33	29.4	188	45	39	16	VC	192.8	6.35	2.62	10.27	48.8	51.2
10/24/94 23:02	54.0	225	26	68	6	N	192.6	4.48	2.62	10.27	24.3	75.7
10/24/94 23:31	81.3	299	34	56	10	N	327.4	5.25	2.62	10.27	34.4	65.6
10/24/94 23:31	81.3	317	33	57	10	N	327.4	5.25	2.62	10.27	34.4	65.6
10/24/94 23:31	89.3	323	39	50	11	N	371.5	5.25	2.62	10.27	34.3	65.7
10/25/94 0:00	95.3	404	42	50	8	N	406.3	5.87	2.62	10.27	42.5	57.5
10/25/94 0:00	95.6	415	44	49	7	N	407.9	5.88	2.62	10.27	42.6	57.4
10/25/94 0:28	96.6	667	70	26	4	VC	666.6	7.75	2.62	10.27	67.0	33.0
10/25/94 0:57	87.2	503	70	27	3	C	431.5	8.30	2.62	10.27	74.2	25.8
10/25/94 0:57	86.5	478	67	30	3	VC	589.6	8.26	2.62	10.27	73.8	26.2
Russell												
11/19/91 8:00	52.4	227	40	57	3	C	218.5	4.84	2.71	7.90	41.1	58.9
11/19/91 10:00	60.3	241	43	53	4	C	257.5	5.05	2.71	7.90	45.0	55.0
11/19/91 12:00	50.5	173	36	58	6	C	209.3	4.79	2.71	7.90	40.1	59.9

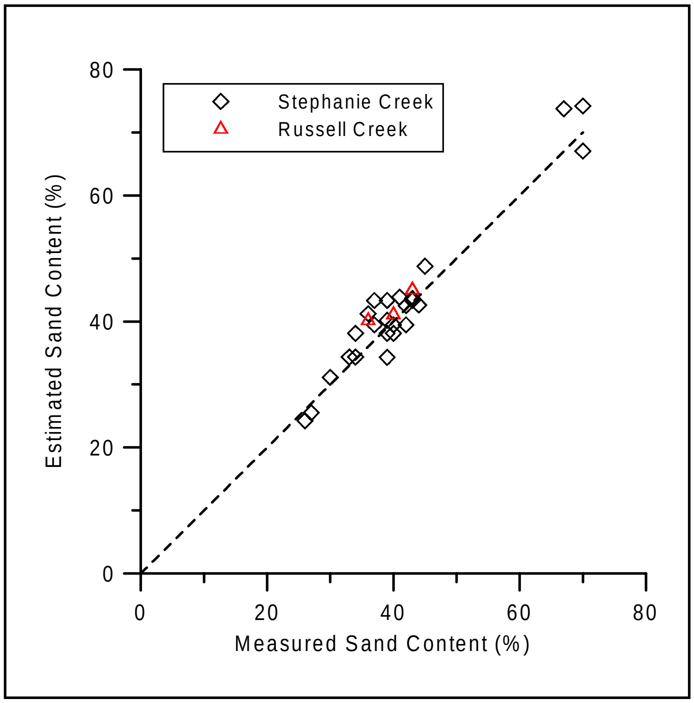


Figure 11. Estimated vs. measured sand content of samples from Russell and Stephanie Creeks. The dashed line represents a 1:1 relationship.

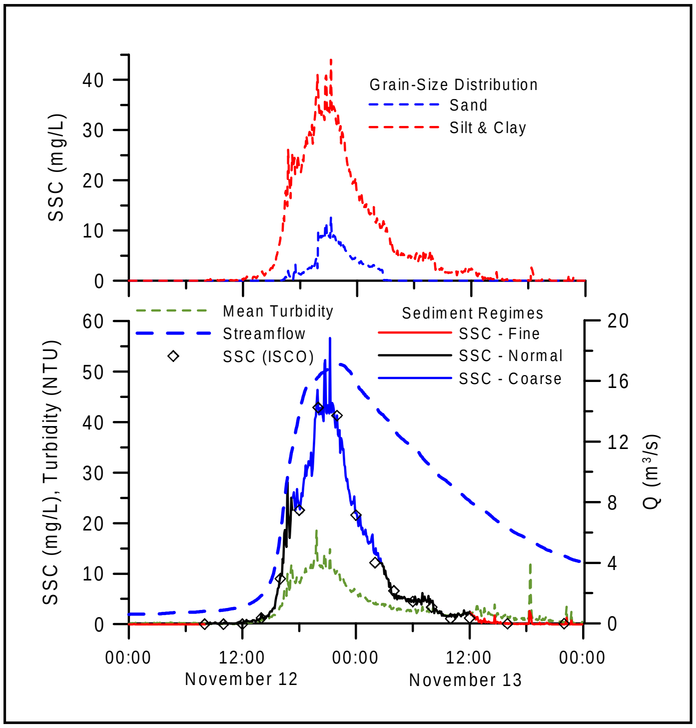


Figure 12. An example of the application of sediment-production regimes (lower graph), and the separation of suspended sediment into fine and sand fractions (upper graph), for Russell Creek, November 1998.

12, upper graph). These results indicate that at peak suspended sediment concentration the suspended sediment load is 22% sand. The total suspended sediment yield for the storm was 18 280 kg, of which 14% was sand.

DISCUSSION

It is generally assumed that sand transport is linked with storage in the channel bed. However, the primary hydrologic threshold associated with the normal-to-coarse regime transitions is rainfall intensity, as opposed to a hydraulic threshold associated with a fixed streamflow. This suggests that the sand component of the suspended load is produced and transported without interaction with the channel bed, at least in part. Under this scenario, the normal-to-coarse transition would occur because heavy rain on exposed sediment has the ability to erode coarser material. The sand component appears to consist primarily of very fine sand in the 63–125 m range (i.e., the slope of the lab calibration for very fine sand is never exceeded by the field calibrations). Presumably the stream would be capable of transporting this fraction as suspended at medium-to-high flow. Further, the normal-to-fine transition after a large storm could be a result of depletion of erodible sand from sediment sources, followed by a period during which the exposed surface of the sediment is loosened again by processes such as freeze-thaw erosion. This creates a new supply of transportable sand and allows the normal-to-coarse transitions to resume during large events. This process explains the sequence of transitions that occurred during the November–December 1998 storms at Russell Creek.

A comparison between the field calibrations at different sites (e.g., the normal regime, Figure 13) suggests that a relationship exists between the steepness of the calibration curve and a site attribute such as mean channel slope (see Table 1). The steeper channels are clearly capable of transporting more sand than the less-steep channels; there is also a relationship between the proportion of sand transported during a storm, and the total volume of sediment produced by that storm (Table 6). This type of information could potentially lead to a regional approach to interpreting turbidity and suspended sediment data.

RECOMMENDATIONS

Results show that there are distinct sediment-production regimes, and they are defined by the quality of sediment that is being transported. Transitions between sediment-production regimes occur both seasonally and during storms. The seasonal transitions are governed by sediment supply, whereas the transitions that occur within storms are related to rainfall intensity and hydrologic conditions. These results are similar to those of Beschta (1978), who found that storms that occurred before the annual peak flow had higher suspended sediment concentrations than post-peak storms.

With proper gauge siting, it is possible to develop usable relationships between suspended sediment and turbidity in conjunction with automatic water sampling. In particular, transitions between regimes can be predicted with reasonable certainty provided that there are no active sediment sources immediately upstream of the gauge. However, without using the procedures described here, the turbidity readings alone would be difficult to interpret. Therefore a proper procedure for using turbidity readings as a basis for calculating suspended sediment concentration can be described as follows:

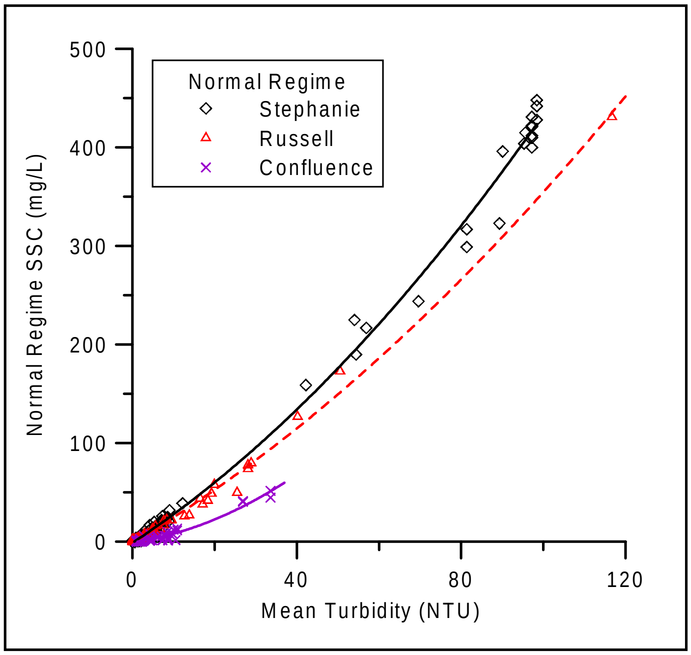


Figure 13. A comparison of normal regime suspended sediment concentration vs. turbidity relationships at three sites. A relationship between grain-size distribution and channel gradient is suggested.

1. Obtain a sample of sediment from the stream into which the turbidity probe is to be installed.
2. Separate the sediment into fractions of fines, very fine sand, fine sand, and medium sand using sieves of 63, 125, 250, and 500 microns. Use these graded fractions to obtain a lab calibration for the probe.
3. Operate the probe in the field along with automatic sediment sampler for a period of time to obtain a field calibration. This will take at least one year, and possibly longer depending on the frequency and magnitude of sediment-production events.
4. Identify sediment-production regimes based on field data. Changes in sediment-production regime should follow a logical pattern based on storm sequences, as described above.
5. Once stable relationships have been established, they can be used to interpret turbidity data in the absence of sediment samples. These relationships can also be used to forecast the distribution of fines and sand in the suspended sediment load.
6. If a logical pattern of regime transitions cannot be identified, it suggests the following options:

   a) The relationship between suspended sediment concentration and turbidity can be averaged into a single relationship, but with a loss of precision. With this option, grain-size distribution probably cannot be determined with confidence, unless the calibration indicates that the suspended load is all fines.

   b) Permanent automatic sampling will be required to accurately interpret the turbidity data. For example, if

Table 6. Sediment yield and proportion of sand for selected storms at Stephanie and Russell Creeks. The sand proportion is related to the total yield, and also to one or more site attributes such as the channel slope above the gauging site.

	Stephanie Creek			Russell Creek		
Storm date	Peak flow (m^3/s)	SS yield (kg)	P sand (%)	Peak flow (m^3/s)	SS yield (kg)	P sand (%)
4/4/96	6.009	71 280	42	34.132	297 236	23
4/7/96	5.991	46 108	14	13.113	22 098	16
9/30/97	3.796	13 721	29	16.210	16 788	16
10/1/97	3.506	8 963	8	12.964	10 410	10
10/3/97	2.346	4 792	4	8.022	783	0
10/15/97	3.475	11 064	14	10.904	12 349	11
10/26/97	1.950	2 085	10	7.390	3 760	8

the purpose of the gauge site is to measure the effect of an individual sediment source (e.g., upper Stephanie), then this would be the desired option.

c) Move the gauge site to a more stable location.

When monitoring turbidity for the purpose of evaluating suspended sediment load, it is important to recognize that at any one site, there may be several different relationships between suspended sediment concentration and turbidity. It is important to recognize this, and the potential limitations of the data. Misinterpretation of turbidity data can lead to large errors in calculating suspended sediment load.

CONCLUSION

Since 1991, the Vancouver Forest Region of the British Columbia Ministry of Forests has conducted research on the sediment budgets of forest streams in the Tsitika River Watershed, in northeastern Vancouver Island in Coastal British Columbia. A method of measuring and correlating suspended sediment concentration and turbidity has been developed to assist hydrologists is assessing sediment production of streams. The effects of forestry activities on sediment production in streams are of concern because excessive sediment is detrimental to fish habitat and drinking water quality.

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