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DETECTING CUMULATIVE EFFECTS ON HEADWATER STREAMS IN THE ROUTT NATIONAL FOREST, COLORADO[1]

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ABSTRACT: This study evaluated the use of a modified pebble count procedure (Bevenger and King, 1995) to detect cumulative watershed effects on headwater streams in the Routt National Forest in northcentral Colorado. The 42 sample reaches were stratified by disturbance (reference or disturbed) and geologic terrane (granitic or mixed sedimentary-volcanic). Water surface slope was a significant control on the number of fine particles in the reference reaches in both terranes, and the data from the disturbed reaches were adjusted accordingly. The disturbed reaches in the granitic terrane generally had a higher percentage of fine particles, and the adjusted number of fine particles was significantly correlated with the number of road crossings. Disturbed reaches in the sedimentary-volcanic (s-v) terrane generally did not have significantly more fine particles, nor were the adjusted numbers of fine particles significantly correlated with any management index. The lack of significant trends in the s-v streams is probably due to differences in weathering between the two rock types, and the location of the sample reach relative to sedimentary outcrops. Two other procedures were also used to assess cumulative watershed effects, with the Pfankuch channel stability rating yielding stronger and more consistent differences between the reference and the disturbed streams than the Tarzwell substrate ratio. We conclude that it may be difficult to define a standard reference condition, and that the number of road crossings is more strongly correlated with the number of fine particles than equivalent clearcut area.

(KEY TERMS: watershed management/wildland hydrology; cumulative watershed effects; sedimentation; stream channels; bed material particle size; forest management; roads.)

INTRODUCTION

The National Environmental Policy Act requires federal land managers to assess the impact on the environment of any proposed management activity (Thatcher, 1990). Although single actions can create an adverse environmental impact, the degradation of water resources is usually a result of multiple activities over time and space. In many forested areas a primary concern is the cumulative effect of management activities on the designated beneficial uses of water, particularly coldwater fisheries (e.g., MacDonald *et al.*, 1991). Numerous methods have been developed to quantify the cumulative watershed effect of forest management activities, and these include the equivalent clearcut area (USFS, 1974), equivalent roaded area (Cobourn, 1989), and computer models such as HYSED (Silvey, 1981) and R1-WATSED (USFS, 1992). However, very few studies have directly tested these procedures with respect to water or sediment yields, or related these indices to stream channel condition, quality of aquatic habitat, or coldwater fish production (Reid, 1993).

Cumulative watershed effects on the Routt National Forest (RNF) in northcentral Colorado result from multiple land use activities including timber harvest, unpaved roads, grazing, and recreation. Timber harvest has been shown to increase annual water yields (Bosch and Hewlett, 1982; Stednick, 1996), the size of peak flows (Bates and Henry, 1928; Troendle and King, 1985), the rate of surface erosion (Everest *et al.*, 1987), and the frequency of mass movements (Sidle *et al.*, 1985; Swanson *et al.*, 1987). Forest harvest and the associated road network usually increase the amount of sediment delivered to the stream channel and basin-scale sediment yields (Everest *et al.*, 1987; Reid, 1993). Literature reviews suggest that roads may be the primary source of sediment rather than the forest harvest *per se* (Everest *et al.*, 1987; Reid, 1993). The deposition of fine sediment is of concern because this can adversely affect macroinvertebrates and fish by filling pools and interstitial

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spaces, decreasing intergravel dissolved oxygen concentrations, and inhibiting fry emergence (MacDonald *et al.,* 1991; Meehan, 1991; Weaver and Fraley, 1993; Waters, 1995).

The bed material particle-size distribution is believed to be one of the first channel characteristics to change in response to management activities (Dietrich *et al.,* 1989; Madsen 1994). Wolman pebble counts (Wolman, 1954) are the most common technique to assess changes in the surface particle-size distribution and thus evaluate management effects on aquatic habitat.

There are several limitations to the use of Wolman pebble counts to assess cumulative watershed effects (CWEs). First, measurements are usually made at a channel cross-section or within a single habitat type such as a riffle or a pool. This does not provide an integrated, reach-scale assessment, even though the reach is often the primary unit of concern to land managers. Second, the statistical procedures used for comparing pebble counts typically focus on a single value, such as the D_{50} or D_{84}. Thus a 100-unit pebble count is reduced to a single metric, and the resulting decrease in sample size greatly weakens the statistical power of the analysis. Finally, recent studies have shown that observer bias and measurement accuracy can limit the accuracy and precision of pebble counts (Marcus *et al.,* 1995; Wohl *et al.,* 1996).

Bevenger and King (1995) addressed the first limitation by longitudinally sampling 150-300 particles at approximately 1-m intervals in a several hundred meter reach. The second limitation was resolved by focussing on the total number of particles with an intermediate diameter less than eight millimeters. Each measured particle is therefore treated as one sample and this greatly increases the sample size. Comparisons over time or between streams can be analyzed by chi-squared contingency tables (Potyondy and Hardy, 1994; Bevenger and King, 1995; Schnackenberg, 1996).

Bevenger and King's study showed that reaches disturbed by forest management had significantly more fine (< 8 mm) sediment than otherwise comparable reference reaches; the observed increase in fine sediment was attributed to land use activities (Bevenger and King, 1995). A particle size of eight millimeters was used because this is a break in phi (log 2) classes (Wolman, 1954) and is close to the 0.25-inch (6.35 mm) threshold considered detrimental to many coldwater fish species (Chapman, 1988).

The primary goal of this study was to evaluate the use of the Bevenger and King (henceforth referred to as B&K) pebble count procedure to assess cumulative watershed effects in the Routt National Forest. However, to accomplish this goal we had to address a series of conceptual and methodological issues, and relatively little additional effort was needed to collect data using two other channel assessment procedures. Hence this study expanded into a more comprehensive attempt to detect CWEs and their potential causes. The specific objectives were to: (1) determine if lithology had a significant effect on the number of fine particles in undisturbed ("reference") reaches; (2) determine if there was a significant autocorrelation between sampled particles (i.e., to verify that each particle was an independent sample); (3) evaluate consistency between observers; (4) determine if one or more local controls (water surface slope, drainage area, elevation, valley slope, or amount of large woody debris) significantly affected the amount of fine sediment in the reference reaches; (5) evaluate the relationship between the number of fine particles in the disturbed ("study") reaches and three indices of forest management; (6) compare the results of the modified pebble count to two other commonly-used procedures to assess stream channel condition (Pfankuch channel stability rating and Tarzwell substrate ratio); and (7) evaluate the relationship between each of the three channel assessment procedures and the management indices. The ultimate goal is to develop and validate one or more procedures to detect the adverse cumulative effects of management activities on stream channel characteristics and, by inference, aquatic ecosystems.

STUDY AREA

The Routt National Forest (RNF) encompasses 4,450 km^2 in northcentral Colorado (Figure 1). Elevations range from 1,970 to 3,690 meters. The continental divide runs along the Park and Gore Ranges and effectively bisects the RNF. Annual precipitation ranges from 40 cm in the lower elevations to more than 150 cm in the higher elevations of the Park Range. The annual runoff hydrograph is dominated by the seasonal snowmelt peak in late May or June.

The RNF has two dominant geologic terranes: (1) crystalline rocks (primarily granitic) in the Park and Gore Ranges; and (2) sedimentary-volcanic rocks in the Elkhead, Flattop, and Rabbit Ears mountain ranges. Within the latter category, the volcanics typically occur on the peaks and high ridgetops, and these are underlain by sedimentary rocks such as sandstones, siltstones, and shales.

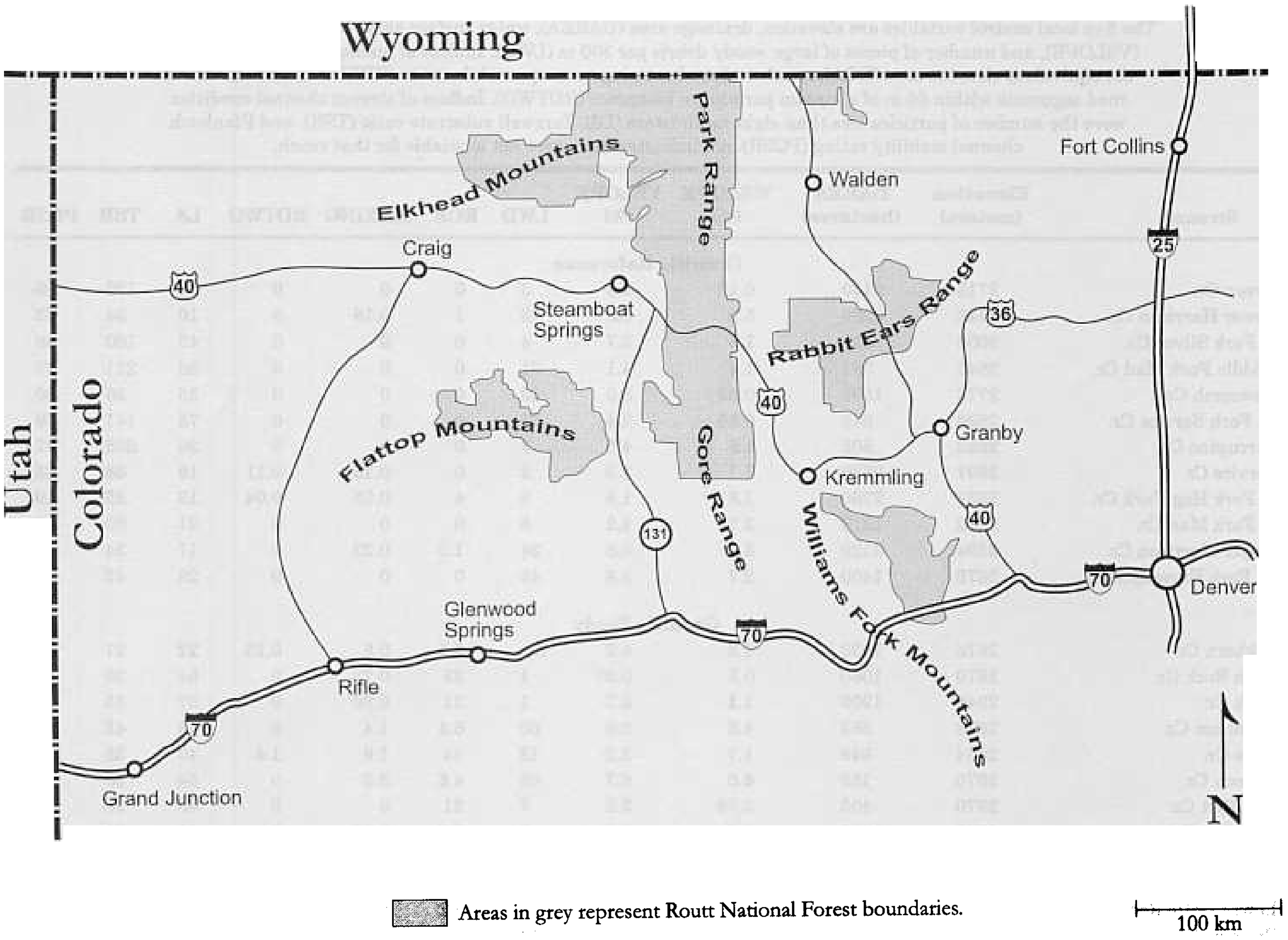

Figure 1. Map of the Routt National Forest and Major Mountain Ranges in Northcentral Colorado. The shaded area southeast of Kremmling is no longer being administered by the Routt National Forest.

METHODS

Forty-two reaches were sampled in the summer of 1994. Reaches were stratified by land use and geologic terrane (granitic or sedimentary-volcanic). We tried to focus on lower-gradient response reaches (Montgomery and Buffington, 1993, 1997), but the mountainous terrain meant that 20 of the 42 reaches had a water surface slope greater than two percent (WSLOPE in Table 1). The median bankfull width was only 4.5 m. If classified by Rosgen (1994), 14 percent of the reaches were type A, 31 percent type B, 38 percent type C, and 17 percent type E.

In each 150-300 m reach 150 particles were sampled at approximately one-meter intervals while traversing diagonally upstream from bankfull to bankfull (Bevenger and King, 1995). Each particle was selected by blindly placing a finger at the toe of one's wader and picking up the first particle touched. The intermediate axis was measured with a ruler to the nearest millimeter, and the percent of particles smaller than eight millimeters was calculated for each reach. To eliminate problems with observer bias, all of the data used in the primary analysis were collected by the same observer. However, we also evaluated observer variability by having two or more people independently sample the same reach. For these comparisons the sample size ranged from 50 to 150 particles per observer, with a smaller sample size and correspondingly shorter reach being used in colder water.

Boxplots, summary statistics, and an F-test for equal variances were used to determine whether bedrock lithology affected the number of fine (< 8 mm)

TABLE 1. Characteristics of Reference and Study Reaches in Granitic and Sedimentary-Volcanic Terranes. The five local control variables are elevation, drainage area (DAREA), water surface slope (WSLOPE), valley slope (VSLOPE), and number of pieces of large woody debris per 300 m (LWD). Indices of management activity were the equivalent clearcut area (ECA), number of road crossings per square kilometer (RDXING), and number of road segments within 60 m of a stream per square kilometer (RDTWO). Indices of stream channel condition were the number of particles less than eight millimeters (L8), Tarzwell substrate ratio (TSR), and Pfankuch channel stability rating (PCSR). n/a indicates data were not available for that reach.

Stream	Elevation (meters)	DAREA (hectares)	WSLOPE (%)	VSLOPE (%)	LWD	ECA	RDXING	RDTWO	L8	TSR	PCSR
Granitic Reference											
Green Cr.	2715	2140	0.12	1.3	3	0	0	0	69	126	93
Lower Harrison Cr.	2145	4380	5.9	6.8	13	1	0.16	0	10	34	53
S. Fork Silver Cr.	3006	533	1.5	3.7	4	0	0	0	45	180	58
Middle Fork Mad Cr.	2642	931	1.4	4.1	21	0	0	0	38	221	77
Newcomb Cr.	2776	1500	0.69	5.0	10	0	0	0	35	36	80
N. Fork Service Cr.	2836	642	0.59	2.4	23	0	0	0	75	141	59
Porcupine Cr.	2933	506	1.5	4.5	7	0	0	0	26	208	
Service Cr.	2697	2620	1.1	3.3	2	0	0.15	0.11	19	38	65
S. Fork Hog Park Cr.	2533	2760	1.8	1.8	8	4	0.25	0.04	13	35	49
S. Fork Mad Cr.	2842	1210	3.7	4.2	8	0	0	0	21	80	47
Upper Harrison Cr.	2594	3120	3.6	4.8	24	1.2	0.22	0	17	34	50
W. Fork Encampment	2679	1400	2.7	3.8	46	0	0	0	28	42	65
Granitic Study											
Elkhorn Cr.	2576	1030	2.8	4.2	n/a	5.3	0.5	0.25	22	27	87
High Rock Cr.	2970	1060	0.5	0.97	1	33	0.73	0	54	30	85
Rock Cr.	2945	1900	1.1	3.7	1	21	0.96	0	37	55	83
Farnham Cr.	2879	363	4.8	9.0	60	6.4	1.4	0	45	45	91
Gore Cr.	2824	948	1.7	2.2	12	43	1.9	1.4	40	25	94
French Cr.	2970	159	6.0	6.7	68	4.6	3.3	0	54	30	89
Red Dirt Cr.	2970	405	0.76	2.5	7	21	0	0	48	38	90
Damfino Cr.	2752	1660	2.6	2.8	8	2.3	0.16	0	11	81	56
Line Cr.	2848	846	1.8	2.4	4	29	0.61	0.3	36	69	79
Upper Little Rock Cr.	2667	533	2.2	3.0	1	2.8	2.9	3.0	52	10	107
Lower Little Rock Cr.	2655	1020	0.60	1.2	0	4.2	2.0	1.8	78	7	91
Burgess Cr.	2230	611	6.7	11	47	11	1.3	0	44	27	61
Sedimentary-Volcanic Reference											
S. Fork Little Snake	2521	808	1.9	2.3	3	4	0.24	0.24	37	27	77
Johnson Cr.	2461	1080	3.2	5.7	18	0	0	0	32	24	77
Lopez Cr.	2497	328	4.6	6.7	18	0	0	0	43	20	91
Lower Roaring Fork	2788	1080	3.9	3.8	8	0	0	0	17	58	69
Lower Trout Cr.	2994	1720	4.8	5.4	29	0	0	0	17	33	76
Upper Trout Cr.	3042	1490	0.44	2.0	8	0	0	0	35	16	95
Oliver Cr.	2497	809	1.8	3.1	33	0	0	0	36	17	82
Upper Roaring Fork	2848	493	1.3	3.4	14	0	0	0	44	27	89
Horse Cr.	2770	457	2.5	10	n/a	0	0	0	39	37	89
Sedimentary-Volcanic Study											
Corral Cr.	2764	1760	2.8	3.9	11	14	2.5	0.59	41	29	n/a
First Cr.	2409	3030	0.82	2.0	2	0	0.17	0.34	58	24	123
Grizzly Cr.	2606	966	3.8	3.9	9	1.7	0.8	1.3	33	26	90
King Solomon	2636	1140	1.4	2.3	24	1	0	0	46	32	108
Lower S. Fork Slater	2558	1840	2.7	3.7	2	9.2	1.5	0.42	28	24	105
Willow Cr.	2776	2210	1.5	2.3	5	36	1.2	0.35	35	57	82
Snyder Cr.	2715	1460	0.68	2.0	4	19	1.4	0.35	79	18	129
Mill Cr.	2485	1220	2.6	3.5	15	9.6	2.8	2.3	24	32	90
N. Fork West Prong	2788	460	2.9	4.1	10	0.7	0.56	0	31	71	99

particles in the reference reaches. Autocorrelation analyses were run for 1 to 16 lags in each reach to determine if each pebble was an independent sample. Samples from different observers were compared using chi-square contingency tables and Fisher's exact two-tailed test (SAS, 1990).

Because this was an exploratory study rather than a monitoring project, five local controls were evaluated for their effect on the particle-size distribution. The five local control variables were elevation, drainage area, valley slope, water surface slope, and number of pieces of large woody debris. Elevation, drainage area, and valley slope were determined from U.S. Geological Survey 1:24,000 topographic maps. Water surface slope was surveyed in the field using an engineers level and stadia rod. The number of pieces of large woody debris was normalized to a reach length of 300 meters. To be counted, a piece of large woody debris had to be longer than half the channel width, thicker than five centimeters at the large end, and influence stream dynamics during bankfull flow. Log jams were relatively rare and were counted as a single piece of large woody debris.

Simple and stepwise regression (SAS, 1990) were used to determine the effect of the five local controls on particle size in the reference reaches in each terrane. The regression model developed from the reference reaches was then used to remove the effect of significant local controls on the number of fine particles in the study reaches. The resulting residuals were regressed against the three management indices to evaluate the relative strength of the relationship between the adjusted number of fine particles and each management index (Helsel and Hirsch, 1992). We used this approach rather than pairwise comparisons because the primary objective was to evaluate the B&K methodology.

The two other indices used to evaluate stream channel condition were the Tarzwell substrate ratio (TSR) and the Pfankuch channel stability rating (PCSR). The TSR is intended to be a dimensionless index of macroinvertebrate productivity (Tarzwell, 1936, 1938), although the values were originally derived from biomass data (J. Chanat, Colorado State University, personal communication, 1995). This procedure ocularly classifies stream substrates according to the dominant particle size, presence of sand infill, and presence of aquatic plants (Ohlander, 1994). Each substrate class is assigned a coefficient that quantifies the standing crop of macroinvertebrates relative to a sand substrate. The TSR value for a reach is equal to the average of 100 samples taken at two-meter intervals along the thalweg (Ohlander, 1994).

The PCSR was developed in the northern Rocky Mountains (Pfankuch, 1978) and is widely used in the western U.S. (Myers and Swanson, 1992). The PCSR quantitatively assesses stream channel condition by evaluating 15 different attributes of the upper banks, lower banks, and channel bottom. The range of possible values for each attribute varies according to an arbitrary weighting system, and the sum of the attribute values is the PCSR. Higher point totals represent less stable channels, and fish biologists have interpreted high PCSR values as less productive reaches.

Three management indices were used to characterize the amount of roads and forest harvest upstream of each sample reach. The first index was the equivalent clearcut area (ECA), and this was originally developed to predict the effect of roads and different types of timber harvest on annual and monthly water yields (USFS, 1974). Coefficients are used to convert the area of each timber harvest, road, or certain other ground-disturbing activities into an equivalent number of clearcut acres or ECAs (e.g., two acres of selection cut harvested with tractors might be considered just under one ECA). This procedure and the analogous equivalent roaded area method have been widely used by the U.S. Forest Service to evaluate watershed-scale disturbance (e.g., Cobourn, 1989; McGurk and Fong, 1995). Hydrologic recovery curves have been explicitly incorporated, and this study assumed a linear 80-year recovery curve for timber harvest (Troendle and King, 1985).

The second management index was the number of stream crossings by roads per square kilometer of watershed area (RDXING), while the third management index was the number of 400-m long road segments within 60 m of a stream channel per square kilometer of watershed area (RDTWO). Both of these indices were selected because roads can generate most of the sediment associated with forest management activities (e.g., Hafley, 1975; Megahan, 1984; Eaglin and Hubert, 1993; Waters, 1995). RDXING and RDTWO were also relatively easy to obtain from a geographic information system that superimposed the road network on the stream network as delineated on USGS 1:24,000 topographic maps. The transportation layer included open and closed roads, but did not include temporary roads or skid trails used in logging operations.

For this study we defined reference reaches as having less than two percent ECA, and RDXING and RDTWO values of less than 0.25 per square kilometer. In a few cases sample reaches were located immediately downstream of roads and harvest units, and these reaches were classified as study reaches even though the basin-scale disturbance indices were relatively low (Table 1). Conversely, two of the reference reaches had unexpectedly high management indices, but in each case the disturbance was primarily on the ridges in the uppermost parts of the basin.

T-tests were used to compare the mean TSR and PCSR values between the study and reference reaches. Differences in the variance between study and reference reaches were assessed by F-tests; if the variance was significantly different, an unequal variance t-test was used to evaluate the difference between means. Stepwise regression was used to assess whether the TSR and PCSR values could be predicted from the three management indices.

RESULTS

Overall Analysis

The granitic reference reaches generally had fewer small particles and significantly ($p = 0.04$) more variability than the sedimentary-volcanic reference reaches (Figure 2). On this basis the two terranes were separated for all subsequent analyses.

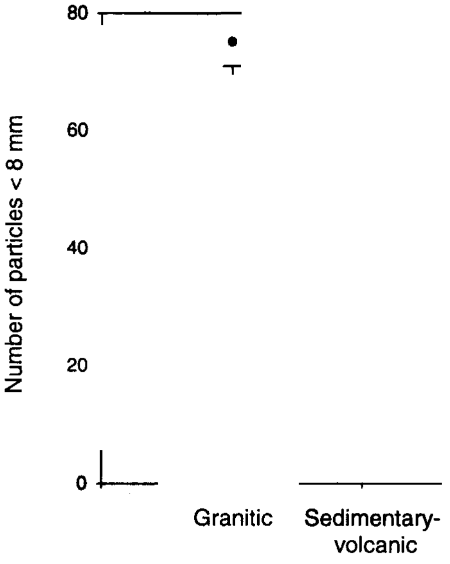

Figure 2. Boxplots Comparing L8 Values for the Granitic and Sedimentary-Volcanic Reference Reaches. The middle line represents the median, while the top and bottom of the box represent the 25th and 75th percentiles, respectively. Whiskers show the 5th and 95th percentiles, and the solid circles indicate outliers

Correlation tables indicated that the number of particles less than 8 mm in diameter (L8) was very highly correlated ($r > 0.9$; $p = 0.0001$) with the number of particles less than 4 and 10 mm, respectively (Table 2). Correlations between L8 and the number of particles less than 2 mm were not quite as strong ($r > 0.80$) but were still highly significant. Hence the results are quite robust with regard to the chosen breakpoint in particle size, and subsequent analyses used just the L8 values.

TABLE 2. Correlation Coefficients (r) and p-Values for Different Size Classes in the Granitic Reaches (n = 24) in the Upper Half of the Table and Sedimentary-Volcanic Reaches (n = 18) in the Lower Half of the Table. L2, L4, L8, and L10 refer to the number of particles with an intermediate diameter smaller than 2, 4, 8, and 10 mm, respectively.

		L2	L4	L8	L10
L2	⇒ r		0.97	0.84	0.93
	⇒ p-value		0.0001	0.0001	0.0001
L4	⇒ r	0.94		0.91	0.97
	⇒ p-value	0.0001		0.0001	0.0001
L8	⇒ r	0.85	0.96		0.97
	⇒ p-value	0.0001	0.0001		0.0001
L10	⇒ r	0.80	0.93	0.99	
	⇒ p-value	0.0001	0.0001	0.0001	

The autocorrelation analysis indicated that there was a significant autocorrelation ($p < 0.05$) in at least one sample reach for 13 of the 16 lags tested (Table 3). Seven of the 42 sample reaches had a significant lag-one autocorrelation (highest $R^2 = 0.22$), and five of the reaches were significantly correlated at lag 10 (highest $R^2 = 0.22$). These results suggest that samples taken one meter apart may not be completely independent, and this would violate one of the key assumptions underlying the use of chi-squared contingency tables. On the other hand, the 36 significant autocorrelations is only slightly greater than the 34 autocorrelations that would be expected by chance (i.e., 16 lags times 42 reaches with a level of significance of 0.05). The mean R^2 for the statistically significant autocorrelations ranged from 0.08 for lags one and ten to 0.04 for most of the other lags (Table 3). These low values, plus the fact that 95 percent of the lags were not significant, led us to conclude that autocorrelation can be a potential problem, but did not significantly affect the results of our study.

Twenty-two pairwise comparisons between eleven different pairs of observers found no significant differences ($p < 0.10$) between observers (Table 4; Figure 3). While this suggests a lack of significant observer bias, the mean difference of 4.2% and the standard deviation of 2.9 percent suggests that observer variability could cause up to a 10 percent shift in the number of fine particles.

TABLE 3. Number, Mean, and Maximum of Statistically Significant ($p < 0.05$) Autocorrelations for One to Sixteen Lags Negative correlations were converted to absolute values to calculate the mean autocorrelation for each lag.

Lag	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	Total
Number of Significant Correlations	7	3	2	1	0	0	2	2	2	5	4	2	0	2	2	2	36
Mean Correlation	0.28	0.23	0.20	0.24			0.23	0.22	0.19	0.28	0.23	0.20		0.24	0.21	0.20	0.24
Maximum Correlation	0.47	0.31	0.21	0.24			0.23	0.24	0.20	0.47	0.32	0.23		0.30	0.24	0.20	0.47

TABLE 4. Comparison of L8 Values Between Observers.

Stream	Number of Particles Counted (per observer)	Observer #1	Number of Particles < 8 mm	Observer #2	Number of Particles < 8 mm	Percent Difference Between Observers	P-Value
Uncompahgre Cr.	100	K. Wolff	21	T. Fratt	29	8.0	0.25
Uncompahgre Cr.	100	K. Wolff	21	J. Almy	25	4.0	0.62
Uncompahgre Cr.	100	T. Fratt	29	J. Almy	25	4.0	0.63
Upper South Fork Slater Cr.	100	L. Schnackenberg	15	S. Cowman	12	3.0	0.68
Upper Little Rock Cr.	150	L. Schnackenberg	53	S. Cowman	42	7.3	0.21
Lower Little Rock Cr.	150	L. Schnackenberg	81	S. Cowman	80	0.7	1.00
Mill Cr.	150	L. Schnackenberg	32	S. Cowman	21	7.3	0.13
Horse Cr.	150	L. Schnackenberg	42	K. Foster	52	6.7	0.26
Gore Cr.	148	L. Schnackenberg	42	S. Cowman	43	0.7	1.00
High Rock Cr.	100	L. Schnackenberg	28	S. Cowman	35	7.0	0.36
High Rock Cr.	100	L. Schnackenberg	28	L. MacDonald	36	8.0	0.29
High Rock Cr.	100	L. MacDonald	36	S. Cowman	35	1.0	1.00
Mule Cr.	150	L. Schnackenberg	96	S. Coulson	100	2.7	0.72
North Fork West Prong Cr.	50	L. Schnackenberg	11	S. Cowman	11	0.0	1.00
King Solomon Cr.	150	L. Schnackenberg	47	S. Cowman	59	8.0	0.18
First Cr.	150	L. Schnackenberg	60	S. Coulson	51	6.0	0.34
North Fork Elkhead Cr.	100	L. Schnackenberg	31	S. Cowman	32	1.0	1.00
North Fork Elkhead Cr.	100	L. Schnackenberg	31	C. Clapsaddle	30	1.0	1.00
North Fork Elkhead Cr.	100	C. Clapsaddle	30	S. Cowman	32	2.0	0.88
Upper Trout Cr.	150	L. Schnackenberg	39	S. Coulson	50	7.3	0.21
Middle Fork Mad Cr.	150	L. Schnackenberg	39	L. Belton	33	4.0	0.50
Burgess Cr.	150	L. Schnackenberg	49	S. Coulson	46	2.0	0.80

Reaches in Granitic Terrane

Stepwise regression showed that water surface slope was the only significant local control on L8 in the granitic reference reaches. The significance of the correlation was strengthened by using the natural log of the water surface slope (LNWSLOPE) (Table 5; Figure 4). The resulting regression model was:

$$\text{Predicted L8} = 38.6 - 16.3 * \text{LNWSLOPE} \qquad (1)$$

This had a R^2 of 0.64 and a standard error of 3.8 percent.

Using the reference reach data, ninety-five percent confidence bands were calculated for both individual points and expected means. The L8 values for the study reaches were plotted on this graph (Figure 5), and all but one of the study reaches plot on or above the regression line. Six of the study reaches fell outside the mean value confidence bands developed from the reference reach data, while four values plotted on or above the 95 percent confidence bands for individual points (Figure 5).

The effect of water surface slope on the L8 values in the study reaches was removed by applying the regression model developed from the reference

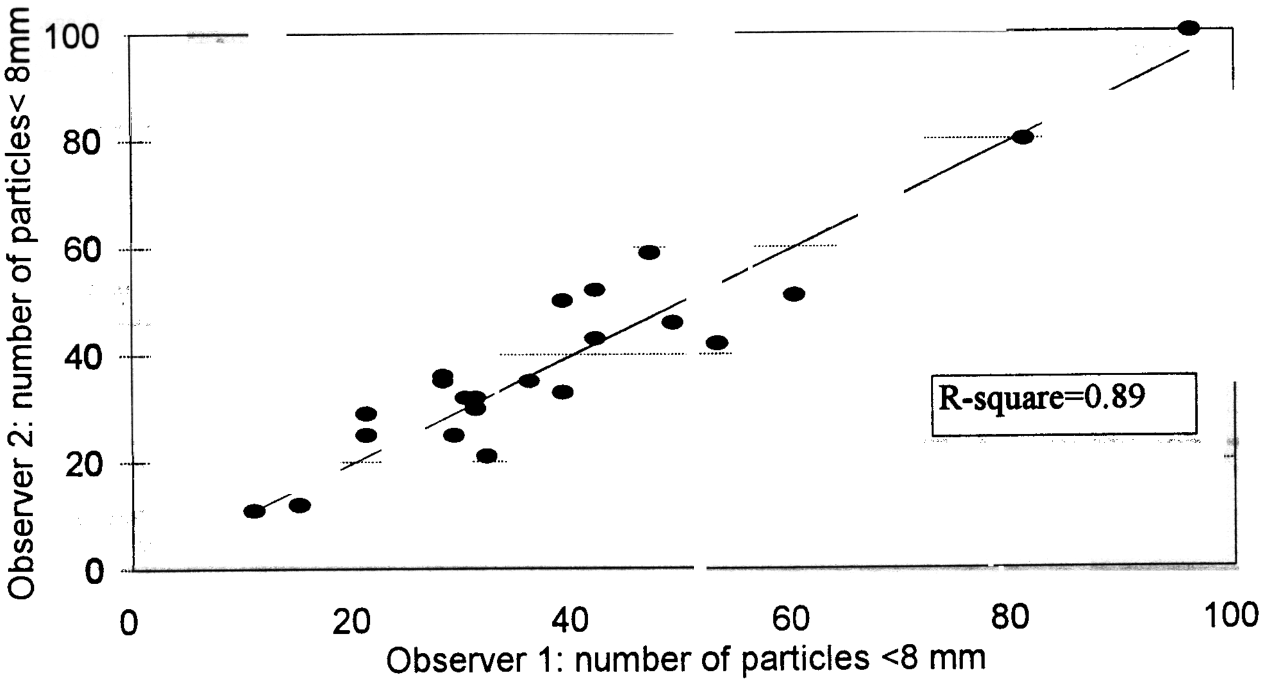

Figure 3. Comparison of L8 Values as Determined by Two Observers in the Same Reach With a 1:1 Reference Line.

TABLE 5. Correlation Matrix for L8 and Local Controls for Granitic Reference Reaches in the Upper Half of the Table, and Sedimentary-Volcanic Reference Reaches in the Lower Half of the Table. The top number in each box is the correlation coefficient, and the lower number is the p-value. Variable names are the same as in Table 1; LNWSLOPE is the natural log of the water surface slope.

	L8	ELEV	DAREA	WSLOPE	LNWSLOPE	VSLOPE	LWD
L8		0.48 0.12	-0.54 0.07	-0.68 0.02	-0.80 0.002	-0.57 0.05	0.001 0.999
	-0.36 0.34		-0.89 0.000	-0.65 0.02	-0.39 0.21	-0.38 0.22	-0.17 0.59
DAREA	-0.76 0.02	0.55 0.12		0.60 0.04	0.30 0.35	0.32 0.31	-0.07 0.83
WSLOPE	-0.50 0.17	-0.16 0.67	0.069 0.86		0.86 0.0004	0.71 0.009	0.23 0.47
LNWSLOPE	N/A	N/A	N/A	N/A		0.69 0.013	0.31 0.32
VSLOPE	0.09 0.81	-0.11 0.78	-0.37 0.33	0.49 0.18	N/A		0.14 0.67
	-0.13 0.76	-0.11 0.79	0.11 0.79	0.32 0.44	N/A	0.42 0.30	

reaches. Stepwise model selection indicated that RDXING was the only management index significantly correlated with the adjusted (i.e., residual) L8 values ($R^2 = 0.61$) (Table 6; Figure 6). This relationship suggests that road crossings have a greater effect on the bed material particle size than the area disturbed by timber harvest.

With regard to the other two channel assessment procedures, the Tarzwell substrate ratios were significantly higher and more variable in the reference

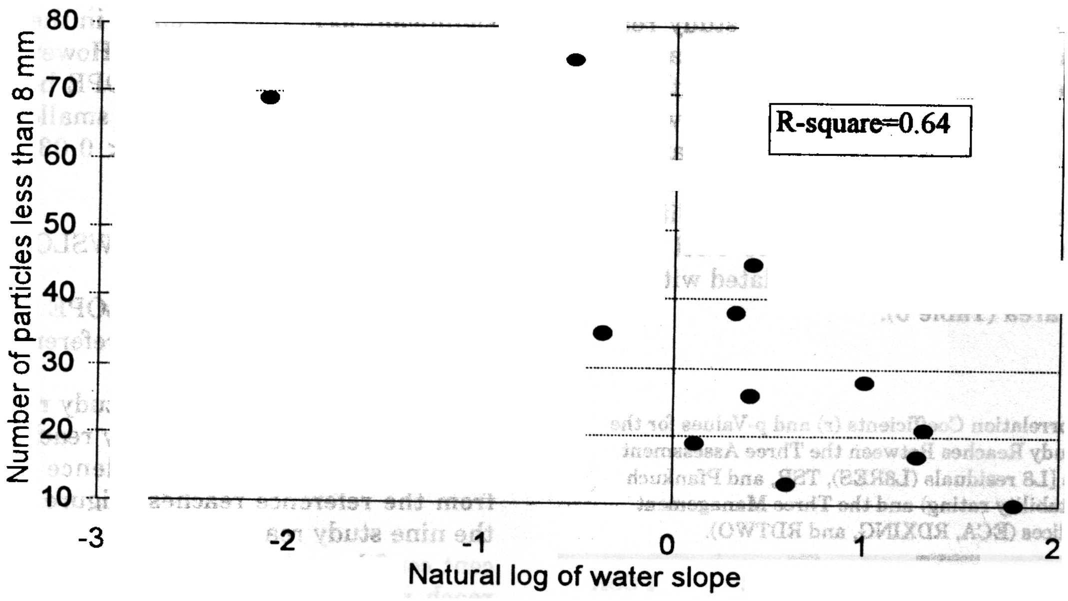

Figure 4. Plot of L8 Versus the Natural Log of the Percent Water Surface Slope (LNWSLOPE) for the Granitic Reference Reaches. The standard error of the regression is 13.1.

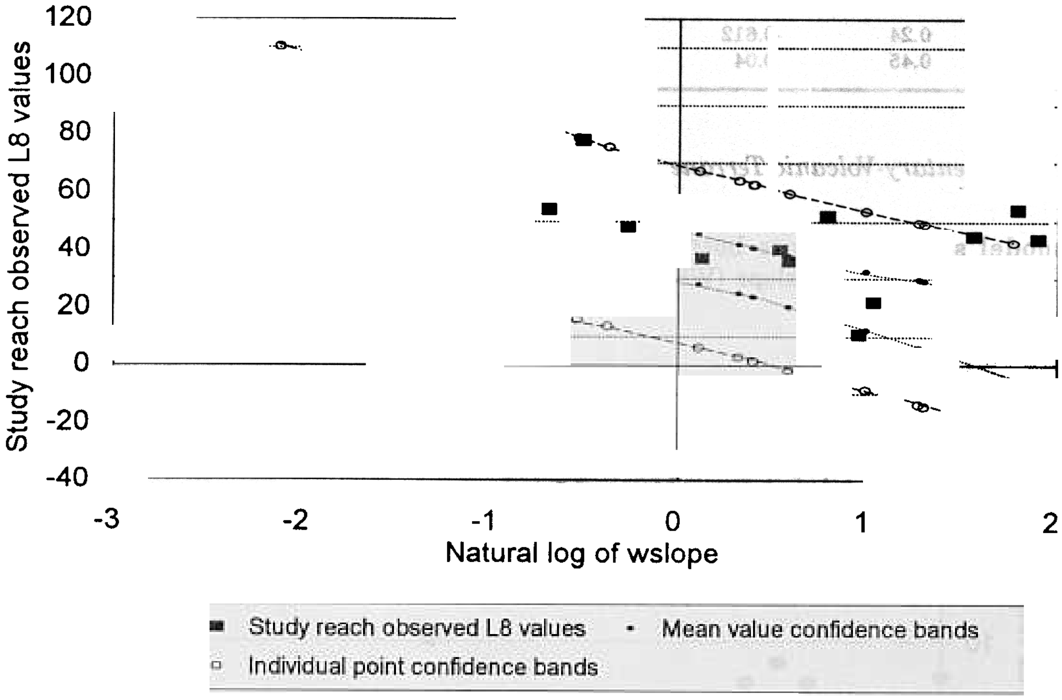

Figure 5. Plot of the L8 Values for the Granitic Study Reaches Versus the Natural Log of Water Surface Slope. The 95 percent confidence bands were developed from the granitic reference reaches.

reaches than the study reaches ($p < 0.02$ and $p < 0.001$, respectively). TSR values were significantly correlated ($p = 0.04$) with both the number of road crossings and the number of road segments adjacent to the channel, but neither management index explained more than 37 percent of the variability in TSR (Table 6).

Results from the Pfankuch stability ratings were generally similar, in that the PCSR values in the reference reaches were significantly lower (i.e., better stream channel condition) than in the study reaches ($p = 0.001$). In contrast to the TSR, there was no significant difference in the variance between the reference and study reaches. The PCSR values were also significantly correlated with both RDTWO and RDXING, but again these management indices did not explain more than 37 percent of the variability in the PCSR values (Table 6). Neither the TSR nor the PCSR values were significantly correlated with equivalent clearcut area (Table 6).

TABLE 6. Correlation Coefficients (r) and p-Values for the Granitic Study Reaches Between the Three Assessment Procedures [L8 residuals (L8RES), TSR, and Pfankuch channel stability rating) and the Three Management Indices (ECA, RDXING, and RDTWO).

		L8RES	TSR	PCSR
ECA	r	-0.38	0.10	0.10
	p-value	0.23	0.74	0.75
RDXING	r	0.78	-0.60	0.53
	p-value	0.003	0.04	0.08
RDTWO	r	0.24	-0.612	0.61
	p-value	0.45	0.04	0.03

Reaches in the Sedimentary-Volcanic Terrane

Stepwise model selection chose both drainage area (DAREA) and water surface slope (WSLOPE) as significant local controls on L8 in the reference reaches in the s-v terrane (Table 5). However, the L8 values were only adjusted for WSLOPE because the reference reaches had significantly smaller drainage areas than the study reaches ($p < 0.03$). The resulting regression model was:

$$\text{Predicted L8} = 42.4 - 3.36 * \text{WSLOPE} \qquad (2)$$

The relationship between WSLOPE and L8 was much weaker than for the granitic reference reaches ($R^2 = 0.25$).

In contrast to the granitic study reaches, there was less of a tendency for the study reaches in the s-v terrane to plot above the confidence bands developed from the reference reaches (Figure 7). Only three of the nine study reaches plotted on or above the 95 percent confidence band for mean values, while only one reach was above the 95 percent confidence band for individual values. One reach (Mill Creek) plotted below the 95 percent confidence band for mean values. Stepwise model selection indicated that none of the management indices was significantly correlated with the adjusted L8 values for the study reaches.

With regard to the other two channel assessment techniques, the mean PCSR in the study reaches was significantly higher ($p = 0.001$) than the mean value in the reference reaches. The variance in the study reaches was also greater than in the reference reaches ($p = 0.09$). However, none of the management indices was significantly correlated with the PCSR values from the study reaches. There was no

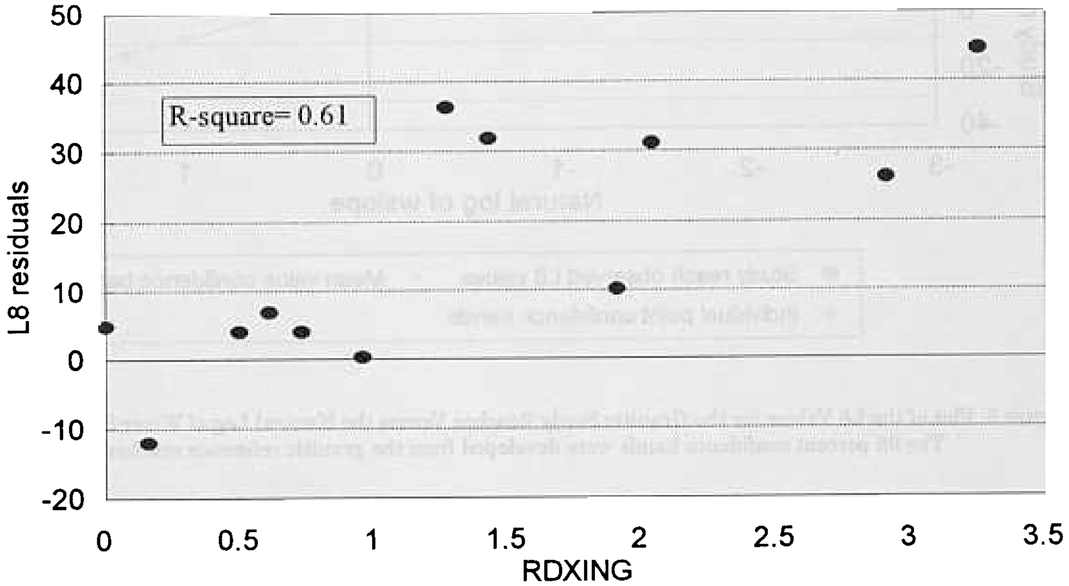

Figure 6. Plot of the Adjusted L8 Values for the Granitic Study Reaches Against the Number of Road Crossings Per Square Kilometer of Watershed Area (RDXING).

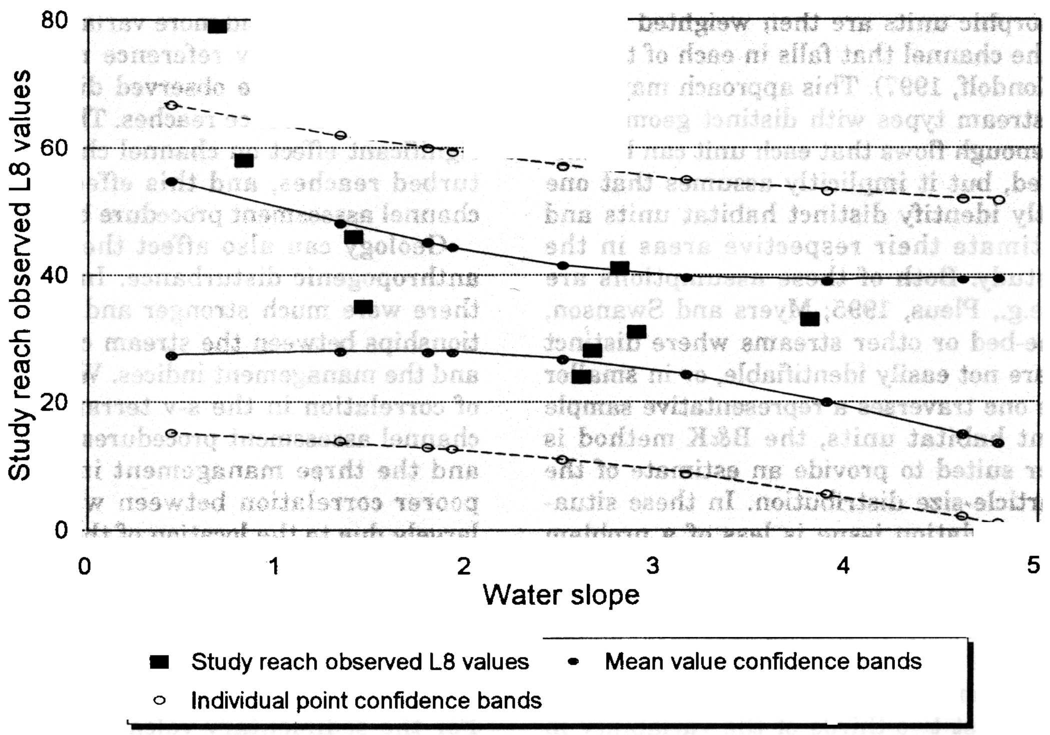

Figure 7. Plot of the L8 Values for the Sedimentary-Volcanic Study Reaches Versus Percent Water Surface Slope The 95 percent confidence bands were developed from the sedimentary-volcanic reference reaches.

significant difference in the mean TSR values from the study and reference reaches, and none of the management indices was significantly correlated with the TSR values from the study reaches.

DISCUSSION

Although none of the 22 pairwise comparisons between observers were significantly different, the percent difference in the number of fine particles ranged as high as eight percent (Table 4). Our experience was that careful training and close adherence to a standardized sampling methodology are essential to reduce observer variability. If pebble count data are to be collected by more than one observer, the variability between observers must be quantified before making any statement regarding differences over time or space. The importance of training in decreasing observer variability has also noted by Bevenger and King (1995), Marcus *et al.* (1995), and Wohl *et al.* (1996). This problem of observer variability may be particularly acute when the data are collected by different employees with widely varying levels of knowledge and experience (Wohl *et al.*, 1996).

Similarly, the potential autocorrelation between samples should be evaluated before embarking on a large-scale data collection program using the Bevenger and King (1995) approach. Given the physical processes that influence the particle-size distribution within stream channels, one would expect some autocorrelation between closely-spaced samples. This autocorrelation is a concern because it violates the assumption of independence between successive samples (pebbles). On the RNF this potential problem might be addressed by extending the sampling interval to two meters, as the streams were relatively small and dominated by smaller particles (median D_{50} was 41 mm). On the other hand, extending the sampling interval while maintaining the sample size will require longer stream reaches with no change in gradient or other factors. This may be a problem in topographically diverse areas or streams with substantial beaver populations.

The sudden increase in significant autocorrelations at lags 7-12 was more surprising, and probably stems from the zigzag sampling path up the stream channel. Depending on the size of the stream, the stream type, and the angle taken by the observer, one could be systematically sampling sequential geomorphic units such as pool-riffle sequences or the thalweg and channel edges.

The known differences in particle-size distributions for different channel locations has led some people to recommend stratified sampling. Samples from different geomorphic units are then weighted by the proportion of the channel that falls in each of the different units (Kondolf, 1997). This approach may work well in those stream types with distinct geomorphic units and low enough flows that each unit can be adequately sampled, but it implicitly assumes that one can consistently identify distinct habitat units and accurately estimate their respective areas in the reach under study. Both of these assumptions are questionable (e.g., Pleus, 1995; Myers and Swanson, 1997). In plane-bed or other streams where distinct habitat units are not easily identifiable, or in smaller streams where one traverses a representative sample of the different habitat units, the B&K method is probably better suited to provide an estimate of the reach-scale particle-size distribution. In these situations the autocorrelation issue is less of a problem than might be suggested by a simple autocorrelation analysis.

Another issue that typically complicates the detection of CWEs is the inherent variability in relatively undisturbed stream channels. Water surface slope accounted for almost two-thirds of the variability in L8 values in the granitic reference reaches. The selection of water slope as a significant local control is consistent with our understanding of the energy available for entrainment and sediment transport (Knighton, 1984). The importance of water surface slope in determining channel characteristics – particularly bed material particle size – was also documented in a study of nearly 100 reaches in northwestern Montana (Madsen, 1994).

A stepped classification of stream type (Montgomery and Buffington, 1993; Rosgen, 1994) will help account for the effect of gradient, but this stratification is not the statistically most effective means to remove the effect of continuous variables such as water surface slope. Failure to account for gradient or other local controls will make it extremely difficult to define standard reference conditions. On the other hand, it is not practical, and probably impossible, to sample enough reaches to quantify the effect of all the important local controls. Thus the combination of measured and unmeasured local controls will always create a range of variability within reference reaches.

This study indicates that it may also be necessary to stratify streams by bedrock lithology to reduce the variation within reference reaches. A comparison of the granitic and s-v reference reaches showed that the TSR was significantly higher ($p = 0.01$) and the PCSR was significantly lower ($p = 0.001$) in the granitic reference reaches than in the s-v reference reaches. The variability in L8 and TSR was also significantly different between the two sets of reference reaches. Although the granitic reference reaches did have larger ($p = 0.03$) and more variable ($p = 0.01$) drainage areas than the s-v reference reaches, this does not readily explain the observed differences between the two sets of reference reaches. Thus geology can have a significant effect on channel characteristics in undisturbed reaches, and this effect will vary with the channel assessment procedure being used.

Geology can also affect the channel response to anthropogenic disturbance. In the granitic terrane there were much stronger and more consistent relationships between the stream channel characteristics and the management indices. We believe that the lack of correlation in the s-v terrane between the three channel assessment procedures (L8, TSR, and PCSR) and the three management indices, as well as the poorer correlation between water slope and L8, is largely due to the location of the sample reaches relative to volcanic outcrops. Field observations suggest that reaches closer to volcanic outcrops had more volcanic particles and lower amounts of fine sediment. Conversely, reaches located in or immediately downstream of sedimentary outcrops had a finer substrate. For the sedimentary-volcanic reaches this geologic control may have a greater effect on bed material particle size than moderate levels of forest management activities. Failure to consider these differences in lithology and weathering could easily bias the results of comparisons between managed and unmanaged basins (Rinne and Neary, 1996).

The observed difference in drainage area between the reference and study reaches in the s-v terrane is another complication in the identification of CWEs. One would normally expect a fining of the bed material with increasing drainage area, and hence the study reaches in the s-v terrane should have plotted even higher above the regression line in Figure 7. From a practical point of view, it is difficult to obtain completely comparable pairs or sets of reference and study reaches, and this will always hinder the identification of CWEs.

In terms of predicting and minimizing CWEs, equivalent clearcut area was not significantly correlated with any of the channel assessment procedures. On the other hand, the strong relationship between the number of road crossings and the three channel assessment procedures is consistent with recent studies that emphasize roads as the primary cause of changes in runoff and sediment production in forested areas (Eaglin and Hubert, 1993; Madsen, 1994; Jones and Grant, 1996). The much poorer correlation in the granitic terrane between the adjusted L8 values and RDTWO may be due to the large variability in the effects of nearby road segments on stream channels. Road crossings provide a direct input of sediment from unpaved roads into the stream, while runoff from road segments near the stream will usually infiltrate downslope (Campbell and Stednick, 1983; Megahan, 1984).

The effect of timber harvest on a particular channel will vary with the proximity to the stream, sideslope steepness, and the amount of overland or channelized flow. The lack of any significant correlations between ECA and stream channel characteristics suggests that ECA is a poor surrogate for the changes in runoff and erosion that might then affect stream channel characteristics. A study in northern Idaho also showed a poor correlation between ECA values and the observed changes in flow due to forest harvest and road building (King, 1989).

One limitation inherent in all three management indices is the problem of defining the amount of recovery over time. The ECA index explicitly includes hydrologic recovery, but the modeled reduction in ECA values over time presumes successful regeneration. In reality, recovery rates will vary considerably with site conditions. The effects of roads will also vary over time according to the rate of regrowth on cut and fill slopes, the amount of traffic, and the amount and type of maintenance activities (Megahan, 1974; Reid and Dunne, 1984). Substantial revegetation on closed roads with adequate drainage may largely eliminate soil erosion and the delivery of sediment to the stream channels. On the other hand, a closed road with surface rilling and inadequate drainage may deliver as much sediment to the stream channel as a well-designed new road with frequent drainage onto vegetated hillslopes.

Another problem in quantifying management indices is the primary emphasis on timber harvest and roads. Other management activities – such as grazing, campgrounds, water diversions, and ski resorts – affect runoff, erosion, and stream channel condition, but these are rarely considered in most CWE assessments. Much of the RNF was intensively grazed at the turn of the century, and although grazing rates have been reduced, the streams may still be recovering. Quantification of grazing effects is difficult because of the confounding effects of wildlife and differences in the season, duration, and intensity of grazing within a basin.

Similarly, the Steamboat Springs ski area may affect water and sediment yields through forest clearing, snowmaking, soil compaction, and road and trail construction, and it is difficult to characterize these effects through a simple index such as ECA or number of road crossings. The impact of the ski area is suggested by the fact that Burgess Creek, which drains most of the Steamboat Springs ski area, was one of the two granitic study reaches with an adjusted L8 above the 95 percent confidence interval for individual reaches. A better quantification of these other management impacts could strengthen the linkage between land-use activities and substrate changes, but it is unrealistic to expect that a single index can accurately quantify changes in both runoff and sediment production.

Regardless of the difficulties in quantifying management impacts, the B&K procedure can be used to detect differences in the amount of fine sediment at a reach scale. The inevitable presence of other sources of variability mean that this technique, like any other channel assessment procedure, is far from perfect, and this uncertainty must be recognized by land managers. The reach-scale approach of the B&K procedure is a useful scale for resource managers, and the focus on bed material particle size does allow a direct link to coldwater fisheries.

With respect to the other two channel assessment procedures, the PCSR indicated significantly poorer channel condition in the study reaches relative to the reference reaches in both terranes. In contrast, the TSR did not show a significant difference between the reference and study reaches in the s-v terrane, and in the granitic terrane the differences between the reference and study reaches were weaker and less consistent than for the PCSR. These results provide some support for the use of the PCSR relative to the TSR.

One limitation to the use of both TSR and PCSR is that these have not been as directly linked to coldwater fisheries as the composition of the bed material. A more explicit evaluation of some of the specific attributes used in the PCSR procedure might provide more insight into stream channel response, and hence more guidance for managers (Myers and Swanson, 1992; MacDonald *et al.*, 1997). Tracking individual attributes might also indicate which channel characteristics are more sensitive or responsive to particular management activities, and provide a more direct linkage to specific designated beneficial uses.

It should also be noted that because this study was conducted in one field season, we were not able to investigate the annual variability in L8 or the other two channel assessment procedures. Knowledge of the annual variability is essential if the pebble count or other procedures are to be used to monitor changes in a reach over time. We purposefully sampled a larger number of streams in one field season to evaluate the relationship between stream channel condition and management activities, and this design also allowed us to address the variation between streams. Assessing change over time could avoid the issues of local controls and consistency between reaches, but this then requires either that sampling take place prior to any management activity, or that one need only to identify trends rather than condition on an absolute scale. In most cases monitoring begins after management activities have been initiated, and a comparative approach means that consistency between reaches must be addressed. The other point is that land management decisions can rarely be put on hold until a trend is clearly established, and this also forces managers into a comparative approach as followed here.

CONCLUSIONS

The modified pebble count technique (Bevenger and King, 1995) can, in some cases, identify significant differences in the amount of fine sediment on a reach scale in the Routt National Forest. The reliability and sensitivity of this procedure will be increased by an explicit evaluation of observer variability, the effect of local controls (such as gradient and geologic terrane), and the interannual variability. Because all the different sources of variation in bed material particle size cannot be accounted for, the range of conditions in the reference reaches must be defined before determining whether one or more study reaches have been adversely affected by management activities. Hence our ability to detect change can be improved by removing some of the variability by stratification or statistical analyses.

While the modified pebble count procedure provides quantitative information regarding changes in the bed material size, supplemental monitoring techniques are recommended to address other stream characteristics and improve reliability. The Pfankuch channel stability rating addresses the upper and lower banks as well as the stability of the substrate, and this appears to provide more consistent results than the Tarzwell substrate ratio.

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