

AN EVALUATION OF TWO
MEASURES OF STREAMBED CONDITION

by

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ABSTRACT

Current regulations surrounding forestry activities and their effects on stream channels require meaningful, rapid, and reliable techniques for monitoring streambed condition. This research evaluates two techniques for estimating stream channel condition, Dietrich's q^* and Kappesser's Riffle Armor Stability Index (RASI), on four reaches of Little Lost Man Creek, California. Variance, optimal sample size, cost, and reliability were estimated for both methods.

The first method, a dimensionless bedload transport rate (q^*), proposed by Dietrich et al. (1989), requires two people and at least one full day of field work, but has a sampling variance as low as 0.003 (mean = 0.34). For reaches A, B, C and D q^* was 0.34, 1.69, 1.75 and 0.91 respectively. The second method, the Riffle Armor Stability Index (RASI) proposed by Kappesser (1992), can be done by one person with a scale within two hours and also has a low variance, but may be prone to bias, especially if done by an untrained investigator. For reaches A, B, C and D the RASI was 72.0, 76.5, 68.3 and 89.5 respectively. An attempt to remove bias by comparing RASI to tracer gravel motion is made. Tracer movement shows nearly equal probability of movement for all particle sizes at bankfull discharge,

suggesting that all RASI values on alluvial channels should equal 85 or more.

Equations using bankfull geometry from Andrews (1983) and Kappesser (1991) were also used to predict mobile particle sizes in place of the 30-count. This tended to over or underestimate 30-counts picked by hand depending on whether the riffle or reach slope was used, but suggests this is a promising approach to removing RASI bias.

Although Little Lost Man Creek has relatively low sediment discharge, both techniques had samples indicating abundant fine sediment, and inconsistent sediment supply between adjacent reaches. The poor performance of these techniques suggests that more refinement may be necessary before they are applicable to every stream. The relationship between the grain size distributions of the bedload and the subsurface needs to be clarified to determine where the size distribution is equal and it is appropriate to sample q^* . RASI should only be done with another method, as a check for bias, until the 30-count can be defined more precisely, either theoretically or in the field.

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INTRODUCTION

The resource needs and constraints of the future cannot be met without accurate and reliable techniques for assessing the impact of human activities on natural systems. Although monitoring is widely used as a tool to evaluate management decisions (MacDonald et al., 1991), there are few accepted methods for quantifying the effects of land use on streambed condition and resulting quality of fish spawning habitat.

MacDonald et al. (1991) identify qualities that the ideal stream monitoring parameter would embody: (1) sensitivity to management activities, (2) low spatial and temporal variability, (3) accuracy, precision and ease of measurement, and (4) direct relationship to designated uses.

This research addresses items (2) and (3) by examining samples of two techniques for quantifying stream channel condition, q^* (Dietrich et al., 1989) and the Riffle Armor Stability Index (RASI) (Kappesser, 1991) taken from a stream known to have low sediment supply (Davies and Pierce, 1981 and Madej, 1991). This study describes methods for both techniques, addresses problem areas (such as site selection), determines optimum sample size, discusses ways to remove bias (especially for the RASI 30-count), and evaluates the cost (in hours and equipment needed), reliability and reproducibility of these two techniques.

Background

Dimensionless Bedload Transport Rate (q^*)

The first measure, q^* , is a dimensionless bedload transport rate introduced by Dietrich et al. (1989). They note that the coarse surface layer in most streams results from selective erosion of fine particles by flows incapable of mobilizing the largest particles (i.e., "static armor" (Milhous, 1973 and Sutherland, 1987)) and is not a property of the transport of poorly sorted sediment (i.e., "mobile armor" (Leopold et al., 1964 and Parker and Klingeman, 1982)). Dietrich et al. (1989) postulate that this selective erosion is caused primarily by transport capacity exceeding sediment supply. The dimensionless bedload transport ratio, q^* , is a measure of this relationship between sediment supply and transport capacity.

Dietrich et al. (1989) propose that streams adjust to increases in sediment supply by fining the bed surface before morphological changes such as infilling of pools. If so, a high q^* value could identify streams impacted by large amounts of sediment, or which might be sensitive to increased sediment load.

Theoretical Framework

Particles on the streambed move when the entrainment force exerted by the overlying water surpasses the forces

resisting movement. Entrainment force, caused by shearing of the overlying flow (called shear stress: τ), is proportional to the product of water depth and water surface slope (Dingman, 1984). Resisting force is proportional to particle diameter and density, as well as particle shape and exposure to flow.

The shear stress exerted on streambed particles by the flowing water is called boundary shear stress (τ_b). Shear stress for steady, uniform flow, such as in a flume, can be represented by the equation:

$$\tau_b = \gamma d S \quad (1)$$

where γ is the unit weight of the fluid (Newtons per cubic meter), d is the average water depth (m), and S is the water surface slope. The shear stress that exactly equals a particle's resisting force (above which particle motion occurs) is called critical shear stress (τ_c).

Although critical shear stress increases with particle diameter for a uniform bed, in a poorly sorted bed, smaller particles fit between the larger ones and therefore require higher critical shear stress to initiate motion. Larger particles are more exposed to the flow and therefore require lower critical shear stress to initiate motion (Andrews and Parker, 1987). The result is that all particle sizes require nearly the same shear stress to initiate motion (Parker and Klingeman, 1982; Parker et al., 1982a; Parker et al., 1982b).

For this reason, when estimating critical shear stress for poorly sorted material we assume τ_c to be roughly proportional to median grain size (Wiberg and Smith, 1987).

Dimensionless critical shear stress (τ_{cr}^*) is a measure of the "ratio of the fluid forces tending to initiate motion of a particle to the gravity force keeping the particle at rest" (Andrews, 1983). Dimensionless critical shear stress can be represented by the equation:

$$\tau_{cr}^* = \frac{\tau_{cr}}{(\rho_s - \rho_w)gD} \approx \frac{h_{cr}S}{1.65D} \quad (2)$$

where ρ_s and ρ_w are the densities of the sediment and water respectively (kg/m^3), g is the force of gravity (m/s^2), D is the particle size (m), and h_{cr} is the water depth at the critical flow (m).

Transport of a particle occurs when the boundary shear stress exceeds the critical shear stress. The simplest bedload equation, based on Yalin (1972), is:

$$q_b = k(\tau_b - \tau_c)^n \quad (3)$$

where q_b is the bedload transport rate (m^3/s), and k and n are empirically determined constants (n is approximately 1.5 or larger (Yalin, 1972)). Because the exponent is larger than one, once τ_b exceeds τ_c , bedload transport rates increase rapidly with small increases in τ_b .

To quantify a supply/transport imbalance, Dietrich et al. (1989), using (3), created a dimensionless bedload

transport rate (q^*) which is "the transport rate for the coarse surface normalized [divided] by the transport rate for a surface as fine as the subsurface or load" (Dietrich et al. 1989). The assumption that the grain size distribution of the subsurface is similar to that of the bedload is based on studies by Parker et al. (1982a&b) and Parker and Klingeman (1982) using data from Oak Creek, Oregon (Milhous, 1973). The equation for q^* is:

$$q_* = \frac{k(\tau_b - \tau_{cs})^{1.5}}{k(\tau_b - \tau_{css})^{1.5}} = \left(\frac{\frac{\tau_b}{\tau_{cs}} - \left(\frac{D_{50s}}{D_{50ss}} \right)}{\frac{\tau_b}{\tau_{cs}} - 1} \right)^{1.5} \quad (4)$$

where τ_{cs} and τ_{css} are the critical shear stresses for the surface and subsurface respectively, and D_{50s} and D_{50ss} are the median grain sizes of the surface and subsurface respectively.

Because armoring could result from transport capacity exceeding sediment supply, the coarser the surface relative to the subsurface, the more undersupplied with sediment is the system and the lower the corresponding value of q^* . The value for q^* should be unity when sediment supply equals transport capacity, decrease as supply is reduced, and increase as supply is increased.

Riffle Armor Stability Index (RASI)

The second technique, the Riffle Armor Stability Index (RASI) (Kappesser, 1991), measures riffle stability by comparing transport competence (determined by the largest surface particles mobile at bankfull discharge) with the particle size distribution of streambed riffles. RASI estimates whether the streambed has a high proportion of mobile sediment which may indicate channel instability, or is composed of immobile coarse particles.

Kappesser first conceptualized RASI while reading Lisle (1982) who shows three changes in stream channels with increased sediment loads; (1) decreased riffle gradient, (2) increased distance between pools, and (3) reduced residual pool depth.

Lisle (1982) and Dietrich et al. (1989) theorize that as sediment loads increase, the size distribution of riffles becomes finer. Kappesser, following Grant (1986), noted that the size of sediment moved by transporting flows should remain constant. Thus, as sediment loads increase, the proportion of the riffle surface finer than the largest mobile particle increases. The frequency and transport capacity make bankfull discharge the most effective at transporting sediment (Leopold, 1994) and the major influence on channel morphology (Wolman and Miller, 1960). Because it is so important, bankfull discharge is used to define the

largest mobile particle size for RASI (i.e., the largest surface particle mobilized during a bankfull event).

RASI is the proportion of the riffle surface finer than the largest mobile particles. The surface particle size distribution is determined from a Wolman pebble count (Wolman, 1954) and the largest mobile particle size is determined by the geometric mean diameter of 30 selected "clearly mobile" particles (called a "30-count"). For example, if the geometric mean of the largest mobile particles was 130 mm, and 82 percent of the riffle was finer than 130 mm, this riffle would have a RASI value of 82.

RASI values range from 20 to 100 with higher numbers representing sediment rich systems (high proportion of fines relative to what the stream transports) and low numbers indicating sediment starved systems (few fines). When Knopp (1993) measured RASI on sediment rich and sediment starved systems he found average values of 77.0 and 52.6 respectively. Kappesser (1992) proposes that the 30-count represents a unique stream characteristic with a fixed relationship to discharge, a hypothesis this study examines.

Because selection of the 30-count is subjective, I examined RASI for bias. I also investigated how bias of the 30-count could be reduced or eliminated.

One method I used to modify RASI involved previous research on mobility of different size fractions of the bed. Andrews (1983) in particular has developed equations, such as

(2), that can predict particle sizes mobile at bankfull discharge. This study examines using equation (2) instead of the 30-count, to estimate the largest mobile particle at bankfull.

Kappesser (1991) also presents an equation to predict the mobile particle size:

$$D = 47.84\tau_b \quad (5)$$

where D is the largest mobile particle size (mm) at bankfull. I also used this equation to estimate the largest particles mobile at bankfull discharge.

Tracer Gravels

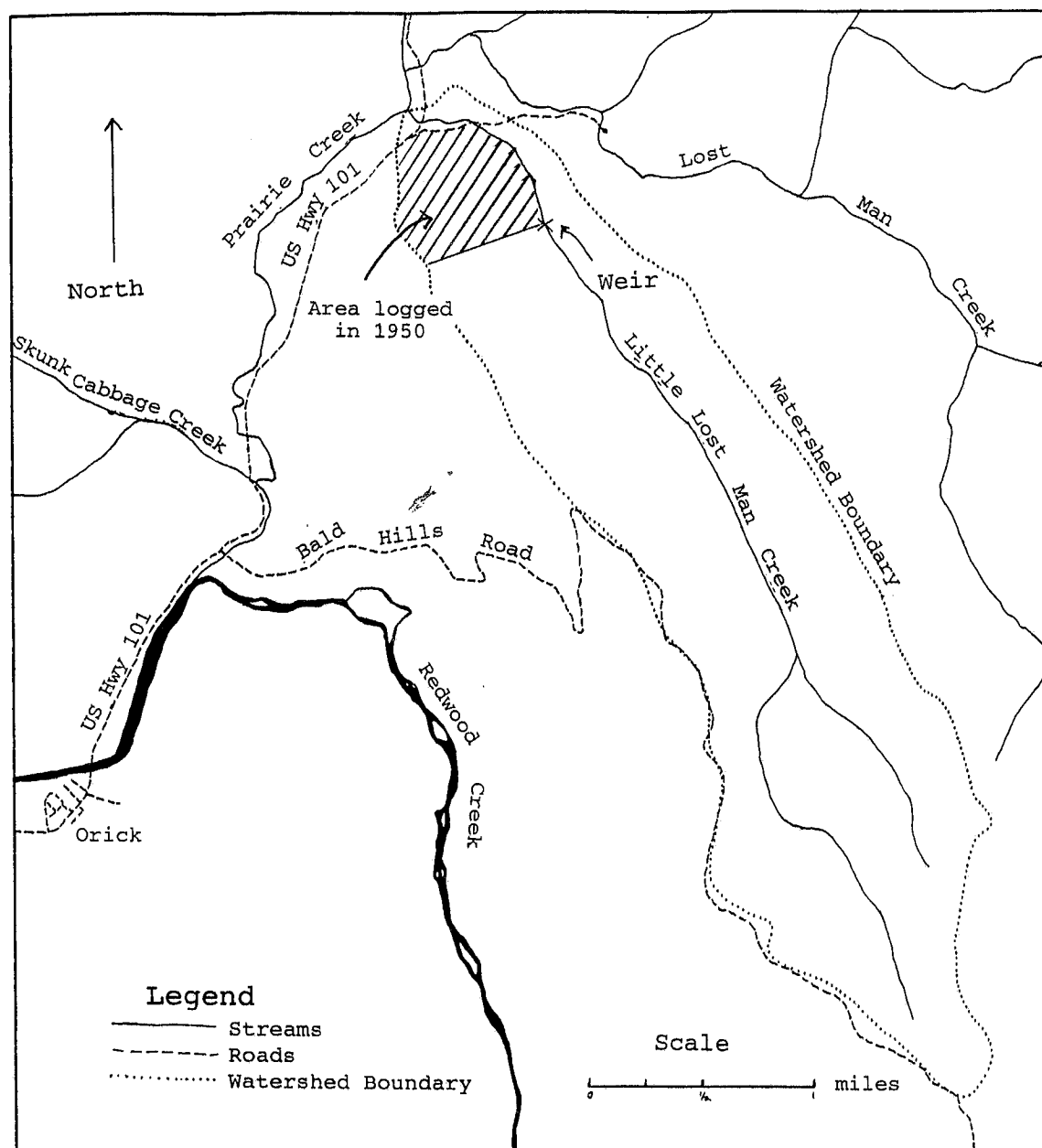
Because the RASI 30-count is a new concept with relationships to accepted theory not experimentally corroborated, I examined the relationship between 30-count theory and actual particle mobility using tracer gravels. Ideally, tracer gravels could define the largest mobile particle at bankfull discharge empirically and show how it compares to 30-counts selected using the techniques proposed by Kappesser.

METHODS

Study Site

This study was conducted on Little Lost Man Creek, a tributary to Prairie Creek, 5.3 kilometers (3.3 mi) north of Orick, California, in Redwood National Park (Figure 1). Field research spanned three water years; October 1992 to March 1995. Little Lost Man Creek is a steep (1 to 3% slope) cobble and gravel-bedded stream with some bedrock and large woody debris controlled reaches (i.e., not strictly alluvial). The drainage area is 10.1 km² (3.9 mi²) with a basin relief of 680 m (2230 ft).

Although a 1.0 km² (0.4 mi²) area in the lower watershed was logged prior to 1950 (Figure 1), Little Lost Man Creek remains pristine with low sediment discharge relative to other local streams (Davies and Pearce, 1981 and Madej, 1991). The heavily armored (coarse and well cemented) streambed remained intact, even through floods greater than bankfull. According to Lisle (1995), shallow depth of scour indicates fine bedload is supply limited. Lisle (personal communication, Tom Lisle, Redwood Sciences Laboratory, 1700 Bayview, Arcata, CA. 95521) has suggested, however, that position of riparian redwood trees away from the channel, high volumes of residual pool sediment, and indications of channel instability above the weir suggest that Little Lost



Area of Detail



Figure 1. Little Lost Man Creek, California.

Man Creek is naturally erodible despite being in pristine condition.

Little Lost Man Creek is also an excellent anadromous fishery. Dozens of adult salmon and steelhead were observed spawning during the study period.

Redwood National Park has operated a stream gauge continuously since 1976 (except WY 90-92) at the downstream end of the unlogged section, approximately 1200 m (3940 ft) upstream from the confluence with Prairie Creek. Drainage area above the weir is 9.1 km² (3.5 mi²).

Four 100 meter reaches were selected for intensive sampling of q^* and RASI (Figure 2). Uniform, straight reaches were selected to approximate the hydraulic conditions under which q^* was developed. Reach A extended 100 meters from the weir downstream and was the steepest and coarsest of all reaches (Figure 3). Reaches B and C were adjacent, from approximately 700 to 900 meters downstream from the weir (Figures 4 and 5). Reach D extended from the bridge (about 1000 meters from the weir) for 100 meters downstream and was the most sinuous and alluvial of the Reaches (Figure 6).

Bankfull Discharge Analysis

Bankfull discharge is critical to the underlying theories of both q^* and RASI. For q^* , the estimate of transport rate for the surface and the subsurface was made for stage and slope corresponding to bankfull discharge. For

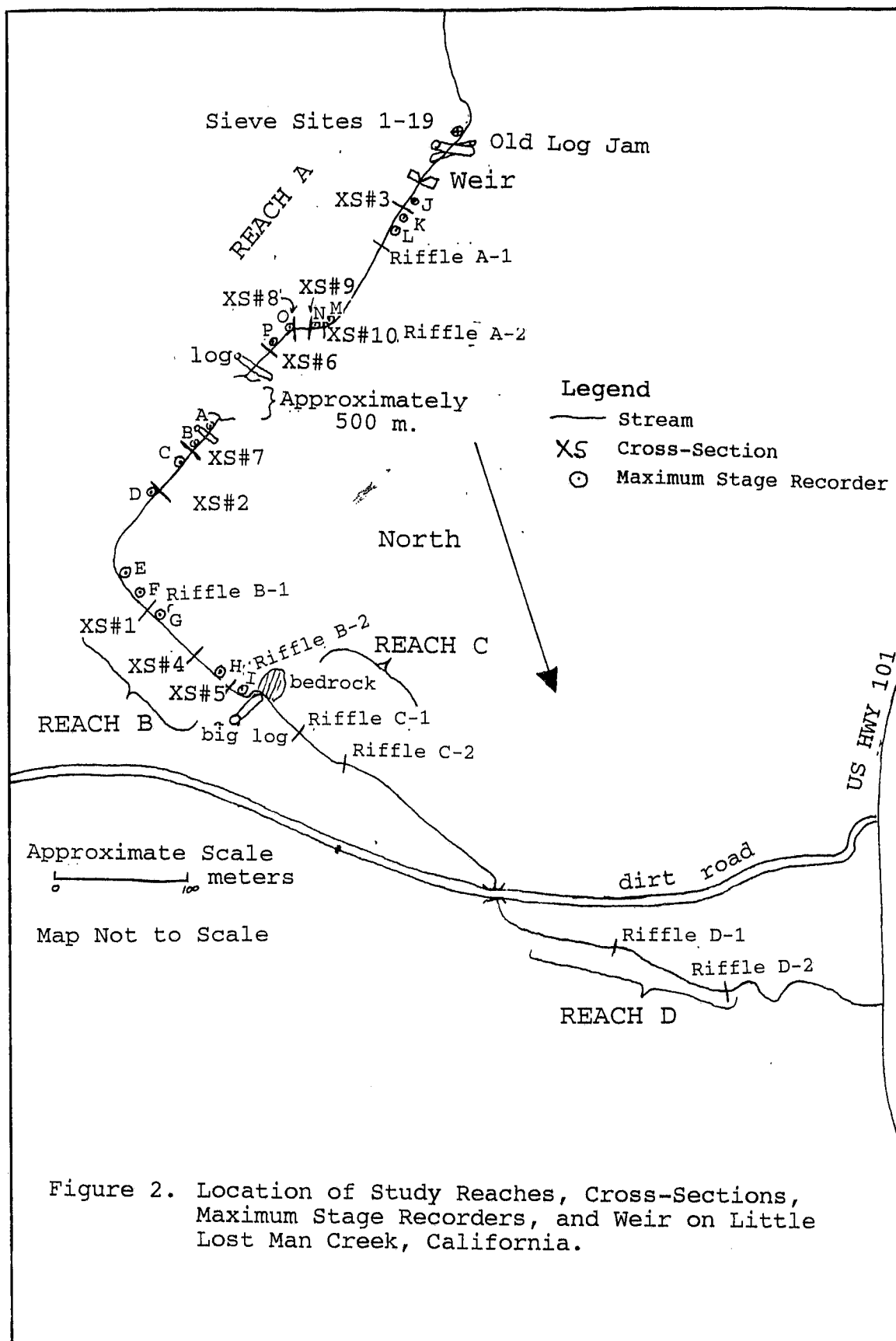


Figure 2. Location of Study Reaches, Cross-Sections, Maximum Stage Recorders, and Weir on Little Lost Man Creek, California.

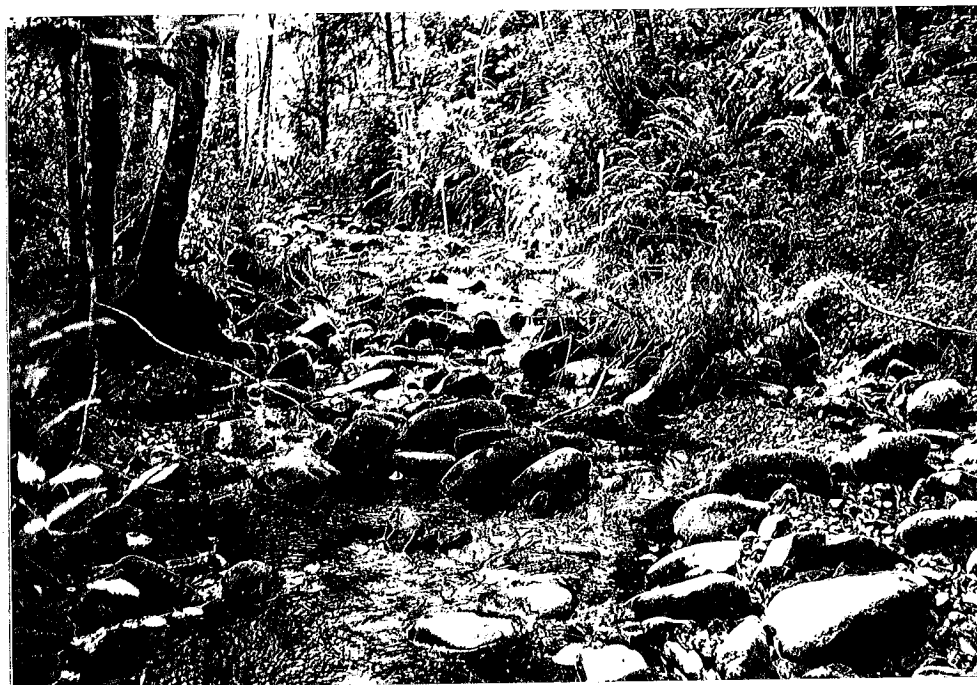


Figure 3. Reach A, RASI Riffle A-1, looking upstream.



Figure 4. Reach B, looking downstream at Cross Section #1.



Figure 5. Reach C, looking upstream.



Figure 6. Reach D, Riffle D-2, looking upstream.

RASI, the 30-count should be representative of the largest particles mobile at bankfull discharge. Thus, an accurate estimate of bankfull discharge is important.

Bankfull discharge was estimated six ways. First, a flood event of 5.95 cms (210 cfs) which occurred on December 11, 1993 appeared to be bankfull (Figure 7). Flood marks from this event on both Little Lost Man Creek and Lost Man Creek (an adjacent watershed) reached bankfull indicators such as the base of large riparian alders and the backs of point bars (Williams, 1978) (Figure 8). This flow had a return period of 0.94 years on the partial duration series and 1.4 on the annual series (Figures 9 and 10), which are common frequencies for bankfull discharge (Williams, 1978 and Dunne and Leopold, 1978).

Second, bankfull discharge was calculated from empirical equations using bankfull channel geometry. Bankfull elevations were based on slope breaks in the cross-section. Roughness coefficients (Manning's "n") were calculated using six surveyed cross sections and discharge from the Redwood National Park gauge at the time the surveys were made using the formula:

$$n = \frac{R^{2/3} S^{1/2}}{u} \quad (6)$$



Figure 7. Reach B at bankfull discharge (12/11/93), looking downstream at Cross-Section #1.



Figure 8. Water flowing over point bar at lower end of reach B, near Cross-Section #5 (12/11/93).

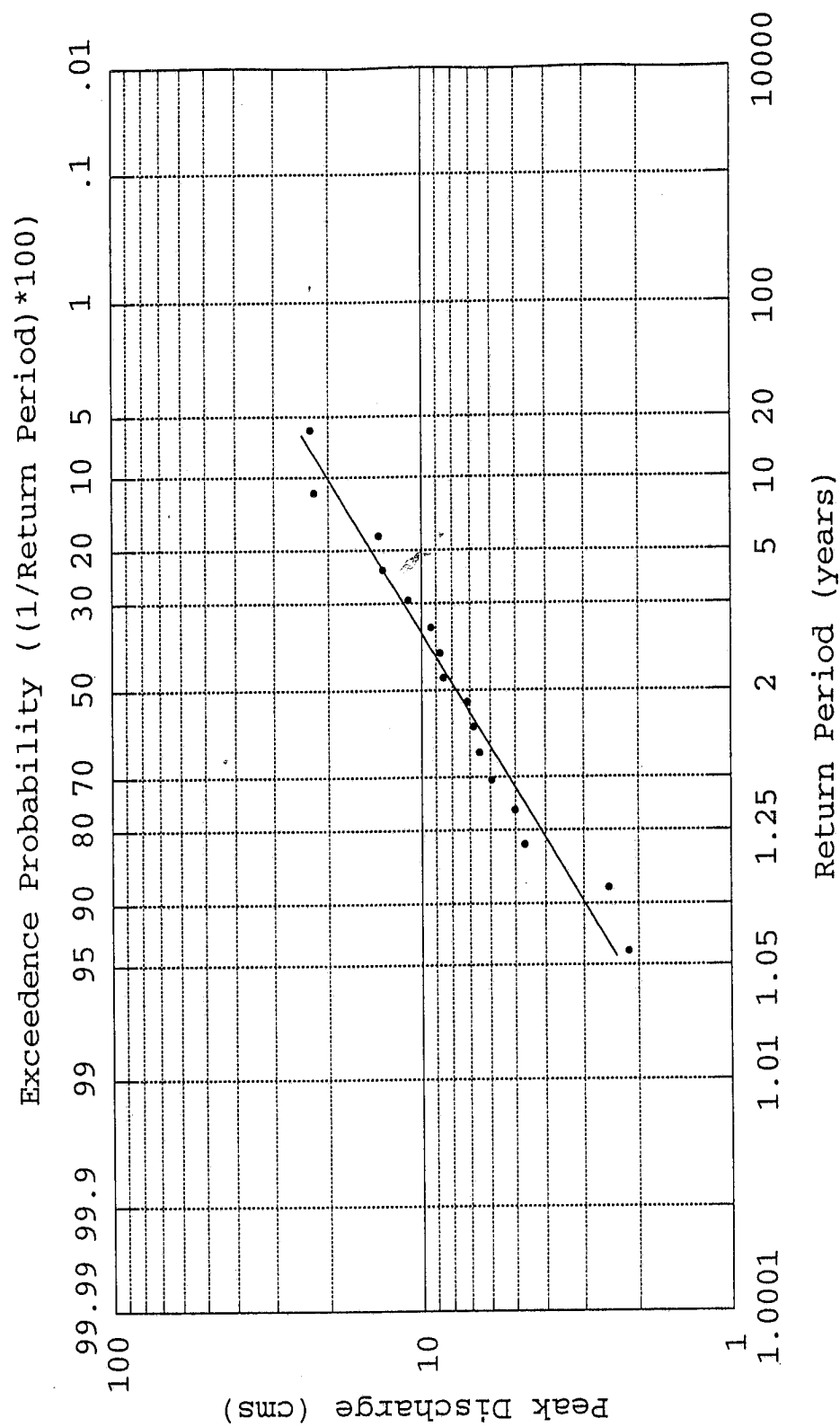


Figure 9. Annual Maximum Flood Series for Little Lost Man Creek, California. Period of Record: 1976-1990, 1993-1995.

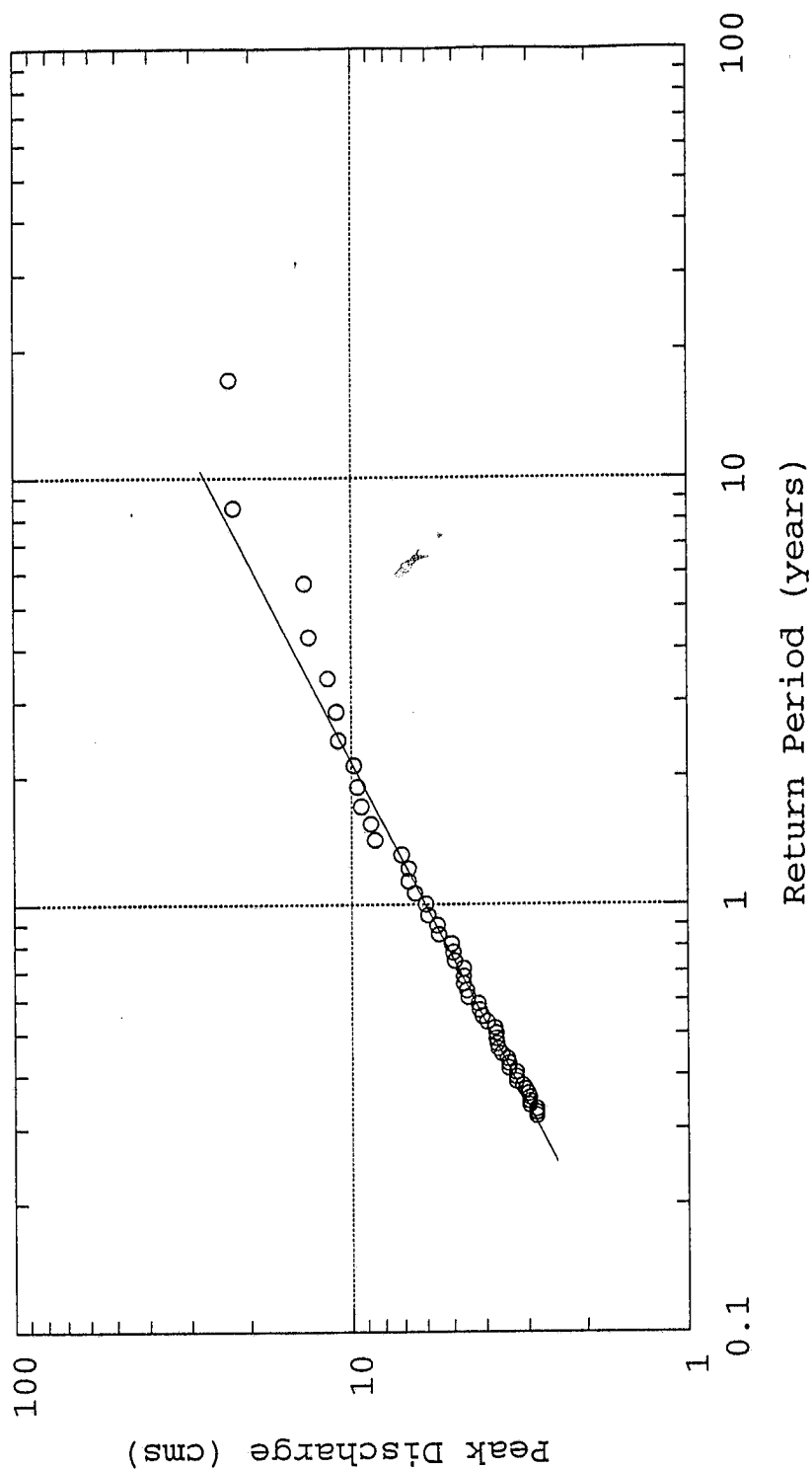


Figure 10. Partial Duration Flood Series (base 2.8 cms) for Little Lost Man Creek, California. Years of Record 1976-1990, 1993-1995.

where n equals Manning's roughness coefficient, R equals the hydraulic radius (m), S equals slope and $\bar{u}$ equals the average velocity (m/s).

Manning's " n " ranged from 0.043 to 0.100 (Table 1). These values were used with bankfull slope and area to calculate bankfull velocity using (6). Discharge was then calculated using:

$$Q = A\bar{u} \quad (7)$$

where Q equals discharge (cms) and A equals area (m^2). Although the range 4.05 cms to 22.3 cms includes other bankfull estimates, the large variation between cross-sections indicates this approach is not reliable (Table 1).

Next, instantaneous peak discharges from the Redwood National Park gauge were used to create annual maximum and partial duration flood series (Figures 9 and 10 respectively). Leopold et al. (1964) defined bankfull as occurring with a return period of 1.5 to 2 years on an annual maximum flood series, roughly corresponding to a return period of 1.0 years on a partial duration flood series. The discharges corresponding to the 1.5 year return period on the annual series and the 1.0 year return period on the partial duration series were 5.8 cms (205 cfs) and 6.0 cms (212 cfs) respectively (Figures 9 and 10).

Little Lost Man Creek was also compared to three nearby streams based on runoff per unit area of watershed (Figure 11). This allowed me to compare Little Lost Man Creek with

Table 1. Six estimates of bankfull discharge for Little Lost Man Creek, California, using channel geometry and Manning's equation.

	XS#1	XS#2	XS#3	XS#4	XS#5	XS#7
Date	20-Jan	21-Jan	20-Jan	20-Jan	20-Jan	20-Jan
Time	1400	1100	1200	1000	1500	1300
Actual cms	2.5	1.8	2.5	2.5	2.4	2.5
Area (sq. m)	2.09	2.40	2.94	2.45	1.95	2.47
Mean Vel (m/s)	1.20	0.75	0.85	1.02	1.23	1.01
Slope	0.0135	0.0137	0.0203	0.0135	0.0135	0.012
Mean Depth (m)	0.286	0.300	0.463	0.415	0.354	0.450
Manning's n	0.042	0.070	0.100	0.063	0.047	0.064
Bankfull Depth (m)	0.891	0.616	0.727	0.486	0.354	0.554
Bankfull Area (sq. m)	8.736	4.623	4.837	3.574	3.611	4.296
Bankfull Ave. Vel. (m/s)	2.55	1.21	1.15	1.13	1.23	1.16
Bankfull Discharge (cms)	22:30	5.60	5.56	4.05	4.44	5.00

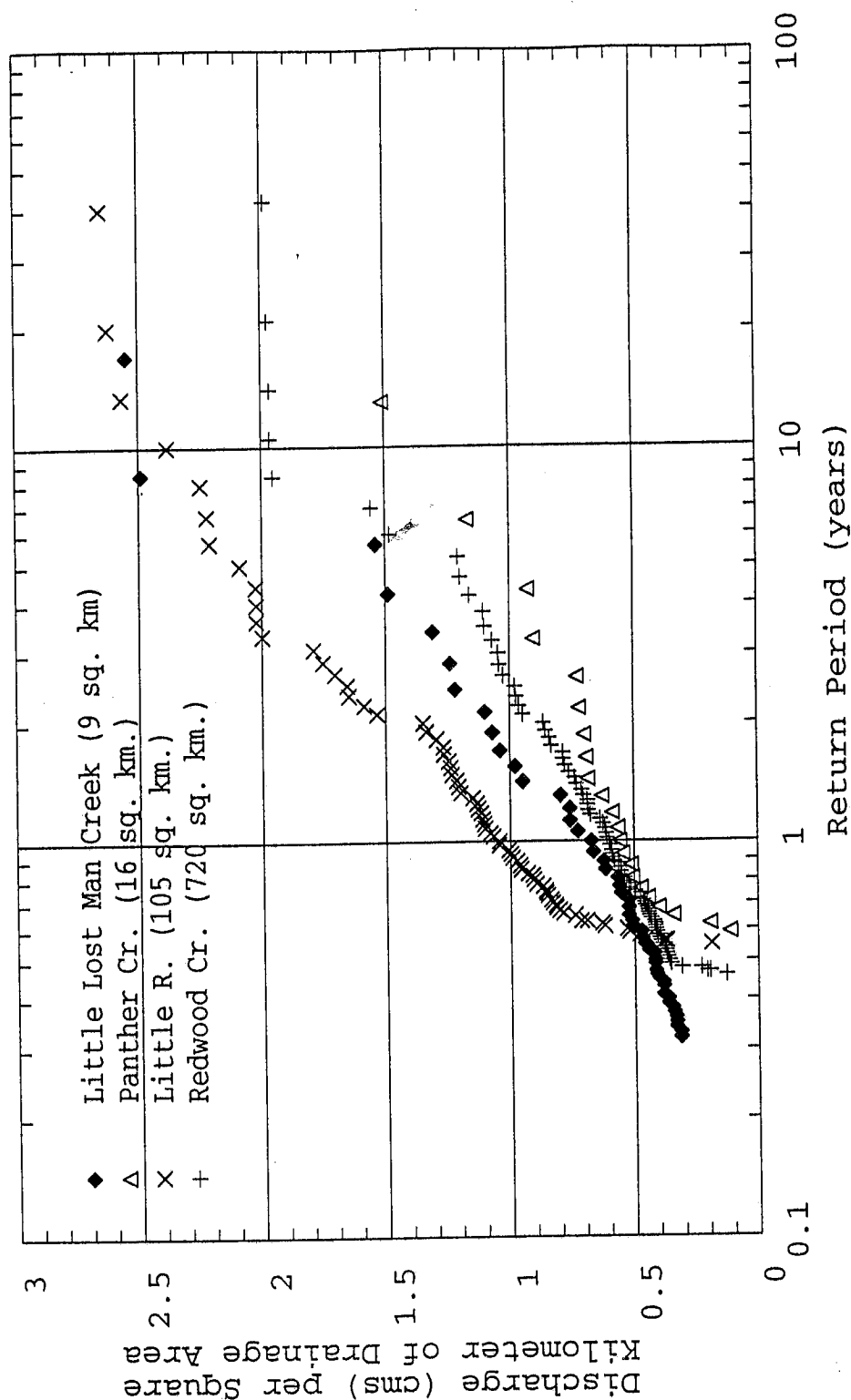


Figure 11. Partial duration series for four Northern California streams normalized by drainage area.

streams that have a longer period of record. All instantaneous peak discharges were divided by drainage area and then a partial duration flood series was created. For a return period of one year, runoff in this region appears to be about 0.65 cms/km^2 (Figure 11), which would produce a flood peak of 5.85 cms (207 cfs) on Little Lost Man Creek. This supports the estimates based on the previous partial duration and annual maximum flood series analyses.

Finally, an empirical relationship found in Dunne and Leopold (1978) page 617, which is based solely on drainage area, was used. This relationship predicts a bankfull discharge of 5.9 cms (208 cfs).

Bankfull estimates range from 5.5 to 6.0 cms (194 cfs to 212 cfs) (Table 2). The best estimate was probably 5.95 cms because it matched field indicators and was within the range of the other estimates.

Dimensionless Bedload Transport Rate (q^*)

Sites for q^* were selected in two stages. First, I found a straight reach of 50 meters or more with uniform slope and width where bankfull shear stress could be estimated from a survey of the bed and banks. Second, I selected areas where the subsurface could be sieved to represent the bedload.

Sieve sites were within the surveyed reach if possible. On Reach A, I did not sample the subsurface for two reasons. First, it was too coarse to sieve practically by hand.

Table 2. Bankfull discharge estimates for Little Lost Man Creek, California, using six methods.

Method of Determining Bankfull	Bankfull Discharge (cms)
Flood observation, December 11, 1993	5.95
Annual Maximum Flood Series. Return period = 1.5 years.	5.80
Partial Duration Flood Series. Return Period = 1 year.	6.00
Empirical relationship found in Dunne and Leopold (1978)	5.90
Runoff per unit area, compared with other streams.	5.85
Bankfull channel geometry and Manning's n	4.05 - 22.30

Second, it was so coarse, I did not think it represented the bedload. On Reach A, I sieved a nearby deposit formed behind an old log-jam to represent bedload.

Reaches B and C did not appear too coarse to sample at first, but after three or four samples it became apparent that the subsurface was very coarse. Observations I made over two seasons using tracer gravels suggested that the bedload distribution of Little Lost Man Creek was finer than the samples we were collecting. Because I did not think they represented the bedload, and collecting these samples was arduous, I did not take more samples. Because sample size is in the denominator, small sample sizes affected calculation of sample variance and optimal size.

Once a site with uniform slope and width was selected, I surveyed longitudinal profiles and cross sections of the bed and banks to estimate bankfull slope and depth. High water marks were surveyed to approximate bankfull slope (Table 3) and slope breaks at cross-sections and along the streambank were surveyed to estimate bankfull stage. To calculate boundary shear stress for input into the q^* equation I used:

$$\tau_b = \gamma d S \quad (1)$$

where γ is the unit weight of the fluid (Newtons per cubic meter), d is the mean water depth (m), and S is the water surface slope.

Table 3. Slope estimates for four reaches
of Little Lost Man Creek, California.

Location	Slope	Survey of	Date	Source
Reach A	0.0202	high water marks, right bank	7/14/93	Survey W
Reach A	0.0204	high water marks, left bank	7/14/93	Survey W
Reach A	0.0207	MSR J-K	12/11/93	MSR data
Reach A	0.0227	water surface elevation	7/14/93	Survey W
Reach A	0.0233	streambed	7/14/93	Survey W
Reach A	0.0204	mean high water slope		
Reach B	0.0093	streambed	7/14/93	Survey A
Reach B	0.0098	water surface elevation	7/14/93	Survey A
Reach B	0.0110	high water marks	7/14/93	Survey A
Reach B	0.0110	high water marks, right bank	12/14/92	Survey J
Reach B	0.0122	high water marks, right bank	7/14/93	Survey A
Reach B	0.0128	high water marks, left bank	7/14/93	Survey A
Reach B	0.0130	MSR G-H	12/11/93	MSR data
Reach B	0.0132	high water marks, left bank	12/14/92	Survey J
Reach B	0.0132	water surface elevation	12/14/92	Survey J
Reach B	0.0141	MSR F-G	12/11/93	MSR data
Reach B	0.0155	water surface elevation	1/30/93	Survey P
Reach B	0.0160	streambed	12/14/92	Survey J
Reach B	0.0160	high water marks	1/30/93	Survey P
Reach B	0.0166	streambed	1/30/93	Survey P
Reach B	0.0168	high water marks, left bank	1/30/93	Survey P
Reach B	0.0171	high water marks, right bank	1/30/93	Survey P
Reach B	0.0137	mean high water slope		
Reach C	0.0113	high water marks, right bank	7/14/93	Survey X
Reach C	0.0125	streambed	7/14/93	Survey X
Reach C	0.0133	high water marks, left bank	7/14/93	Survey X
Reach C	0.0139	water surface elevation	7/14/93	Survey X
Reach C	0.0123	mean high water slope		
Reach D	0.0116	streambed	7/14/93	Survey Y
Reach D	0.0117	high water marks, right bank	7/14/93	Survey Y
Reach D	0.0122	water surface elevation	7/14/93	Survey Y
Reach D	0.0117	mean high water slope		

Critical shear stress for the streambed surface (τ_{cs}) was estimated using the median particle size of the bed surface and the dimensionless critical shear stress using the equation (based on Dietrich et al., 1989, and Kinerson, 1990):

$$\tau_{cs} = \tau_{cr}^* (\rho_s - \rho_w) g D_{50s} \quad (8)$$

where: τ_{cr}^* is the dimensionless critical shear stress (0.0457), ρ_s and ρ_w are the density of the sediment and water respectively (kg/m^3), g is gravitational acceleration (m/sec^2) and D_{50s} is the median particle size of the bed surface (m).

The literature does not currently agree on the numerical value of the dimensionless critical shear stress. Initial studies by Meyer-Peter and Muller (1948) showed initiation of bedload transport near τ_{cr}^* values of 0.02. Other studies have shown that a majority of transport occurs near values of 0.06 (Wiberg and Smith, 1987), and that dimensionless critical shear stress rarely exceeds 0.07 in natural channels (Parker, 1978).

Dimensionless critical shear stress is dependent on the particle size relative to adjacent particles, represented by the D_{50} . Andrews (1994) suggests the equation:

$$\tau_{cr}^* = 0.0384 \left(\frac{D_i}{D_{50}} \right)^{-0.887} \quad (9)$$

be used where D_i is a particle diameter of interest and D_{50} is the diameter of the median particle size of the bed surface. Using this equation, the dimensionless critical shear stress for the D_{50} is 0.0384. When calculating q^* , Dietrich et al. (1989) use a dimensionless critical shear stress value of 0.045 and Kinerson (1990) uses 0.0457. The difference between the value of q^* obtained using these three values of dimensionless critical shear stress is small and does not change the overall analysis. The value of 0.0457 was used in presenting the findings of this study.

To calculate the surface D_{50} , I counted surface pebbles in the surveyed area by laying a grid across the bankfull channel and sampling 100 bed particles systematically as suggested by Wolman (1954). Particles were then ranked from smallest to largest and plotted on probability paper. The size of the D_{50} (the median particle size) was estimated from the graph (Appendix B).

To calculate the D_{50} of the subsurface, sieving of the bed material was necessary. Subsurface sampling should be done under the facies type corresponding to the median particle size (Lisle, personal communication), which should represent average shear stress and bedload transport conditions. To do this, the surface of the reach was mapped, separating the surface by eye into fine, medium and coarse facies types (Appendix A). "Fine" facies had a D_{85} less than 21 mm (Figure 12). "Coarse" facies had a D_{85} greater than 128



Figure 12. Fine facies type; ruler is 10 centimeters.

mm (Figure 13). Facies with a D_{85} between 21 mm and 128 mm were labeled "medium" (Figure 14).

A random sample could be generated by ranking the medium facies type areas and using a random number generator to select the sample areas. On Little Lost Man Creek haphazard samples were taken from areas larger than 1 m² with a "medium" facies type.

Once I selected the subsurface sampling area, I scraped away the surface layer (as thick as the largest surface particle diameter) with a shovel. Then the subsurface (also as thick as the largest surface particle diameter) was shoveled into a five gallon bucket. Because most sampling areas were small, only one sample was usually taken from each area. For calculation of variance and optimal sample size, one five gallon bucket (approximately 25 kg) was the smallest sample unit.

Using a shovel is an excellent way to sample the subsurface. Young et al. (1991) compare shovel samples with those taken by freeze core devices and McNeil sediment samplers, and find shovel samples the most accurate for coarse sediment.

After the sample was extracted, I sieved the sample, using Udden-Wentworth size classes, with the different fractions separated on a tarp. The fractions were: less than 4 mm, 4 mm to 8 mm, 8 mm to 16 mm, 16 mm to 32 mm, 32 mm to 64 mm, 64 mm to 128 mm, and greater than 128 mm. Because the



Figure 13. Coarse facies type. Ruler is 10 centimeters.



Figure 14. Medium facies type. Ruler is 10 centimeters.

subsurface material was wet, I washed it through the sieves. Particles less than four mm were caught in a large pan. Water and some suspended sediments were periodically poured off. Because I was concerned with bedload only, the loss of suspended material did not affect calculation of D_{50} .

After an entire bucket was sieved, I weighed each fraction in the field using a 20 kg hanging scale (Appendix B), and then discarded the sample. Small sub-samples (approximately five kg) of the fractions less than 16 mm were taken from the last subsurface sample of the day to be dried and weighed. These data were used to create a graph to convert all fractions finer than 16 mm to their dry weight (Figure 15). I assumed the water weight contained in the larger fractions was insignificant (Church et al., 1987).

Reaches A and D were sieved until the largest particle was less than 5% of the total weight as recommended by Church et al. (1987). For reaches B and C the largest particle was less than 10% of the total sample weight.

I plotted the cumulative weights of all fractions on log-probability paper (see Appendix B). D_{50} was determined from the graph. According to Church et al. (1987), bulk samples can be compared to pebble counts without conversions.

I calculated the critical shear stress for the subsurface (τ_{css}) by substituting the subsurface D_{50} for the surface D_{50} into equation (5). The q^* value was obtained by substituting into (4).

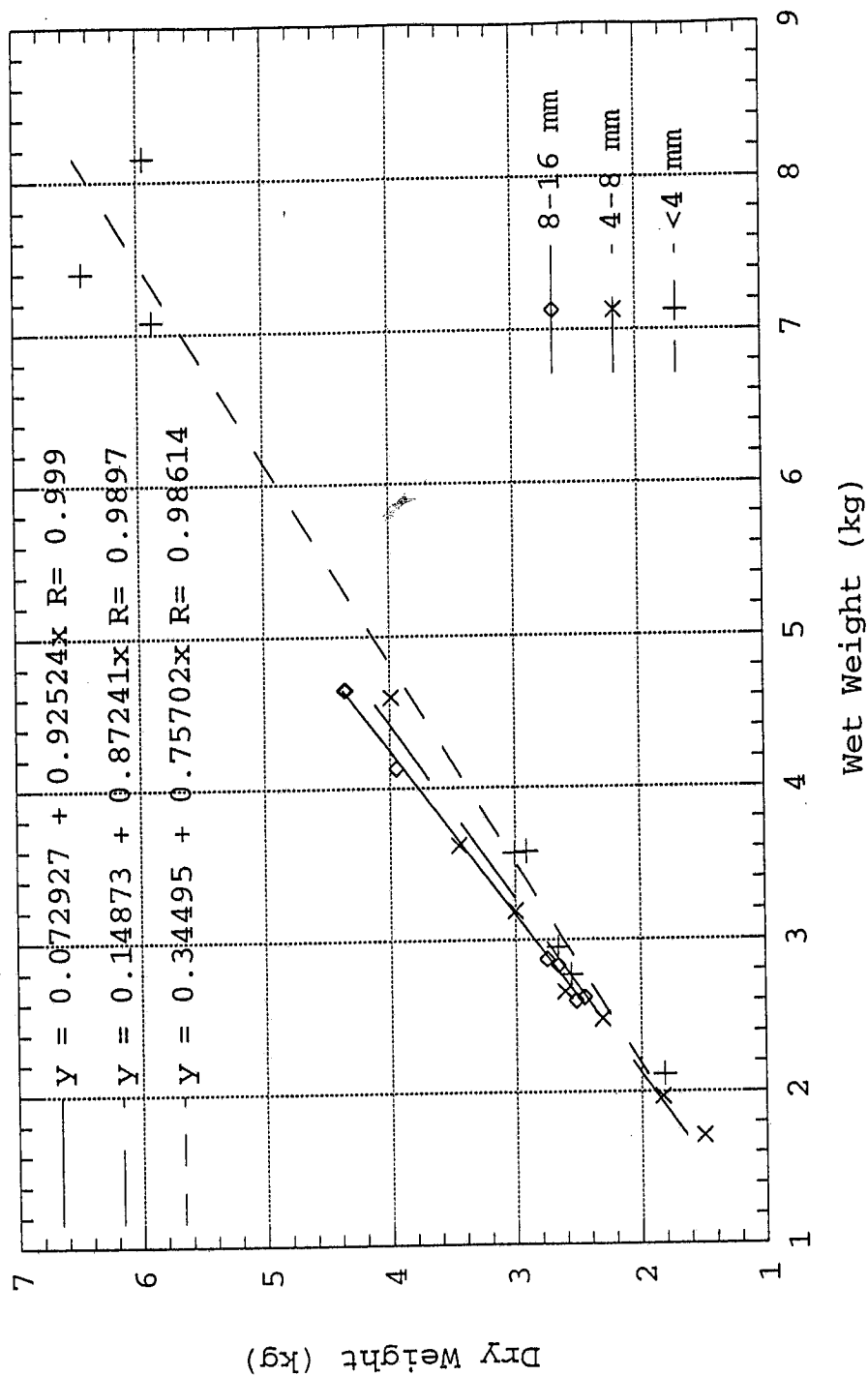


Figure 15. Equations used to convert wet subsurface samples less than 16 mm to dry weight.

Statistics

Selection of sieve sites was considered simple random sampling where each sample has an equal chance of being selected. Actually, sampling was done in a haphazard fashion, but because no system was used to select the sample, and an infinite number of samples could be taken, I used the assumptions for simple random sampling to model the sampling procedure.

For simple random sampling the true population variance is expressed as:

$$S^2 = \frac{\sum_{i=1}^N (y_i - \mu)^2}{N-1} \quad (10)$$

where S^2 equals the population variance, N is the number of elements in the population, y_i is the unit value, and μ equals the population mean (Cochran, 1977). The true population variance cannot be calculated without measuring each element of the population. An unbiased estimator of the population variance can estimate the true value when only a sample of the population is taken. For simple random sampling the unbiased estimator of the variance is:

$$S^2 = \left(\frac{N-n}{N} \right) \frac{s^2}{n} \quad (11)$$

where n equals the number in the sample, and s^2 is the sample

variance, equal to:

$$s^2 = \frac{\sum_{i=1}^n (y_i - \bar{y})^2}{n-1} \quad (12)$$

where $\bar{y}$ equals the mean of the sample values. Since I assumed the population was very large, almost infinite, equation (10) reduces to:

$$S^2 = \frac{s^2}{n} \quad (13)$$

Once I had an estimate for the true population variance, I estimated the optimal sample size for a given level of error using:

$$n = \frac{S^2}{\frac{B^2}{4} + \frac{S^2}{N}} \quad (14)$$

where B is the bounds on error (i.e., an 80% confidence interval would have a bounds on error equal to 20% of the value being estimated).

RASI

Kappesser (1992) suggests the streambed surface be sampled on riffles and the 30-count be selected on the back of the corresponding point bar. Because of the poorly defined morphology of Little Lost Man Creek (i.e., no well-developed point bars), this was not possible. I used low gradient riffles with relatively uniform shear stress for both surface pebble counts and for selection of the 30-count.

I determined the surface particle size distribution by measuring bed surface particles from a grid across the bankfull channel (Wolman, 1954). Because RASI is sensitive to this distribution, in some cases 200 pebbles were counted instead of the usual 100 (Appendix B). Pebble sizes were ranked and plotted on log probability paper.

Selecting the 30-Count

Selecting the 30-count was critically important. The guiding phrase, to select the largest particles mobile at bankfull discharge, is very subjective in the field. One attempts to select the largest particle size that moves at bankfull discharge, but not at lower or higher flows. Care should be taken to account for the recent flow history and in particular not to select particles moved during events larger than bankfull. Conversely, if a bankfull event has not occurred for several years, few particles may look actively mobile.

I used four criteria to distinguish these critical rocks:

- (1) Rocks should be loose on the bed surface. One should be able to roll them easily with the hand or boot. Given a choice, always pick the looser, less imbedded rock.
- (2) Rocks should be as free as possible of living things. Moss, lichen, algae and attached benthic

invertebrates are all signs that a rock has been stationary for awhile. Given a choice, select rocks without such life forms. Although rocks should be clean just after a bankfull event, they may develop large communities of algae and moss if a bankfull event has not occurred for some time. Thus, depending on season and flow history, good 30-count rocks may not always be clean.

(3) Rocks should be as uniformly shaped as possible. All three axes should be similar. These rocks are surrogates for stream competence. Tractive force equations assume the intermediate diameter of a particle is proportional to the entrainment force and shear stress needed to mobilize it. This is not necessarily true for all particle shapes. Oblong or platy rocks should be rejected in favor of spheroid or ovoid rocks.

(4) Rocks in the sample should be consistent in size. This seems contradictory at first, but is actually very important. It is not necessary to count 30 particles to get a good estimate of the stream's power, but doing so provides 29 replications upon which confidence can be based. Particle sizes which range widely indicate that stream competence has not been clearly estimated. Time should be spent before selection to become familiar with what is available. Discarding the first few rocks that get selected before the eye is calibrated may be necessary to select the best sample. Generally, a sample in which the smallest particle is within

20 percent of the largest particle is considered acceptable (Knopp, 1993).

Because selecting these particles is so subjective, I examined the variability between observers. I asked ten professional hydrologists to select samples of the 30-count from Riffles B-1 and B-2. This allowed me to measure if investigator bias was significant.

In March 1995 I resampled Little Lost Man Creek using a modified technique. A near bankfull event had occurred in January, so mobilized rocks were clean and loose on the bed surface. This time I selected all large rocks within the riffle down to 100 mm that had been mobilized.

I also surveyed corresponding cross-sections and longitudinal profiles to estimate bankfull geometry for use in Andrew's equation (2) and Kappesser's equation (5). Flood lines from the event were still visible in many places.

Tracer Gravel

To examine the mobility of different size fractions of the bed, I placed 10 cross-sections on Little Lost Man Creek. My goal was to compare tracers moved during a bankfull event with RASI 30-counts. I sampled different types of riffles to get an average for Little Lost Man Creek and to examine any differences between these environments. After data collecting, sample size was found too low to significantly compare different riffles and only pooled data are presented.

Five cross-sections (#1, #2, #5, #6, #10) were placed on low gradient riffles (Figure 16) similar to that used for RASI. Four cross-sections (#3, #4, #7, #9) were placed in deeper, run-type riffles (Figure 17), and one (#8) was placed on a steep riffle (Figure 18). Surveys of each cross-section and the long profile can be found in Appendix A.

I selected tracer gravels from Little Lost Man Creek and other nearby streams draining similar geologic types. Rocks were washed and dried thoroughly before being painted with yellow or red Aervo™ highway marking paint; two or three light coats gave the best results. Black boat enamel was used to number each rock.

First year (WY 1993) tracer sizes varied widely (from 18 mm to 181 mm) in a random assortment. Second year (WY 1994) tracers had, for each cross section, ten replicates for each of three sizes (D₃₅, D₅₀, D₆₅) and five each for the D₈₅ and D₉₀. Because tracer sizes were specific to the grain size distribution of their cross section, tracer sizes were different for each cross section (Table 4). Pebble counts for each cross section can be found in Appendix B.

Percentage of tracers recovered was high both years because the armored surface of Little Lost Man Creek remained intact throughout the entire period. There was motion of armor particles, but not enough to break up the armor layer, therefore, tracers were usually sitting on top of the bed and



Figure 16. Cross-Section #1, on a low gradient riffle.



Figure 17. Cross-Section #4, in a run.

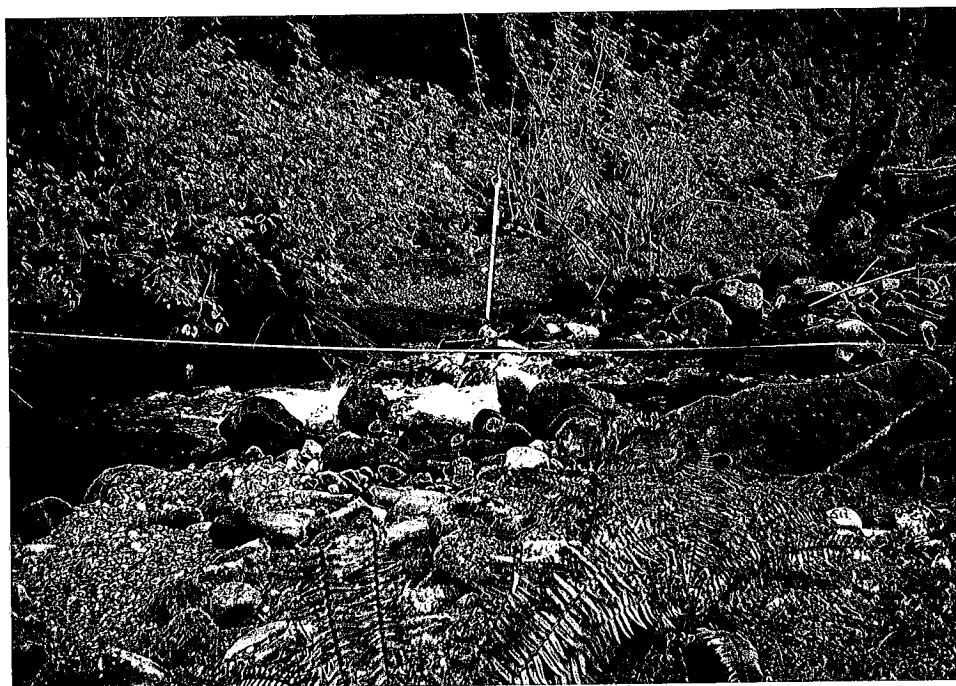


Figure 18. Cross-Section #10, on a steep riffle.

Table 4. Summary of particle sizes (mm) used for tracers on Little Lost Man Creek, California.

Cross Section	D35	D50	D65	D85	D90
XS#1	30	50	85	160	180
XS#2	60	81	112	168	197
XS#3	35	52	116	223	280
XS#4	46	76	118	164	186
XS#5	26	44	77	142	174
XS#7	25	33	39	56	76
XS#8	93	121	155	210	247
XS#9	18	31	64	162	211
XS#10	32	66	105	170	180

easy to find after flood events. Cross-sections were virtually unchanged throughout the study period.

Recording tracer location was done by stretching a tape between the cross section pins and looking vertically down at the tracer. Because small variations in angle of view cause variation in the apparent location of tracers, I assumed a measurement error of five centimeters. Tracers were counted as having moved if they appeared more than ten centimeters downstream from where they were placed, or were not found.

Distance moved to define mobility was kept as small as possible to increase sample size of mobile tracers and because rocks frequently are entrained for only small distances. Leopold and Rosgen (1991) find average distance moved by a tracer in a single excursion less than two feet, regardless of discharge magnitude.

Placement and recovery techniques were not constant throughout sampling. For the first year there were modifications for each event as the placement methodology was refined and improved.

First (WY 1993), I placed tracers near the cross section in a haphazard fashion. After a flood event, I noted tracer distance from the cross section tape in size categories intended to express the degree of movement, and the tracer taken out.

After the first event (Table 5), tracers were placed haphazardly on the streambed near the cross section tape.

Table 5. Record of flood events during study period on Little Lost Man Creek, California, and tracer cross-sections monitored.

Event	Date	Peak Discharge (cms)	Return Period (yrs)		Cross-Sections Monitored
			Partial Series	Annual Series	
1	12/10/92	8.78	1.55	2.43	1,2,3,4,5,7
2	12/31/92	4.47	0.61	1.20	1,2,3,4,5,7
3	1/21/93	6.80	1.13	1.80	1,2,3,4,5,7
3.3	2/11/93	2.41	0.30	1.10	2,3,7,8,9,10
3.6	2/22/93	2.69	0.34	1.10	2,4,5,7,8,9,10
4	3/18/93	3.46	0.44	1.20	1,4,5
5	3/23/93	4.96	0.74	1.30	1,2,3,4,5,7,8,9,10
6	4/4/93	4.67	0.68	1.20	1,2,3,4,5,7,8,9,10
6.3	4/18/93	1.70	0.20	<1	
6.6	5/5/93	1.42	0.10	<1	
7	6/2/93	2.78	0.34	1.10	7,8,9,10
8	12/9/93	4.67	0.65	1.21	
9	12/11/93	5.95	0.94	1.42	1,2,3,4,5,7,8,9,10
10	1/25/94	2.41	0.30	1.10	1,2,3,4,5,7,8,9,10
11	2/18/94	2.83	0.32	1.10	
12	1/9/95	9.35	1.7	2.8	
13	2/1/95	3.26	0.4	1.2	RASI riffles
14	3/15/95	3.26	0.39	1.2	

For the first event only, approximately one third of the tracers were imbedded flush with the bed surface. No tracers were imbedded in the surface after the first event.

After the second event, I became concerned that the size categories did not provide adequate information on tracer location and movement. From this point on, all tracers had their exact distance from the transect measured before and after each event. Sampling error in tracer location is about five cm. A particle was determined to have moved if it was found more than 10 cm away from where it was placed, or if it was not found at all.

As the season progressed, I also became concerned about the micro-topography of each tracer and how I might be introducing biases by placing each tracer before each event. There is considerable evidence that particle exposure plays a critical role in entrainment (Wiberg and Smith, 1987; Kirchner et al., 1990). Thereafter, I manipulated tracers as little as possible. Before Event 4 I tried to place the tracers on the cross sections where they were neither exposed nor protected from the flow, to mimic natural bed particles. After this, I manipulated a tracer only if necessary to read its number. I assumed that after one event, tracers would be in a natural state.

After Event 5, distance along the cross section tape was also noted for each particle, before and after each event. This helped keep track of individual tracers.

The second year (WY 1994) methods were consistent for all events. Rocks were placed near the cross section tape before the first event in places where they were neither exposed to nor hidden from the flow. I noted tracer location on the tape and exact distance downstream before and after each event (Appendix C). Rocks were not manipulated between events if possible. Tracers that traveled over 10 meters or beyond the feature represented by the cross section (e.g. from a riffle into a pool) were replaced near the cross section tape.

Event magnitude was measured at the Redwood Park gauge as well as peak stage recorders near the cross sections (Appendix A). Peak stage recorders consisted of slotted PVC pipe hose-clamped to fence posts with wooden dip sticks and finely shredded cork.

RESULTS

The dimensionless bedload transport rate q^* predicts that Reaches B and C are sediment rich (Table 6 and Figure 19) whereas RASI indicated only Reach D is sediment rich (Table 7). Because Reaches B and C may be unrepresentative for q^* the median and mean were used in Table 6. Sample size was not equal for all reaches (Table 6).

Sample variance for Reach D, which is the most suitable for q^* (see Discussion), suggests an optimal subsurface sample size (at a 80% confidence level) of seven five gallon buckets (about 170 kg) (Table 8). This agrees with the recommendation to sieve until the largest sample particle is no more than five percent of the total sample weight (Church et al., 1992).

RASI values for Little Lost Man Creek were high for a pristine stream, and show a 60% increase between Reaches A and D (Table 7). Mobile particle sizes predicted using equations from Andrews (1983) and Kappesser (1991) were similar to 30-counts picked by hand, but too variable to be used as a substitute for the 30-count (Table 9).

Variance estimates for RASI are greater than the mean in five out of eight estimates (Table 10). Corresponding optimal sample size calculations show that in most cases 80% confidence can be achieved with only one sample.

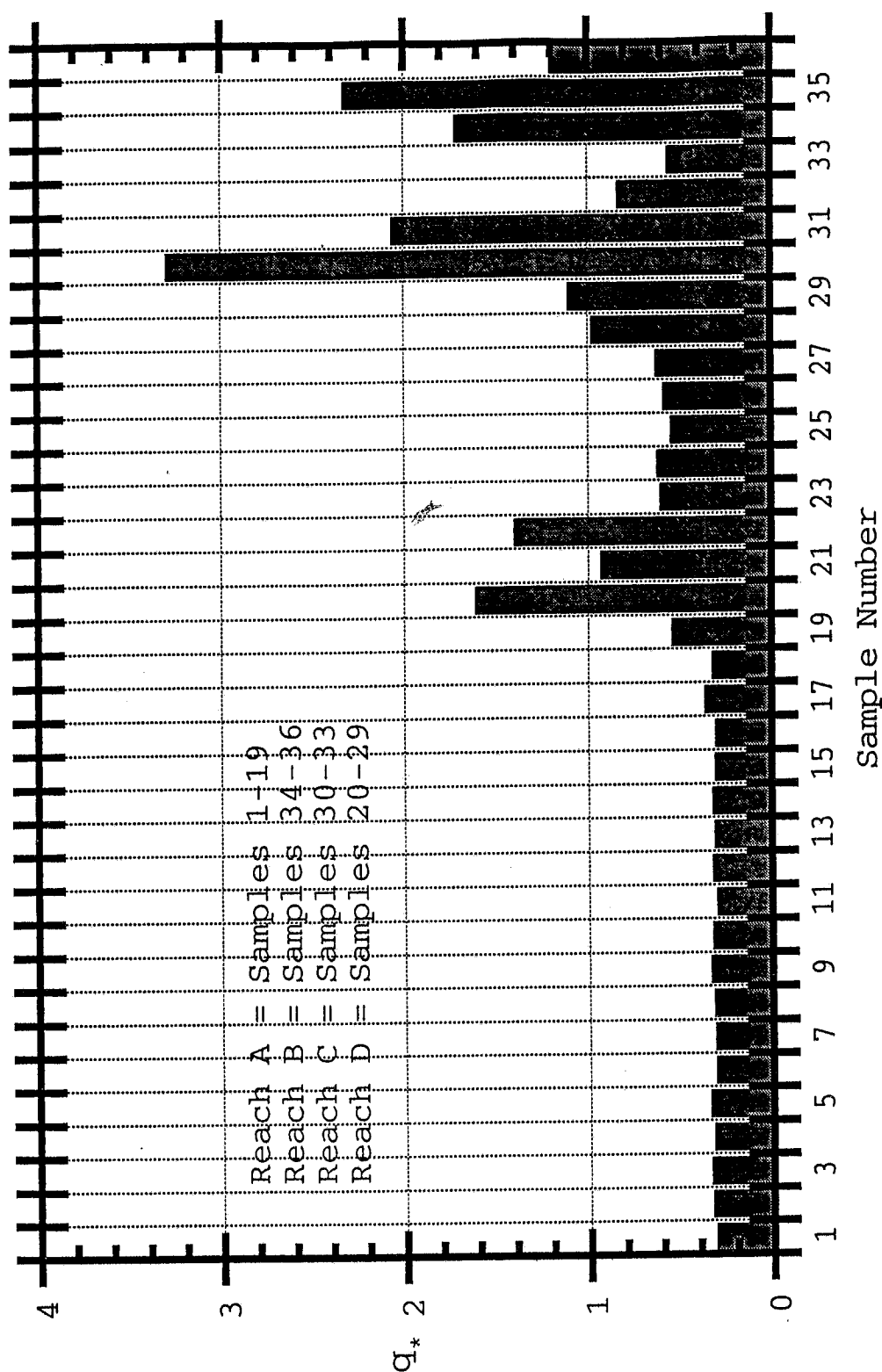


Figure 19. Thirty-six samples of the dimensionless bedload transport rate (q^*) from Little Lost Man Creek, California.

Table 6. Dimensionless bedload transport rate (q^*) input variables and results for 36 samples from Little Lost Man Creek, California.

Sample	Reach	Bankfull Depth (m)	Bankfull Slope	Surface D50 (m)	SubSurface D50 (m)	q^*
1	A	0.62	0.0204	0.095	0.011	0.32
2	A	0.62	0.0204	0.095	0.017	0.34
3	A	0.62	0.0204	0.095	0.019	0.34
4	A	0.62	0.0204	0.095	0.014	0.33
5	A	0.62	0.0204	0.095	0.020	0.35
6	A	0.62	0.0204	0.095	0.010	0.31
7	A	0.62	0.0204	0.095	0.011	0.32
8	A	0.62	0.0204	0.095	0.013	0.32
9	A	0.62	0.0204	0.095	0.018	0.34
10	A	0.62	0.0204	0.095	0.015	0.33
11	A	0.62	0.0204	0.095	0.007	0.31
12	A	0.62	0.0204	0.095	0.014	0.33
13	A	0.62	0.0204	0.095	0.012	0.32
14	A	0.62	0.0204	0.095	0.015	0.33
15	A	0.62	0.0204	0.095	0.010	0.31
16	A	0.62	0.0204	0.095	0.010	0.31
17	A	0.62	0.0204	0.095	0.026	0.37
18	A	0.62	0.0204	0.095	0.015	0.33
19	A	0.62	0.0204	0.095	0.059	0.55
20	D	0.73	0.0137	0.045	0.063	1.62
21	D	0.73	0.0137	0.045	0.042	0.93
22	D	0.73	0.0137	0.045	0.059	1.41
23	D	0.73	0.0137	0.045	0.018	0.61
24	D	0.73	0.0137	0.045	0.020	0.63
25	D	0.73	0.0137	0.045	0.012	0.55
26	D	0.73	0.0137	0.045	0.016	0.59
27	D	0.73	0.0137	0.045	0.020	0.63
28	D	0.73	0.0137	0.045	0.044	0.98
29	D	0.73	0.0137	0.045	0.049	1.11
30	B	0.54	0.0123	0.050	0.076	3.30
31	B	0.54	0.0123	0.050	0.068	2.06
32	B	0.54	0.0123	0.050	0.044	0.84
33	B	0.54	0.0123	0.050	0.028	0.57
34	C	0.65	0.0117	0.035	0.057	1.72
35	C	0.65	0.0117	0.035	0.066	2.33
36	C	0.65	0.0117	0.035	0.044	1.21
Median=						0.46
Mean=						0.76

Table 7. All samples of the Riffle Armor
Stability Index (RASI) taken from
Little Lost Man Creek, California.

Date	Reach	Observer	30-count (mm)	RASI
7/13/93	A	ATD	123.1	76
3/3/95	A	ATD	175	64
3/3/95	A	ATD	173	76
	A	Mean		72
6/22/93	B	Observer 1	143	82
6/22/93	B	Observer 2	120.8	75
6/22/93	B	Unknown 1	67	57
6/22/93	B	Observer 3	137.6	81
6/22/93	B	Observer 4	126	77
6/22/93	B	Knopp/Dresser	123.1	76
6/22/93	B	Observer 5	188	93
6/22/93	B	Observer 6	113	72
6/22/93	B	Observer 7	120	75
6/22/93	B	Unknown 2	109	70
7/13/93	B	ATD	109.2	78
3/3/95	B	ATD	144	70
3/3/95	B	ATD	165	88
	B	Mean		76
7/13/93	C	ATD	110.6	52
3/3/95	C	ATD	150	71
3/3/95	C	ATD	157	82
	C	Mean		68
7/13/93	D	ATD	104.8	84
3/3/95	D	ATD	148	85
3/3/95	D	ATD	131	94
3/3/95	D	ATD	145	95
	D	Mean		90

Table 8. Sample size, mean, median, variance, estimate of true population variance, and optimal sample size for the dimensionless bedload transport rate (q^*).

	All Reaches	Reach A	Reach B	Reach C	Reach D
Number in Sample	36	19	4	3	10
Mean	0.77	0.34	1.69	1.75	0.91
Median	0.46	0.33	1.45	1.72	0.78
Sample Based Variance	0.48	0.003	1.57	0.32	0.14
Estimate of Pop. Variance	0.0132	0.0001	0.3932	0.1053	0.0141
Optimal Sample Size (95% C.I.)	145	8	880	220	110
Optimal Sample Size (80% C.I.)	10	1	55	14	7

Table 9. Comparisons of Rifle Armor Stability Index (RASI) values using the standard methodology and using equations from Andrews (1983) and Kappesser (1991) to estimate the largest Mobile Particle Size (MPS). Ranges reflect the difference between reach and rifle slope.

Rifle	A-1	A-2	B-1	B-2	C-1	C-2	D-1	D-2 Bar	D-2 rifle
Geometric mean of 30-count (mm)	175	173	144	165	150	157	148	131	145
Number of rocks in 30-count	45	17	81	33	43	34	40	39	30
Surface D50 (mm)	88	66	91	68	88	98	77	56	56
Rifle Slope	0.025	0.074	0.038	0.032	0.011	0.065	0.05	0.061	0.061
Reach Slope at Bankfull	0.0204	0.0204	0.0137	0.0137	0.0123	0.0123	0.0117	0.0117	0.0117
Slope from MSR, if available	0.0207	0.0254	0.0141	0.0238	0.0123	0.0123	0.0117	0.0117	0.0117
Bankfull Area (Sq. m)	3.9	8.69	3.59	7.36	4.95	6.51	5.13	9.60	9.60
Bankfull Width (m)	8.7	14.5	7.5	11.5	9.9	11.1	8.4	20	20
Bankfull Depth (m)	0.45	0.60	0.48	0.64	0.50	0.59	0.61	0.48	0.48
Andrews' MPS (mm)	144-177	193-700	103-287	138-323	87-97	114-602	113-482	89-462	89-462
Kappesser MPS (mm)	90-110	120-434	64-178	86-200	54-60	71-373	70-299	55-287	55-287
RASI Using Standard Methodology	64	76	70	88	71	82	85	94	95
Andrews RASI	59-65	85-100	54-97	80-100	50-56	65-100	75-100	76-100	76-100
Kappesser RASI	50-54	63-100	36-80	61-95	33-36	35-100	35-100	50-100	50-100

Table 10. Mean, variance, sample size, and optimal sample size for samples of the Riffle Armor Stability Index (RASI) from Little Lost Man Creek, California.

	Mean	Variance	Number of		Optimal Sample Size (80% C.I.)	Optimal Sample Size (95% C.I.)
			Samples	Size		
Reach A	72.0	48.0	3	2		30
Reach B	76.5	78.9	13	1		7
Reach C	68.3	230.3	3	7		32
Reach D	89.5	33.7	4	1		18
All Samples	77.1	115.2	23	1		4
All Samples Made by ATD	77.9	134.1	14	1		6
Samples Made by ATD, Reach B	78.0	56.0	4	1		21
All Ten Observers, Reach B	78.5	85.1	10	1		9

Achieving 95% confidence raises the optimal sample size to four or more (Table 10).

Tracer movement at bankfull discharge showed a slight decrease in mobility between D50 and D65 but still over 40% mobility for the D90 (Figure 20). The stream reached bankfull discharge on December 11, 1993.

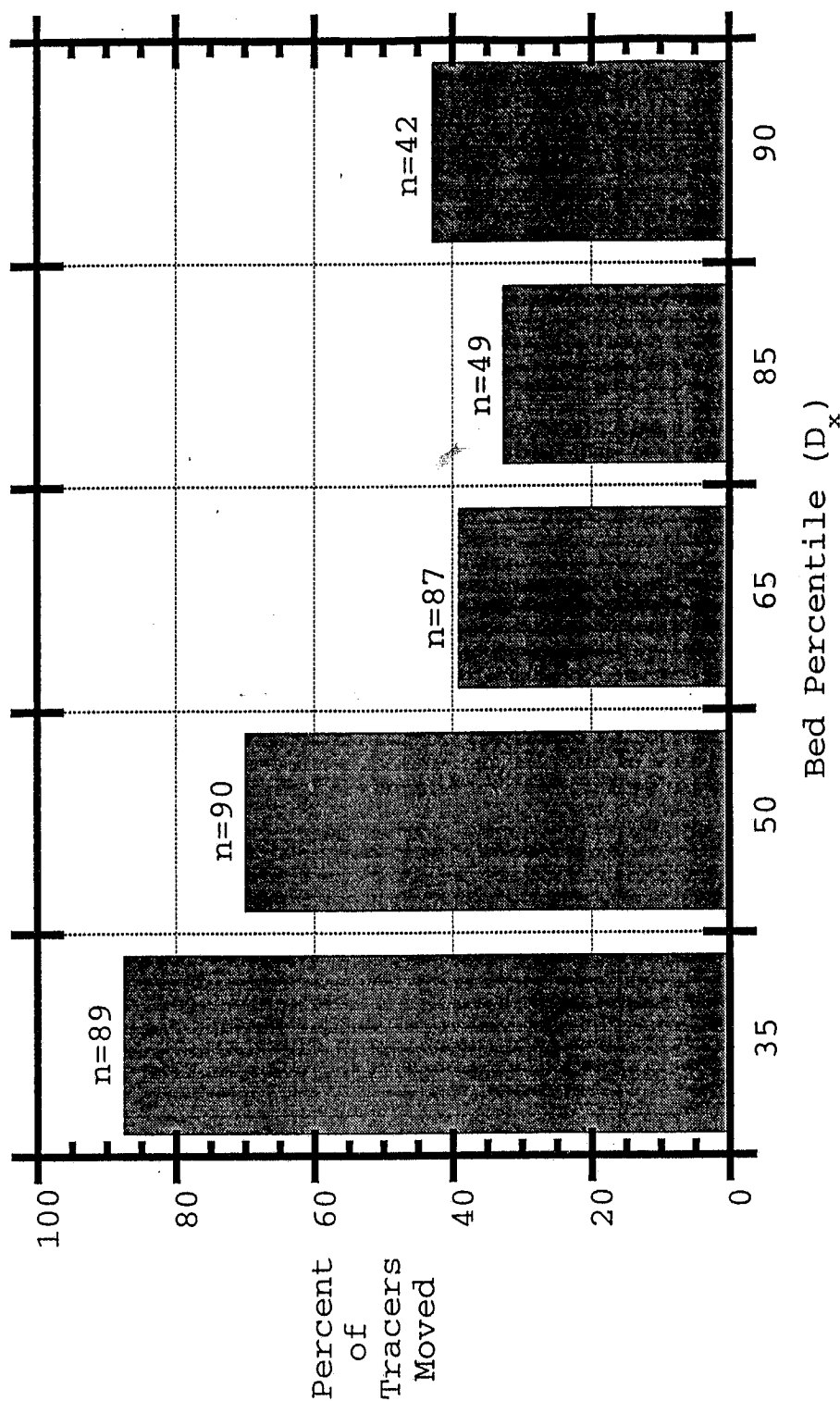


Figure 20. Percent of tracer class moved during a bankfull event, December 11, 1993 (Event #9, 6.0 cms, annual series return period = 1.4 years). n = number of tracers.

DISCUSSION

The combination of q^* and RASI measurements with tracer information allows examination of theories underlying these indexing techniques. All areas of the streambed may not be suitable for q^* . RASI may not be suitable for any stream reach, because all streambed sizes are mobilized at bankfull discharge. Several ways to reduce RASI bias by eliminating the 30-count are discussed.

Dimensionless Bedload Transport Rate (q^*)

A stream that has a sediment load equal to its transport capacity should have a q^* value of unity. If Little Lost Man Creek has low sediment supply, q^* should be less than one. Samples of q^* for Little Lost Man Creek ranged from 0.31 to 3.30. This suggests that some reaches are under-supplied with sediment, while adjacent reaches are over-supplied. Alternately, if we accept that Little Lost Man Creek is sediment poor, it suggests that q^* performed well on some reaches and poorly on others.

Most q^* samples over 1.00 were from Reaches B and C, which had high values and high variance (Table 8). These reaches had very coarse subsurface samples, much coarser than the surface. Some subsurface samples had rocks as large as 200 mm weighing 22 kg.

Subsurface samples which are coarser than the surface bring into question the model that the subsurface grain size distribution is equal to the bedload grain size distribution, as found in previous studies (Parker et al., 1982 and Milhous, 1973). Recent research by Lisle (1995) shows the subsurface is up to three times coarser than the bedload, especially in smaller streams such as Little Lost Man Creek. This suggests that subsurface samples from low order streams are inappropriate for q^* or need to be weighted to account for this difference. Some other way to estimate bedload may be more appropriate for small streams, such as bedload trapped by log-jams or other features.

A finer surface layer also suggests that Little Lost Man Creek is not armored in the usual sense. The fact that Little Lost Man Creek has a coarse, strongly cemented bed which remains intact even at floods above bankfull discharge suggests that a new type of armor may need to be defined.

The spatial variability of both armoring and subsurface particle size distribution is not clear. Studies by Dietrich et al. (1989), Lisle et al. (1991), and Lisle et al. (1993) show that armoring may not occupy the entire channel and that the active bedload transport may be confined to a small strip down the center of the channel. This suggests that the location of q^* measurements is critically important and more work is needed to clarify site selection procedures to assure subsurface samples represent

bedload. My research suggests subsurface samples from steep or non-alluvial reaches may not represent bedload.

Suitability of Reaches for q^*

The high q^* values of Reaches B and C suggest that q^* may give false readings under certain circumstances. The representation of the subsurface as the bedload particle size distribution is suspect for these reaches. Because Little Lost Man Creek is a low sediment stream, q^* values over one indicate failure of this technique. Only Reach D had subsurface samples indicating low sediment supply (Reach A samples were from a log-jam deposit). Reach D may be the only reach appropriate for the q^* technique using subsurface samples to represent bedload.

Reach A had a low q^* , indicating low sediment supply, and low variance. Presumably, if the subsurface of Reach A were sieved it would be as coarse as Reaches B and C. I did not sieve the subsurface here because it was not practical and I thought the subsurface would be coarser than the bedload.

The low variance of the Reach A samples may be because all the bedload samples were taken from a sediment deposit caused by a log-jam. Theoretically, this log-jam created a reservoir, trapping a representative sample of bedload during the years it was in place. However, this may not be true because sorting may have occurred during deposition.

I took 19 samples from the log-jam deposit. I assumed that the grain size distribution of the deposit was uniform, in part, to examine the variance inherent in the sieving process. Correspondingly, I found the variance of these samples to be very low (Table 8). Thus I can conclude large variance for samples from other reaches is due to variability in the subsurface and not an artifact of the sieving process.

Reach D is the most alluvial reach, having a lower slope and greater sinuosity than the other reaches, and no obvious bedrock or woody debris controls. Reach D also has the only subsurface-based q^* to fall in the predicted range for a stream with low sediment supply (i.e., less than one). This suggests that use of subsurface samples for q^* may not be applicable to high gradient or non-alluvial stream reaches.

Because the reaches are close together with no major tributaries, the bedload size distribution should be similar for all reaches. Therefore, the size distribution of the bedload trapped behind the log-jam on reach A may be a better estimate of the size distribution of the bedload for reaches of Little Lost Man Creek than the local subsurface. Using the mean of samples from the log-jam in place of the subsurface D50 for reaches B, C and D lowers q^* to below 0.71 (Table 11), predicting low sediment conditions on all reaches.

Table 11. Dimensionless bedload transport rate (q^*) for three reaches of Little Lost Man Creek, California, using D50 from subsurface samples compared to D50 from a log-jam deposit.

	Reach B	Reach C	Reach D
Surface D50	0.050	0.035	0.045
Mean D50 of subsurface samples	0.054	0.056	0.034
Mean D50 of log-jam deposit	0.016	0.016	0.016
Mean of original q^* values	1.69	1.75	0.91
New q^* using log-jam deposit	0.45	0.71	0.59

Critique of the Assumptions of q^*

One major assumption of q^* is that excess sediment supply will cause a fining of the surface layer only (Parker et al., 1982). Results from this study indicate the stream surface may be finer than the subsurface under low sediment conditions.

Jobsen and Carey (1989) find that fines accumulate on the surface only if the D_{15} of the surface armor is smaller than nine times the D_{85} of the fine sediment, otherwise fines infiltrate the streambed. If fines are allowed to infiltrate into the streambed, they fill interstitial voids in the gravel from the bottom up (Beschta and Jackson, 1978), possibly causing disproportionately fine subsurface samples if the increase in sediment supply is a recent phenomenon. In this case, the q^* technique could predict excess transport capacity when, in fact, there is excess sediment supply.

Optimal Sample Size

The optimal number of subsurface samples for q^* varies widely by reach (Table 8). Reach A, which had the lowest variance, had the lowest optimal sample size at eight samples at the 95% confidence level. Reach D, which may be most suitable for q^* , had an optimal sample size of seven buckets at the 80% confidence level and 110 buckets at the

95% confidence level. Reaches B and C had optimal sample sizes of over 200 buckets at the 95% confidence level.

On Little Lost Man Creek, we sieved about one sample unit (a 25 kg bucket) per hour. With the surveys and surface counts needed, two field workers could sieve about 6-8 samples of subsurface material in a day. This would allow Reaches A or D to be sampled in one day.

The largest particles on Reaches A and D were 7.1 kg and 6.8 kg respectively. To achieve the 5% rule, sample sizes of 142 kg and 136 kg would be required respectively. If average bucket weight is 25 kg, six buckets would be required, which is below the optimal sample weight predicted for Reach D at the 80% confidence level.

Summary of q^*

Although q^* may not apply to steep or non-alluvial stream reaches, where a good estimate of bedload can be made, q^* may be a reliable, low variance technique for estimating the balance between sediment supply and transport capacity. Because of the amount of surveying and subsurface sieving required, q^* is time consuming and requires specialized equipment.

Riffle Armor Stability Index (RASI)

RASI values range from 52 to 95 (Table 7). Values increase in the downstream direction. Because the 30-count

values for samples taken on July 13, 1993 were similar, the downstream increase in RASI suggests that the surface is progressively finer downstream, while transport competence remains similar. This is consistent with pebble counts from Little Lost Man Creek and other research (Lisle, 1995 and Paola and Seal, 1995) which show a fining of the bed downstream.

Samples from March 3, 1995 showed interesting patterns (Table 9). I took two RASI samples per reach. One riffle was straight and one riffle was slightly curved on each reach (Riffles 1 and 2 respectively).

First, the RASI values were lower on the straight riffle for all four reaches (Table 9). This suggests that curved riffles can mobilize a higher percentage of their bed at bankfull discharge. This may reflect higher mean shear stress exerted on bed particles for straight riffles, causing a coarser surface.

Second, RASI values for both straight and curved riffles showed progressive increases downstream. This appears to result primarily from decreases in size of the 30-count downstream (contrary to the RASI measurements made on 7/13/93 which showed fairly uniform 30-counts for all reaches). This may suggest a decrease in transport competence downstream, perhaps reflecting decreases in slope.

Third, the surveys for determining shear stress revealed differences between straight and curved riffles. On every reach, curved riffles had: (1) greater bankfull width; (2) greater bankfull area; (3) greater bankfull depth (except Reach D); and (4) greater bankfull slope (except Reach B). This is probably due to higher flow resistance from bends in the channel which decrease the proportion of average shear stress on the streambed.

Only Reach D had a true point bar which would allow me to compare 30-counts taken from the back of a point bar as recommended by Kappesser with those taken within the riffle. The 30-count for the riffle was 14 mm larger, changing the RASI from 94 to 95. Thus, RASI estimates taken from the point bar and from the riffle were virtually identical.

Such high RASI on reach D suggests that 95% of the riffle is mobile. Perhaps this is true. Equal mobility theories (Parker et al., 1982, Parker and Klingeman, 1982) and near equal mobility of my tracers at bankfull discharge suggest these may be the only RASI samples that actually selected the "largest commonly mobile" rocks for the 30-count. If so, it brings into question whether a high RASI indicates high sediment load. Either the index is inaccurate, current interpretation of the results is incorrect, or Little Lost Man Creek has a high sediment load.

Why RASI Should Not Work

The tracer data from Little Lost Man Creek suggest that there is nearly equal mobility of all bed particle sizes at bankfull discharge (Figure 20). Because most RASI values are less than 90, the 30-count rocks are clearly not the largest mobile size transported at bankfull discharge.

If all bed particle sizes have an equal chance of mobility, the RASI should be 90 or above for all riffles. Most RASI values have been less than 90 and many less than 80 (this study and Knopp, 1993). The overall Little Lost Man Creek RASI of 77.1 represents 30-count particles (which would be D77 of the surface) which were less than the largest mobile size at bankfull discharge (Figure 20).

Even though this evidence suggests that the 30-count theory may not be accurate, RASI seems to work in practice. Knopp (1993) found RASI a good indicator of land use patterns. In addition, I found RASI repeatable on three of the four reaches. The selection process which determines the 30-count apparently produces a repeatable sample which describes streambed condition accurately in most cases (Table 7). If this sample does not represent the largest mobile particles at bankfull discharge, what does it represent?

Most of my RASI values were between 65 and 85. This means 30-count particles were between the D₆₅ to D₈₅. Of course, any attempt to define the 30-count from substrate

distribution would predetermine the value of RASI. The 30-count particles must be hydraulically determined.

The challenge of the 30-count method is to select a sample that has theoretical validity, defined by hydraulic criteria. A key aspect of selected rocks under the current methodology is that they are not imbedded. Imbeddedness alone might be used, for example, to select the 30 largest non-imbedded rocks on a riffle.

Bias of RASI

Because selecting the 30-count is subjective, RASI was also examined for bias. Ten professional hydrologists of varying experience were asked to select 30-counts from Reach B of Little Lost Man Creek. Seven contributed data sheets showing the median and range of their counts (Figure 21). The mean and variance of all ten RASIs were 75.8 and 85.1 respectively (Table 10).

The series of RASIs done by one observer have a lower variance (Table 10). There is greater agreement between samples taken on the same day than between samples taken at the same place months apart, even for the same observer. Flood history and changes in the observer's perception of what is mobile undoubtedly play large roles in this phenomenon.

RASI measurements should be examined for systematic errors. Comparisons between observers should be made

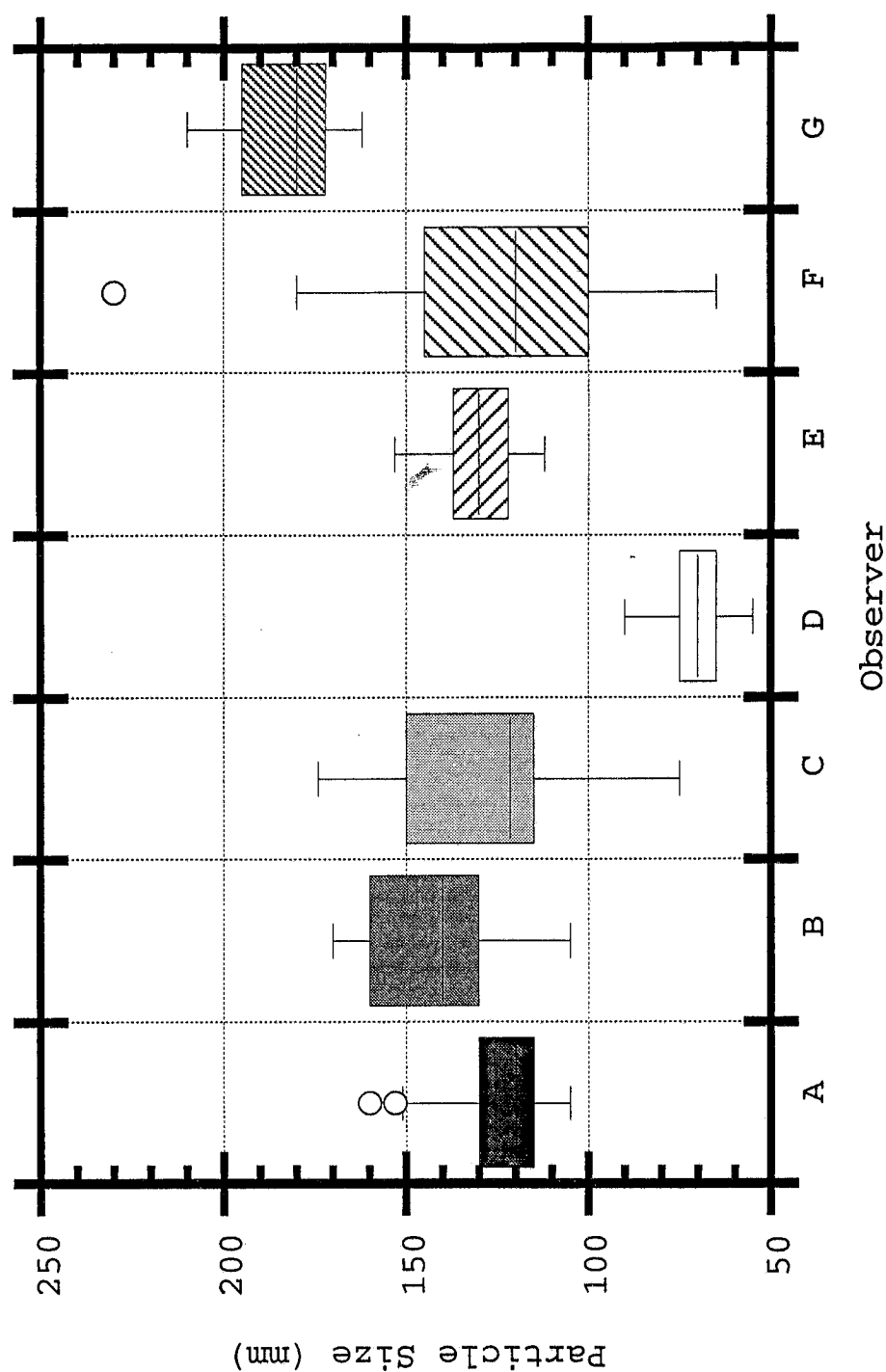


Figure 21. Median, standard deviation, and range for 30-counts made by seven observers on reach B, Little Lost Man Creek, California.

cautiously. One way to check for bias would be to perform RASI in a two-stage sampling scheme where RASI was done together with a different, less subjective technique, such as q^* .

Suggestions for Removing Bias from RASI

There are several ways that RASI could be modified to be less biased. First, the 30-count could be defined more precisely. If the investigator had less choice about what rocks to pick (e.g., the largest rocks or the largest non-imbedded rocks), bias could be reduced.

Second, the 30-count could be replaced by another estimate of transport competence. Stream power (slope times discharge), for example, has been shown to be proportional to bedload transport (Bagnold, 1966). Dividing stream power by some representation of the bed surface size distribution (such as the D_{50} , D_{85} , or D_{15}/D_{85} ratio) would produce an index similar in concept to RASI. Another index might compare bankfull critical shear stress to the D_{50} . Further study is needed to determine if such indexes would be useful tools for determining stream condition.

Knopp (personal communication, 1995) suggests using the bankfull channel geometry and Andrews' (1983) particle motion equation (2), to predict the largest mobile particle size. Using the particle size predicted by (2) in place of the geometric mean of the 30-count, I calculated RASI and

found six of eight were much higher than the 30-count method (Table 9). I believe much of this is from the steep slope immediately over the riffle. Using the overall slope for the reach, predicted sizes were smaller than the 30-count in eight of nine cases. The slope that mobilizes the 30-count rocks may be somewhere in between.

Using the formulas provided by Kappesser produced similar results (Table 9). When the slope of the riffle was used, RASI was very high, and when the overall reach slope was used, RASI was very low. For four riffles bankfull slopes are available from the maximum stage recorders, which all show slopes between the other estimates (Table 9). Using the correct slope (between slope of the riffle and slope of the overall reach) this method could eliminate the 30-count and greatly reduce bias of RASI.

Optimal Sample Size

RASI estimates had a variance of 115.2. This suggests an optimal sample size of four 30-counts at the 95% confidence level (Table 10). Previously, Knopp (1993) used three 30-counts to define a one kilometer stream reach. If each RASI takes an hour, several streams could be sampled in one field day, making RASI a rapid and inexpensive technique.

Summary of RASI

RASI is a rapid, relatively low variance measure of streambed condition. The subjective nature of this index, though it may introduce bias, can be exploited by a skilled investigator (who could rapidly assess the mobile size). Unfortunately, this subjectivity can also be used to select rocks for the 30-count that are a little larger, or a little smaller, depending on the desired outcome of RASI.

Although selection of the 30-count seems to result in valid, repeatable samples, there is no theoretical basis for why this should be. Current thinking (Parker, et al., 1982; Parker and Klingeman, 1982) and my tracer data suggest that all bed sizes are mobilized during flood events. This should result in uniformly high RASI values, which have not been observed.

I recommend eliminating the 30-count completely and creating a new index using Andrew's particle motion equations in relationship to the surface particle size distribution to predict streambed condition. Initial tests using my data suggest that given a procedure for how to determine the appropriate slope, it may be possible to remove bias using Andrews shear stress equations to replace the 30-count. If RASI is used in its current form, it should be paired with another less subjective technique (such as q^*) to help identify investigator bias.

CONCLUSIONS AND RECOMMENDATIONS

Both the dimensionless bedload transport rate (q^*) and RASI had samples that predicted sediment rich conditions. If we accept that Little Lost Man Creek is a stream with low sediment supply, sediment rich samples indicate a failure in the sampling technique.

The dimensionless bedload transport rate (q^*) seems reliable on low gradient, alluvial reaches. The steep, non-alluvial reaches of Little Lost Man Creek had subsurface samples that were highly variable and unexpectedly coarse, causing q^* to predict sediment rich conditions. For these reaches, the assumption that the subsurface grain size distribution is similar to the grain size distribution of the bedload may not be valid.

Variance for q^* is low on alluvial reaches (reach D). Optimal sample size for alluvial reaches is seven samples, a level of sampling that could be done in one field day by a trained technician.

RASI also did not consistently predict the low sediment conditions present on Little Lost Man Creek and showed investigator bias. Attempts to remove bias by substituting Andrew's particle motion equations for the 30-count were promising, but need clarification on how to measure slope before widespread adoption. Optimal sample

sizes for RASI indicate a sample with a 95% confidence interval can be attained in less than one field day.

Comparisons of the 30-count to tracer gravels showed that, in general, 30-count rocks were smaller than the largest particles mobile at bankfull discharge. Tracer movement supported the theory of equal mobility, which suggests that all RASI values be 90 or above on alluvial streams.

Recommendations

The dimensionless bedload transport rate (q^*) is the more reliable, albeit more intensive, of the two methods. Care must be taken to avoid steep or non-alluvial reaches where my data suggest the subsurface may not represent the bedload.

RASI is a rapid, low variance stream assessment technique. RASI is also susceptible to bias. When using RASI, use other sampling techniques (such as q^*) to account for bias. Although the theoretical assumptions of RASI may be true, my data show that the reasoning behind the 30-count is incorrect. The largest particles mobilized at bankfull discharge are larger than what is usually selected for the 30-count.

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