Field verification of predictive bedload formulas in a coarse bedload mountain stream
by Nicholas Bugosh

A thesis submitted in partial fulfillment of the requirements for the degree of Master of Science in Earth Sciences
Montana State University

Abstract:
Field verification of the applicability of bedload predictive formulas to coarse-bedload high-gradient mountain streams has received relatively little study as compared to similar work in sand bed streams. This study attempted to verify the applicability of two types of predictive bedload formulas, a discharge type and a tractive force type, to Squaw Creek, a coarse bedload high-gradient mountain stream. The Schoklitsch (1934) formula was chosen as a discharge type and the Meyer-Peter and Muller (1948) formula was selected as a tractive force type. The predictions of these formulas were also compared to predictions generated from Bagnold's simple theoretical expression for unit stream power.

Discharge, water surface slope, bed slope, water density, bedload particle size and bedload quantity were measured instantaneously during the 1983 and 1984 bedload transport events. A technique, which proved very successful, was developed for simultaneously measuring water surface and bed slope. The appropriate parameters were substituted into the formulas and the resulting predicted quantity of bedload was compared to the quantity actually measured in the stream. Field observations of channel features and changes in channel morphology were made to enable explanations for any variance between predictions and measurements.

The catastrophic dispersal of an old log jam in the study reach was observed and recorded during the 1983 bedload event. The dispersal of this log jam and the resulting instantaneous changes in stream power parameters had greater effect on bedload in Squaw Creek than any other parameter studied. Approximately 730 metric tons of bedload passed through the study reach during the twenty-three day 1983 bedload event. Thirty percent of this bedload moved in a three day period and is directly attributable to the burst of the log jam.

The Schoklitsch formula predictions were closest to measured values. The complex Meyer-Peter and Muller formula yielded predictions very similar to those of the simple stream power expression. The formulas overpredicted bedload in Squaw Creek by approximately two orders of magnitude. One order of magnitude of the overprediction can be attributed to sampling and analysis error. The remaining order of magnitude overprediction is attributed to the formulas' inability to account for variance in sediment supply, sediment storage and spatial and temporal variations in bedload transport in a high-gradient coarse-bedload stream.

FIELD VERIFICATION OF PREDICTIVE BEDLOAD FORMULAS IN A COARSE BEDLOAD MOUNTAIN STREAM

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Master of Science

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Earth Sciences

MONTANA STATE UNIVERSITY
Bozeman, Montana

May 1988

APPROVAL

of a thesis submitted by

Nicholas Bugosh

This thesis has been read by each member of the thesis committee and has been found to be satisfactory regarding content, English usage, format, citations, bibliographic style, and consistency, and is ready for submission to the College of Graduate Studies.

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Date May 18, 1988

ACKNOWLEDGEMENTS

I thank Dr. Stephan G. Custer for introducing me to Squaw Creek and for his personal time and money that he contributed to the project. Appreciation is also extended to Dr. Joseph M. Ashley and Dr. Howard S. Peavey, members of the reading committee, for their time and suggestions. I thank Steve Glasser for his technical help and words of encouragement. I thank Birgit Auschner for her help in the field during the 1984 season. Additional thanks are due to the Castle Rock Baptist Bible Camp who kindly provided electricity, to the United States Forest Service who approved access and to the many friends who cheerfully served as field assistants. I thank my wife, Patricia, for her help with the drafting and editing and for her moral support. I thank my father, Andrew Bugosh, for his constant encouragement and for showing me many years ago that worthwhile achievements often require great perseverance. Finally, I wish to thank R.A. Bagnold (1966, p. I2) who inspired this project when he wrote, "The most serious factual inadequacy in the field of sediment transport is, I suggest, our lack of data on the unsuspended transport of bedload by a turbulent fluid."

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ABSTRACT

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CHAPTER 1

INTRODUCTION

Purpose and Scope

Coarse bedload in high-gradient (slope(S) >0.01) mountain streams has received little study (McPherson, 1970; Hollingshead, 1971; Milhous and Klingeman, 1973; Nanson, 1974; Laronne and Carson, 1976; Ackers and White, 1980; Parker, Klingeman and McClean, 1982; Custer and others, 1987; Reid and Frostick, 1987) as compared to bedload in sand-bed streams. Although others have studied bedload, their works have been largely confined to sand-sized particles in flumes and low-gradient streams. These workers have proposed many theories to describe bedload, as well as theoretical and empirical formulas to predict quantity of bedload a stream is capable of transporting. Verification of the applicability of this groundwork to coarse (gravel through boulder) sediment, high-gradient streams has only begun in earnest by a few workers in the last two decades (Shulits and Hill, 1968; White, Milli and Crabbe, 1975). The apparent neglect is due in part to sampling difficulties. The tremendous stream power necessary to transport pebble, cobble, and boulder size particles makes sediment sampling extremely difficult and hazardous (Novak, 1957; Hubbell, 1964).

The purpose of this work is to: (1) measure stream power parameters in a high-gradient coarse bedload stream; (2) measure quantity of bedload; (3) attempt to verify applicability of some existing bedload transport formulas to such a stream; and (4) to offer explanations for variance between the predicted bedload and measured bedload to serve as the basis for further refinement of these models.

Site

Squaw Creek is a major tributary of the West Gallatin River, one of three headwater streams (West Gallatin River, Jefferson River, Madison River) which converge to form the Missouri River. The study site is in Gallatin County, Montana about 38.4 kilometers south of Bozeman (Figure 1). The study site is at the confluence of Squaw Creek and the West Gallatin River (latitude 45°26'28" N, longitude 111°13'20" W, in SE 1/4, Sec. 33, T.4 S., R.4 E., Montana) in hydrologic unit 10-02-00-08. Table 1 summarizes some of the quantifiable physiographic and hydrologic characteristics of the area.

Climate and Vegetation

The climate is typical of sub-alpine to alpine areas at high latitudes. Snow cover is intact most of the year with mid-June through late October being clear of snow in most of the lower part of the basin. Precipitation averages 81.8 centimeters (cm) for the drainage. The mean basin altitude is 2,268 meters. The great relief, as well as the northern and southern exposures, contribute to great variety in vegetative types. The basin is mostly heavy forest, but large areas with southern exposures support mainly sagebrush and juniper. The forest types vary from aspen in the foothills to Douglas

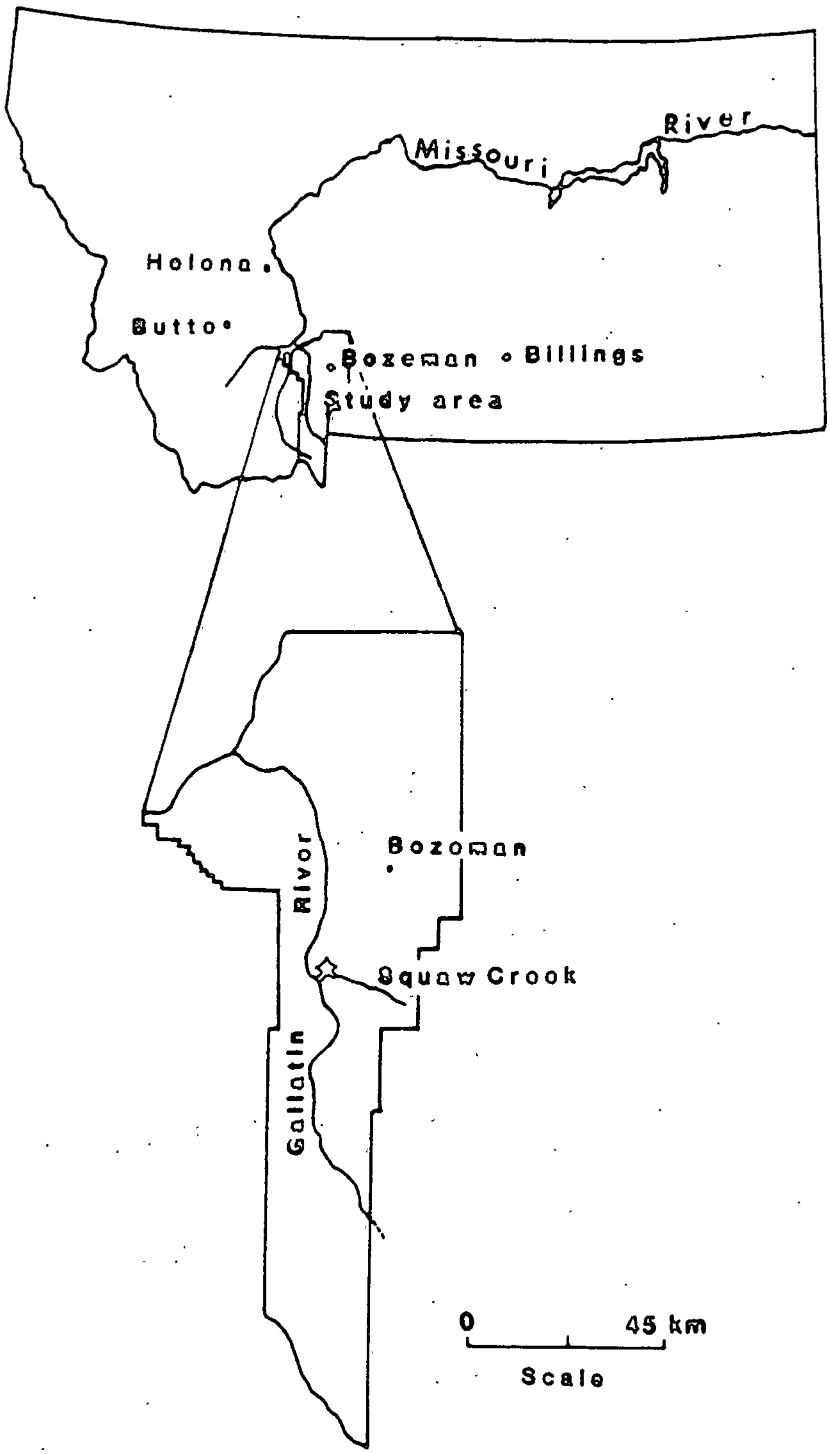

Figure 1. Location map of study area, Squaw Creek, Gallatin County, Montana. The study location is represented by the star.

fir in the sub-alpine zones to Engleman spruce. Typical forest understory plants are blue huckleberry and grouse whortleberry.

Table 1. Physiographic and hydrologic characteristics of Squaw Creek study site.

Drainage basin area	105.7 square kilometers (km^2) (40.4 square miles (mi^2))
Relief	1520.0 meters (m) (4.987 feet (ft))
Mean basin slope	25.0°
Stream order (Strahler)	4, based on U.S.G.S. topographic quadrangle
Total stream length	103.6 kilometers (km) (64.4 mi)
Main channel length	22.0 km (13.7 mi)
Mean particle size (d_{50}) armor	94 millimeters (mm) (Dunne and Leopold, 1978)
Mean particle size (d_{50}) bar	43.3 mm (Folk, 1980)
Mean particle size (d_{50}) bedload (76.2 mm H-S)	8.5 mm (average 1983 and 1984) (Folk, 1980)
Pcp (snow)	45.7 centimeters (cm) (18.0 in)
Pcp (rain)	35.6 cm (14.0 in)
Bankful discharge ($Q_{1.5}$)	5 cubic meters per second (m^3/s) (176.55 ft^3/s)
Width ($Q_{1.5}$)	8.6 m (28.2 ft)
Depth ($Q_{1.5}$)	0.3 m (1.0 ft)
Lag time (snow melt)	7 hours (hr) (peak arrives at site 20:00 hr)
Lag time (rain)	1.5 hr
Q average annual flow	1.1 m^3/s (38.7 cubic feet per second) (ft^3/s)
Q peak flow 1959-1975	8.5 m^3/s (298.3 ft^3/s)

Hydrologic Characteristics

Table 1 gives some of the quantifiable hydrologic characteristics of Squaw Creek. Some qualitative description of Squaw Creek is appropriate because it is the very nature of high gradient mountain streams which has both limited the amount of research done on them and frustrated successful application of many bedload formulas to them.

Most of the year Squaw Creek is a calm, clear mountain stream moving little, if any, sediment load. Through most of the water year it is about 0.3 m deep and 7.62 m wide at the study reach. The bed is a jumble of boulders, cobbles, pebbles, sand, beaver dams and log jams. Squaw Creek flows, in its 22.0 km length, from greater than 3,048 m above mean sea level at the head of the basin to 1,676 m at the mouth. Each spring from about mid-May to mid-June the character of the stream changes suddenly.

As the warm days melt the snowpack, discharge increases dramatically - two to threefold in a 48-hour period. For example, from 24-26 May, 1983 discharge on the rising limb of the hydrograph rose from 2.0 to 5.0 m^3/s. Flow over the boulder and cobble strewn bed becomes extremely turbulent and, though less than 0.6 m deep, it becomes unwadable. Due to the very steep slope, the discharges present are capable of transporting the cobble and boulder size bed material. The author has witnessed cobbles (approximately 150 mm in diameter) bouncing 0.3 m above the water surface! It is this high energy, explosive nature of high-gradient mountain streams that makes bedload sampling both difficult and hazardous.

CHAPTER 2

METHODS AND MATERIALS

Site Preparation

The study reach contains a United States Forest Service (U.S.F.S.) stream gaging station (Squaw Creek Bible Camp). The U.S.F.S. gaging station was used on a cooperative basis during the research. It consists of a staff gauge and a Leupold-Stevens Type F Model 68 recording stream gauge mounted on a stilling well. The station is located at a bridge which crosses Squaw Creek allowing access to the camp. Immediately upstream of this bridge a wooden plank catwalk was installed across the stream to provide a platform which allowed repeatable, safe, point measurements of the study parameters during peak discharge.

Stream Power Parameters

Velocity

Stream flow velocity was measured from the catwalk with a General Oceanics velocity meter at 0.6 stream depth (United States Department of the Interior, 1982). Discharge measurements thus obtained were compared with U.S.F.S. measurements, which at low flows were made on a waded channel traverse downstream of the bridge with a Scientific Instruments Price AA current meter. During peak flow U.S.F.S.

measurements were made off the bridge with a current meter attached to a 75 pound Columbus weight suspended by cable, in accordance with standard hydrometric procedure (United States Department of the Interior, 1982).

Water Density

Water density was estimated using temperature and suspended sediment. Water temperature was taken using a hand-held mercury thermometer. Suspended sediment load was measured from the catwalk at 10 evenly spaced intervals using a hand-held DH-48 sampler (United States Department of the Interior, 1982). The sampler was dipped into the flow at each measurement point so that a cross-sectionally integrated sample representative of total suspended sediment transport was obtained. The water temperature was converted to pure water density using data tables (Weast and others, 1967). The suspended load (mg/1) was added to the pure water density to obtain the water density in the stream.

Slope

Bedslope and water surface slope were measured simultaneously (Figure 2). Stakes were driven into the right and left banks upstream of the bridge and also into the heavy bridge abutments at either end of the catwalk. Nylon cords were stretched taut across the stream at these two traverses. Leveling of the lines in 1983 was initially done with a Brunton hand-transit (compass). The compass was used because a catastrophic bedload event occurred during set-up and rapid installation was necessary to measure the passing event. The lines were later resurveyed horizontal by plane table and earlier measurements were adjusted to fit the more accurate survey. Nylon was chosen because of its stability in changing moisture conditions once the initial stretch is taken out. These lines provided fixed horizontal datum to which distance-to-bed and distance-to-water surface measurements could easily be made using a measuring stick. The measuring stick is placed into the stream and down to the bed perpendicular to the nylon datum line and water and bed surfaces. The distance from the bed and water surface to the datum line can be read simultaneously. While upstream measurements had to be made by wading, due to a lack of funds to construct another catwalk, the downstream measurements could be made from the catwalk at the bridge. The bed and water surface elevations (y_1 and y_2) and the distance between nylon datum lines (x) allowed easy calculation of bed and water surface slope ($S=y_2-y_1/x$). The slope measurements were taken at five longitudinal profiles along the channel. A similar method has also been used successfully by Bridge and Jarvis (1982).

Water surface slope measurements were checked using a water level method (Figure 3). Flexible plastic tubing, 7.9 m long and 1.6 cm diameter, was placed in the stream longitudinally and allowed to fill with water. The upstream end of the tube was then raised until its meniscus (x_1) was level with the water surface. The downstream end of the tube was then also raised vertically. Due to atmospheric pressure the meniscus at the downstream end of the tube (x_2) will rise to the same level as the upstream meniscus. The distance from the downstream meniscus to the water surface (y_2-y_1) is then measured as is the distance between the upstream and downstream meniscus $(x_2 - x_1)$ (Ergenzinger, personal communication).

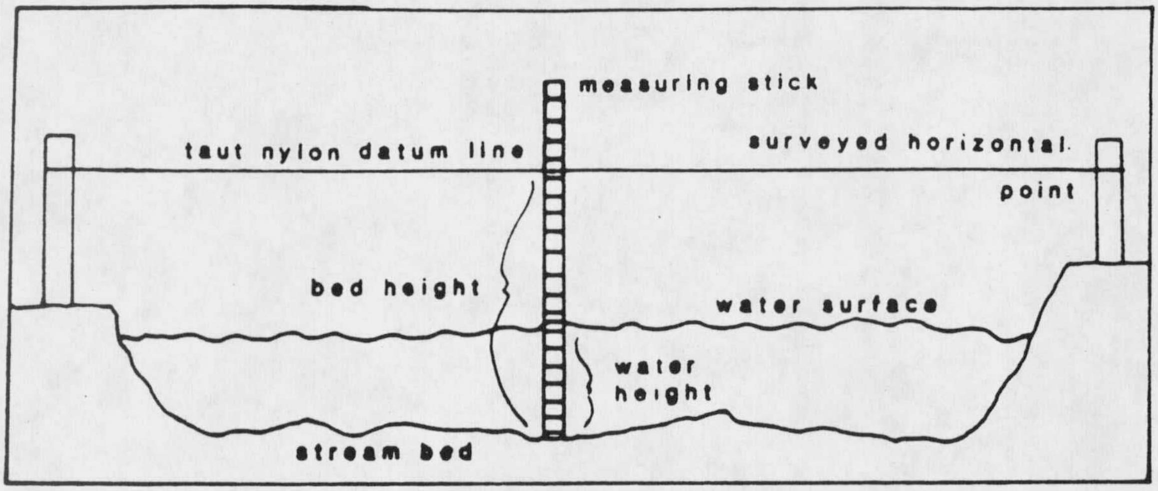

Figure 2. Techniques for measuring bedslope and water surface slope simultaneously (flow direction normal to page, towards reader).

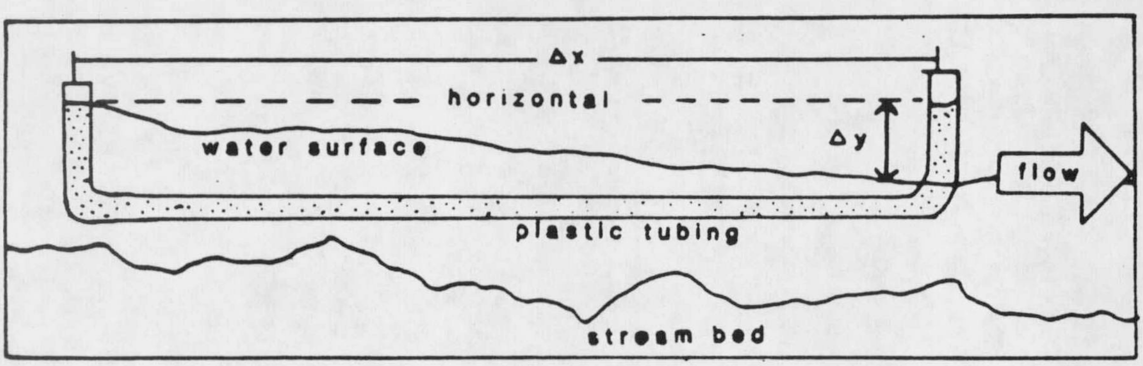

Figure 3. Water level technique for measuring water surface slope.

Sediment Sampling and Analysis

Introduction

Bed material was sampled while in transport from the main channel at higher discharges. Bed material was sampled while immobile from bars, dry channels, and the main channel at low flow. A variety of sampling techniques were tested for suitability. A description of these follows.

Bedload

Modified Mulhoffer Basket. During the 1982 runoff a modified Mulhoffer basket (Ergenzinger and Custer, 1983) with coarse (1 cm x 1 cm) mesh screening was used. The basket was mounted to the bridge overhead in a manner such that it could be swung forward and down into position against a log fastened flush to the streambed. During peak flows a hand winch was necessary to force the basket into position against the current.

Helley-Smith Bridge-Mounted Sampler. In 1983 and 1984 a Helley-Smith bridge-mounted (7.62 cm x 7.62 cm) bedload sampler was also tried (Emmett, 1980). This consisted of the Helley-Smith pressure differential sampler nozzle and bag mounted to a heavy steel weight. The sampler has vanes attached to the rear to keep the nozzle pointing upstream into the flow. It is lowered to the stream bottom on a cable from a bridge by means of a hand winch mounted on a trolley.

Helley-Smith Hand-Held Sampler. The third sampling technique, tested in 1983 and 1984 was a Helley-Smith (7.62 cm x 7.62 cm) hand-held sampler (Emmett, 1980). The sampler was used in conjunction with the catwalk, which was marked at 0.30 m intervals across the stream width to define 23 repeatable sampling sites. To obtain cross channel integrated samples, every other marked site was sampled for 30 seconds, yielding a total of 10 sites in 5 minutes.

Problems were encountered in using each sampler. These will be elaborated upon in the results and discussion sections.

Freshly Deposited Sediment

Static bed material samples were gathered after deposition resulting from bedload events of 1983 and 1984. The samples were taken from representative loci of new deposition, i.e., center of new bar, center of channel, upstream of a new log jam. A volume of material sufficient to fill a 3.8 liter plastic milk jug was carefully dug out to sample both the armor and subarmor layers. The armor layer is a tightly packed, imbricated surface layer of bed material which is not transportable by the discharges present during most of the year. Only during peak flows is the channel armor broken, allowing the finer grained, matrix filling sediment trapped below in the subarmor as well as the coarser armor material to be entrained as bedload. It is important to sample both layers to avoid obtaining a sample biased towards the larger sizes of the armor layer, which is not representative of all the sizes which actually are entrained as bedload. The samples were then dried and sieved for size analysis.

Bedload Grain Size Analysis

Sieving was done using a 1/4 Phi interval except when impossible due to a few missing screens or when deemed unnecessary in the fine fraction due to a preponderance of coarse material. Coarser material was hand sieved, while the sand and silt sizes were sieved on a Ro-Tap for 15 minutes per sieve stack. Each fraction was then weighed and the resulting cumulative weights were plotted by computer for analysis. Occasionally one large cobble would represent the bulk of the sample, causing the curve to begin at the size class represented by the cobble. In this case the grain size distribution plot was extrapolated from this known point to the x-axis, at the point representing the next largest Phi size, to complete the plot.

Bed Armor

The bed armor of Squaw Creek is too large both to facilitate transport of bed samples to the lab and for sieve analysis. A random point-count method suggested by Dunne and Leopold (1978) was employed instead. Samplings were conducted by wading the study reach downstream of the bridge on random transects, stopping every couple of steps and measuring the b-axis of the particle touched by the toe of the sampler's boot. The particles are grouped into size classes to which an average weight for particles in the class has been determined. A sample of 102 particles was used.

Channel Morphology

The changes in channel morphology were recorded by two methods. Plane table mapping of the study reach before and after bedload events was augmented by aerial photos also taken before and after the events occurred. A time lapse photo sequence also recorded channel morphology changes resulting from the catastrophic dispersal of a log jam during the 1983 spring runoff. In addition to these methods, bedload events were also verified using an in-stream magnetic cobble counter.

Magnetic Cobble Counter

A magnetic cobble counter (Ergenzinger and Custer, 1983) was used to record bedload both continuously through the day and as spot samples, especially during sampling of stream parameters.

Bedload Formulas

The formulas chosen to test were of three types; a theoretical expression based on concepts from general physics (Bagnold, 1966), a discharge formula (Schoklitsch, 1934) and a tractive force formula (Meyer-Peter and Müller, 1948). A discussion of each formula and the criteria for its inclusion in the study follows.

Stream Power Expression

In 1966 R.A. Bagnold proposed that the problem of bedload prediction could be resolved through an approach from general physics. He reasoned that unit stream power, (ω), the power of a stream to move sediment per unit of stream width, must be the product of discharge (q), water surface slope (S), water density (ρ), and the force of gravity (g). That is,

$$\omega = qS\rho g.$$

If we assume that gravity is essentially constant over a reach and water density varies negligibly, stream power can be conceived of as a function of slope, discharge and a constant. Bagnold (1966) noted that stream power is strongly related to bedload transport. Perfect efficiency of transport, indeed, is related to stream power directly. It is for this reason that stream power is useful as an index of transport capacity. Since streams are not perfectly efficient, transport would be expected to be less than that predicted using ω. Although Bagnold's 1966 ω expression was intended to quantify unit stream power, not to predict quantity of bedload transport, unit stream power is a useful predictive tool. For this study, bedload was predicted using an expression based on the unit stream power concept. That is,

$$b_{\omega} = qS\rho g.$$

The symbol b is used to differentiate predicted bedload transport using the unit stream power expression from Bagnold's (1966) stream power, ω. This expression was included in the study to serve as a reference with which to compare the predictive formulas. By comparing more complex formulas with this simple, fundamental concept it can be determined if the complex mathematical manipulations of the other formulas really improve predictive accuracy in a coarse bedload, high-gradient mountain stream.

Shulits and Hill (1968) provide an excellent summary of bedload formulas. Review of their work showed that two formulas, the Schoklitsch (1934) and Meyer-Peter and Müller (1948) would be most likely to yield acceptable results on Squaw Creek. A description, summarized from Shulits and Hill (1968), of these two formulas, which were originally published in German, follows.

Schoklitsch (1934) Formula

The Schoklitsch (1934) formula is of the discharge type. In this type of bedload formula, transport rate is considered primarily a function of discharge. In metric units the formula can be expressed as

$$G_1=7000\ [S^{3/2}/d^{1/2}]\ (Q_1-Q_{01})$$

where

G_1 = bedload transport rate per unit stream width (kg/m-s)

S = water surface slope

d = grain size (mm, approximately d_{35})

Q_1 = discharge per unit width ($m^3/s/m$)

Q_{01} = critical discharge ($m^3/s/m$)

$= 0.00001944d/S^{4/3}$

A corrective factor for grain size variation is included ($S^{3/2}/d^{1/2}$) as is the concept of critical discharge (Q_{01}). Critical discharge addresses the idea that not all available discharge is used up in sediment transport as bedload. Thus critical discharge (Q_{01}), that threshold discharge at which bedload transport initiates, is subtracted from total discharge (Q_1) to yield that part of the total (Q_1-Q_{01}) which is available to move sediment as bedload. This formula is included because it has shown very consistent results in comparison to other discharge type formulas when used with a wide variety of data sets (Shulits and Hill, 1968).

Meyer-Peter and Müller (1948) Formula

The Meyer-Peter and Müller (1948) formula is of the tractive force type, that is, bedload transport is considered a function of the tractive force of the stream. It is the result of 14 years of work combining both field and flume data. The formula may be written as

$$G''_1{}^{2/3} = \frac{v\,[Q_b/Q]\,[K_B/K_G]^{3/2}\,HS - 0.047\,v''_s d_E}{0.25\,[v/g]^{1/3}}$$

in the metric system, where

v = specific weight of water (metric tons/m^3)

Q_b = bed discharge (liters/s)

Q = total discharge (liters/s)

K_B = Strickler roughness coefficient for the bed ($m^{1/3}$/s)

= $Q_b \;/\; A_b R_b{}^{2/3} S^{1/2} = 1/n$,

n = Manning bed roughness

K_G = particle or grain roughness ($m^{1/3}$/s)

= $26/[d_{90}]^{1/6}$

H = depth (water, m)

S = slope (water surface)

v''_s = submerged specific weight of sediment (metric tons/m^3)

= $v_s - v$ = specific weight in air of sediment − specific weight in water of sediment

d_E = effective diameter of the bed material (m)

g = acceleration due to gravity (m/s^2)

G''_1 = immersed bedload transport rate (metric tons/s-m)

In this formula vHS is the tractive force term upon which the formula is based. The other terms of the formula reduce total tractive force of the stream to that amount of force actually available for bedload transport. $[Q_b/Q]$ accounts for the fact that only a part of the total discharge acts on the bed. $[K_B/K_G]^{3/2}$ is a reducing factor to account for tractive force losses to form resistances, such as bars and ripples. The term $0.047v''_s d_E$ is the critical tractive force, that at which the bed is just barely at rest. When this critical tractive force is subtracted from the total tractive force of the stream the remainder is the force available to move sediment as bedload.

The Meyer-Peter and Müller (1948) formula was included because it has been shown to be in agreement with a wide range of tractive force formulas (Shulits and Hill, 1968) and because it is often used by workers studying bedload transport.

CHAPTER 3

RESULTS

Introduction

Measurement of quantities and size of material transported within the channel allowed comparison with material deposited during changes in channel morphology to help identify in-stream sources of material and permit verification of bedload calculations. The results of this investigation are summarized in Tables 2-4 and Figures 4-5.

Table 2. Comparison of total bedload transport predictions and measurements and coefficient of adjustment k.

Sample type (number of complete sets of measured parameters used to determine)	Predicted Bedload (metric tons dry)	Measured Bedload (metric tons dry)	k $\left(\frac{\text{measured}}{\text{predicted}}\right)$
1983 Entire channel width Stream power formula (13 sets)	b_ω = 244,022	727	3.0×10^{-3}
1983 Entire channel width Schoklitsch formula (12 sets)	G_1 = 136,610	727	5.3×10^{-3}
1983 Entire channel width MPM formula (12 sets)	G''_1 = 292,268	727	2.5×10^{-3}
1984 Entire channel width Stream power formula (9 sets)	b_ω = 195,225	522	2.7×10^{-3}
1984 Entire channel width Schoklitsch formula (9 sets)	G_1 = 65,775	522	7.9×10^{-3}
1984 Entire channel width MPM formula (9 sets)	G''_1 = 172,529	522	3.0×10^{-3}

Table 3. Average values ($\bar{k}$) of coefficient, k, for 1983 and 1984 and percent variation from average.

Formula	k_{1983} $\left(\frac{\text{measured}}{\text{predicted}}\right)$	k_{1984} $\left(\frac{\text{measured}}{\text{predicted}}\right)$	$\bar{k}$ $\left(\frac{k_{1983} + k_{1984}}{2}\right)$	% variation from $\bar{k}$ $\left(\frac{(\bar{k}-k \text{ 1983 or 1984}) \times 100}{\bar{k}}\right)$
Stream power	3.0×10^{-3}	2.7×10^{-3}	2.9×10^{-3}	5
Schoklitsch	5.3×10^{-3}	7.9×10^{-3}	6.6×10^{-3}	20
MPM	2.5×10^{-3}	3.0×10^{-3}	2.8×10^{-3}	9

Table 4. Error analysis.

Variable	Typical error in measurement of variable (%)		Percent change in bedload predicted by formulas due to introduction of error in parameter					
			Steam power		Schoklitsch		MPM	
	1983	1984	1983	1984	1983	1984	1983	1984
Water density,	5	5	0.5	0.5	–	–	–	–
Discharge, Q	5	5	4	4	5	5	7	7
Water surface slope, S	10	5	0	0	15	8	17	10
Mean particle size, d_{50}	10+30*	10+30*	–	–	5	5	0	0
Particle size, d_{90}	10+30*	10+30*	–	–	–	–	3	3
Water depth, h	10	5	–	–	–	–	17	10
Variables combined in worst possible case			±15	±10	±16	±8	±52	±31
With sampler bias added			–	–	58	47	21	3

*10% for sieve analysis and 30% for sampler bias (see Discussion text)

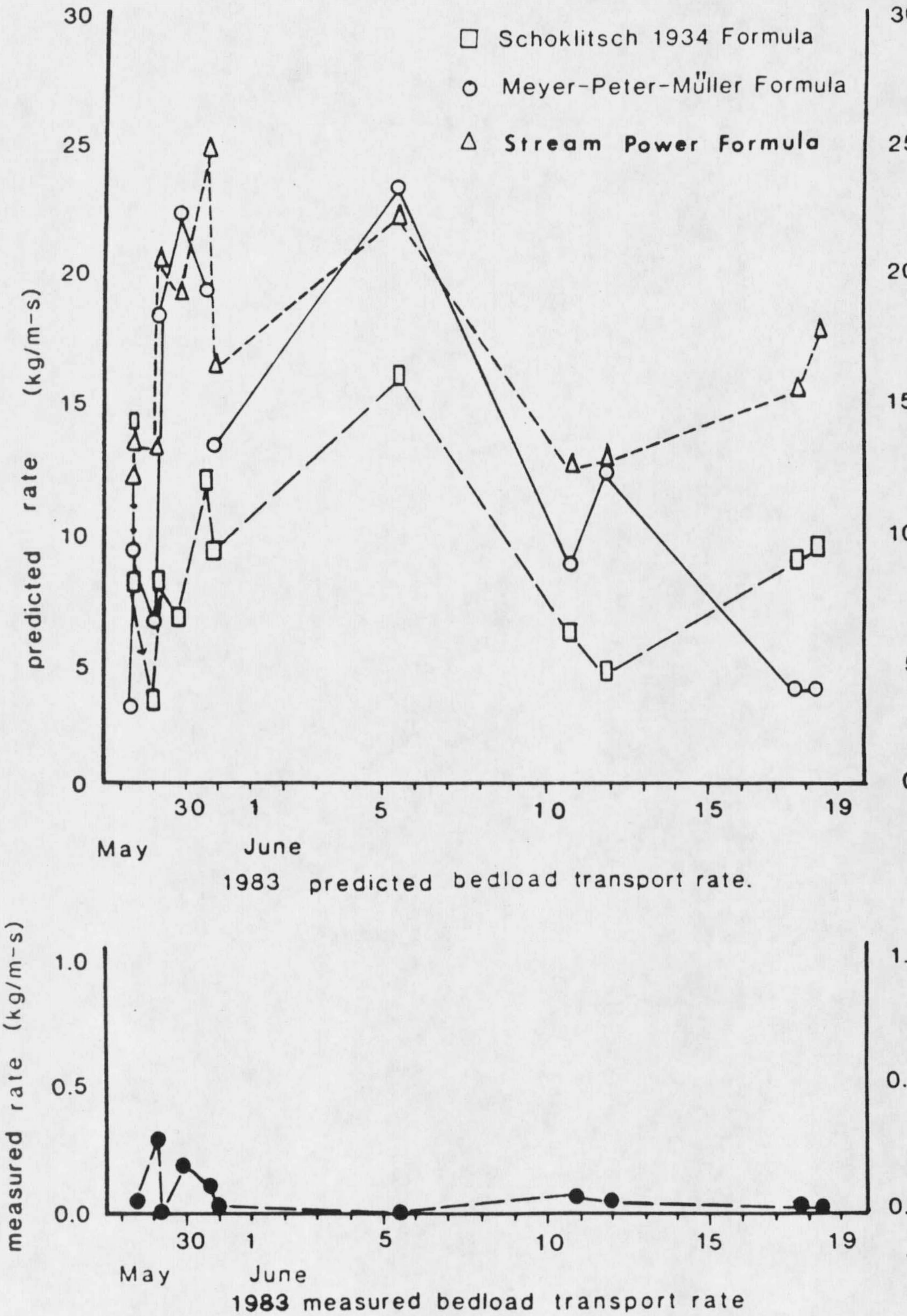

Figure 4. Graph of measured and predicted bedload during 1983 event.

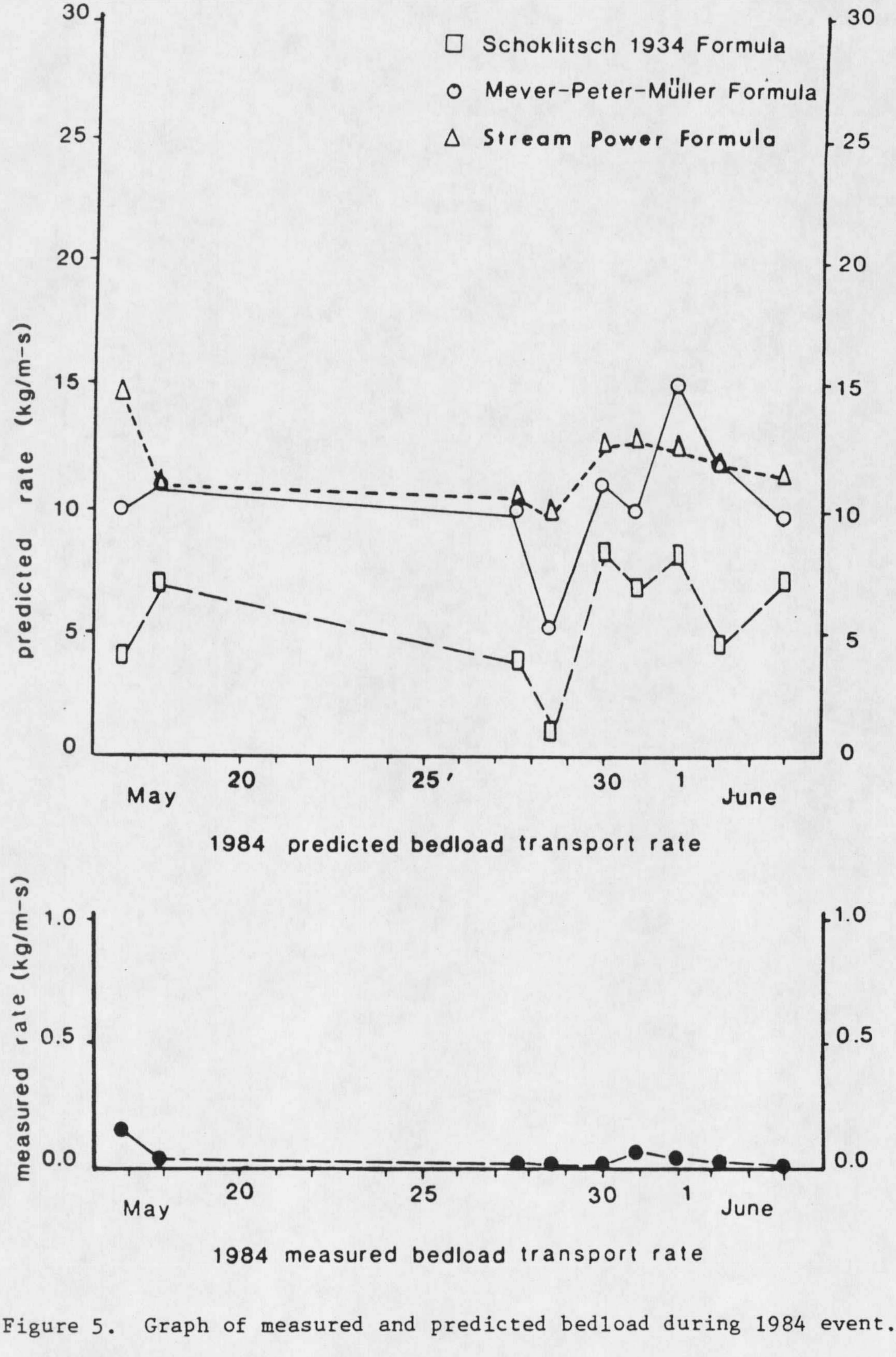

Figure 5. Graph of measured and predicted bedload during 1984 event.

All three of the formulas tested with Squaw Creek data predicted bedload over two orders of magnitude greater than that which was measured. The bedload measurement techniques are discussed later. The Schoklitsch (1934) formula prediction was closer to measured bedload for both the 1983 and 1984 data sets. The stream power and Meyer-Peter and Müller (MPM) formulas gave very similar results for both years, MPM being 20% greater than the stream power prediction in 1983 and 12% less than the stream power prediction in 1984, as determined from Table 2.

Column two, in Table 2, lists the metric tons of bedload predicted by each of the formulas and column three, in Table 2, lists the metric tons of bedload measured for the 1983 and 1984 transport events. The instantaneous transport rates per unit width were multiplied by the period of time the stream maintained that rate and the stream width to yield metric tons of bedload. These calculations are based upon complete sets of measured parameters, as applicable to each formula. (Many parameters had to be measured "instantaneously" and problems often caused delays in measurement of one or more parameters resulting in an incomplete set of "instantaneous" measurements.) The fourth column lists the empirically determined adjustment coefficient, k, which adjusts the bedload predicted by the formulas to that actually measured in the stream. The coefficient k is determined by dividing the measured bedload by the predicted bedload.

The k values for each formula in Table 2 vary from year to year. The consistency of each formula's prediction from year to year can be calculated as the percent variation from each formula's average k value (Table 3). The stream power prediction was more consistent from year to year varying ±5% from its average k value.

Some of the overprediction and yearly variation in the formula's predictions is attributable to error in parameter measurements. Results of analysis of this parameter measurement error are presented in Table 4. The Schoklitsch formula was least affected, by a slight margin over the stream power prediction, by error in measurement of the parameters. Predictions by the Schoklitsch formula varied ±16% in the worst possible case for 1983 data and ±8% for the 1984 worst possible case. The MPM formula was the most affected varying ±52% and ±31% for the same data. Error analysis is discussed later.

The bedload transport rates predicted by the formulas are presented in Figures 4 and 5. Figure 4 plots twelve predicted points and Figure 5 plots nine points. In making the many instantaneous parameter measurements required by the formulas, cases occurred in which measurement of a parameter was impossible due to some field conditions. This resulted in many sets of incomplete instantaneous parameter measurements. The points plotted in Figures 4 and 5 represent those times at which all study parameters were measured simultaneously - there are no estimated values. As a result, all of the data obtained in the field was not used to plot Figures 4 and 5. There are 12 complete sets of instantaneous parameter measurements for 1983 and 9 for 1984 contained in Appendices A-D. To test the effect that this small set of data points would have on formula precision, incomplete parameter sets were also plotted for comparison with complete parameter sets using estimated values as necessary. Although not shown here, the estimated data sets provided 146 points for 1983 and 87 points for 1984. The estimated and non-estimated data sets yielded predictions within 20% of each other. The 20% difference between the estimated and non-estimated data sets is insignificant as compared to the two orders of magnitude overprediction. Based upon this comparison it was assumed that results based upon the smaller number of complete data sets were valid for the study and did not run the risk of introducing error by including estimated parameters.

Data analyses indicate that formula overprediction not attributable to error, as mentioned above, was affected by the following factors to varying degrees. Effects of these factors and relevant observations are presented briefly here as results and are discussed in detail in Chapter 4.

Discharge

Discharge was very accurately and easily measured from the catwalk. The convergence of flow by the bridge abutments was proved, by comparison with U.S.F.S. measurements taken downstream of the bridge, to not adversely affect accuracy of the measurements. Measuring discharge from the catwalk did, however, improve the ease and safety with which the measurements were made.

Water Density

Variations in water density caused by change in temperature and suspended sediment were found to change stream power an insignificant amount (0.01%) on Squaw Creek. A constant value of 1,000 kg/m^3 can be used with negligible error in the stream power expression.

Datum-Line Slope Measurement Technique

The datum line slope measurement technique used proved to be very precise and easy to use. It was checked by the water level method only twice because two people were necessary to use the water level method. Both times the water level method yielded water surface slopes 50-100% larger than the datum line method. This difference in water surface slope values probably is due to local variations in water surface slope on the study reach, not to great differences in the precision of the two methods. The tubing used to measure water surface slopes by the water level method was 7.9 m from y_2-y_1. This is only a fraction of the datum-line method y_2-y_1 distance of 38.1 m. The central section of the study reach measured by the water level was a riffle. The steeper water surface slopes measured there by the water level method probably reflect local variation in water surface slope due to the greater bed slope at the riffle. The water surface slopes obtained by the water level method were very close to bed slope values obtained by the datum line method.

Bedload Samplers

Modified Mülhoffer Basket

The Mulhoffer sampler basket proved ineffective as turbulence created by flow through the basket mesh was great enough to wash out bedload that was captured.

Bridge-Mounted Helley-Smith

The bridge-mounted Helley-Smith sampler also proved insufficient. It had the advantage of easy retrieval during peak flows, but its use was discontinued because accurate point measurements were not possible. As soon as the sampler frame on its cable contacted the water surface it was swept towards the thalweg frustrating attempts to measure bedload at desired points across the channel width.

Hand-Held Helley-Smith

The catwalk provided a solid platform for measurement and was very beneficial in allowing repeatable point sampling of bedload. At peak flows a great deal of strength was needed to maintain control of the 76.2 mm nozzle hand-held Helley-Smith sampler. Handling was enhanced by the addition of a handle extension made from galvanized steel fence rail stock. The added weight and length improved control substantially. Even with this modification, most field assistants could not maintain control of this sampler at peak flow. This sampler proved most effective and was used to measure bedload.

Spatial Variation in Bedload

Bedload was not observed to be spatially continuous across the stream bed. Bedload was consistently greatest approximately 5.8 m from the left bank in early 1983 and 3.8 m from the left bank after the channel changes resulting from the dispersal of the log jam. These points roughly coincide with the thalweg. Only 83% of the stream width was involved in sediment transport as bedload.

Sediment Supply

Sediment supply greatly affected bedload transport on Squaw Creek. Predictions made using the formulas assume a constant supply of transportable sediment. Bagnold (1966, p. I29) noted that a river may transport "less sediment than it could if more transportable sediment were available" and that this "deficiency of sediment supply" might cause predicted transport rates to be considerably larger than measured transport rates. To determine if such a sediment deficiency existed at Squaw Creek during the period of the study, the channel and its tributary streams, which cut mapped landslides units, were searched by foot and vehicle for extra-channel sediment sources, such as avalanches, rock slides, and debris flows. No fresh extra-channel sediment supply zones were identified in the basin suggesting Squaw Creek is a sediment deficient stream, at least during the period of this study. Small areas of bank failure could be found upstream and downstream of the study reach during all the years of the study. Figures 9 and 10 show where bank failure occurred within the study reach in 1983. The only new load identified was reworked sediment introduced by bank failure.

Sediment Storage

Sediment storage also had great affects on bedload. Bedload is stored within the channel at Squaw Creek in the bed armor, pools and log jams, and bedforms. The armor layer remained cohesive at most discharges during 1983 and 1984 preventing release of the subarmor material. The armor was broken following the dispersal of a log jam in 1983 resulting in the release of sediment stored in the subarmor.

Bedload increased as sediment was released from storage in pools on rising limbs of runoff hydrographs. As these events subsided they were followed by a decrease in bedload until the next sediment input. This can be seen by comparing Figures 4-5 and 6-7.

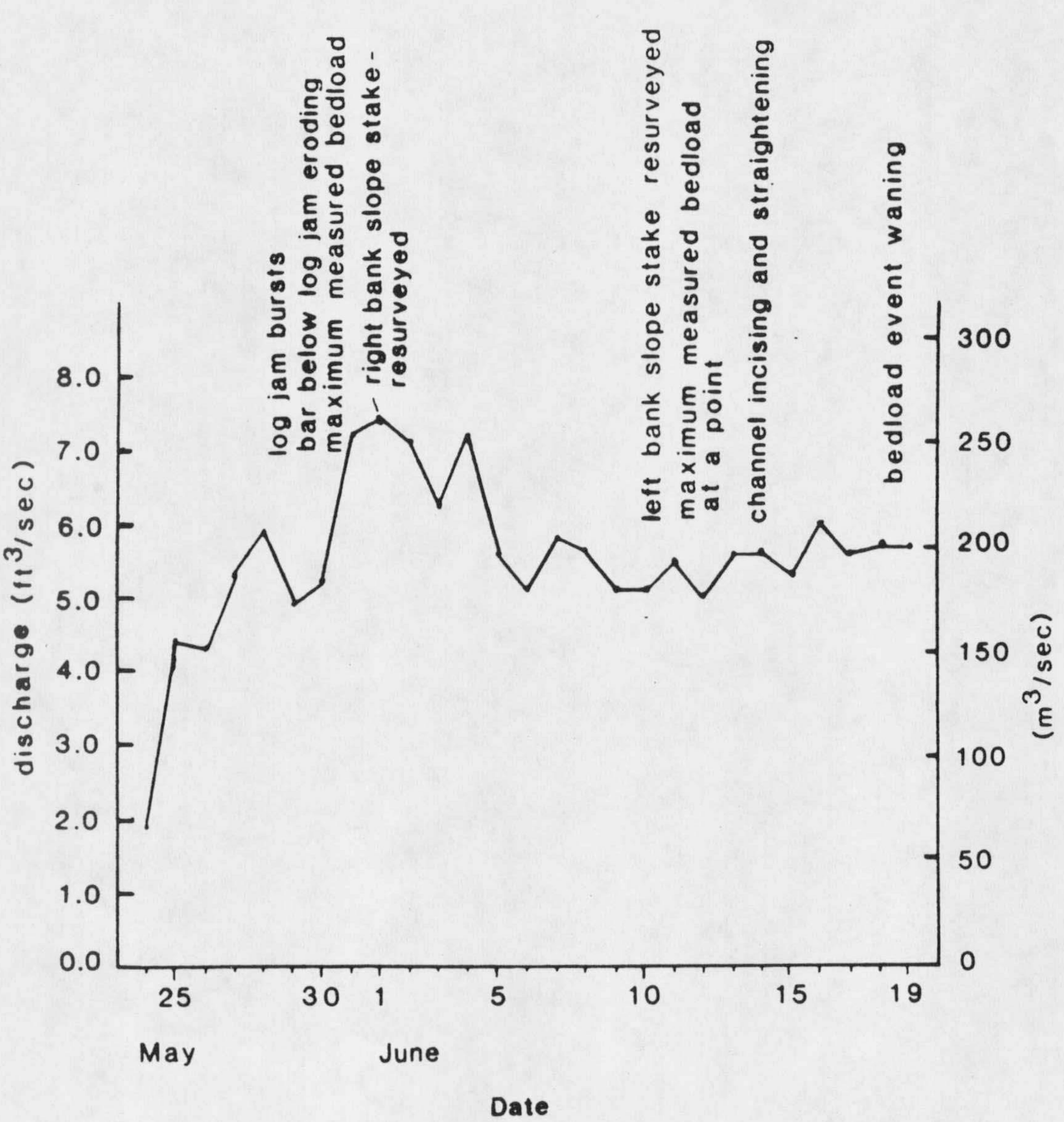

Figure 6. 1983 hydrograph during bedload event.

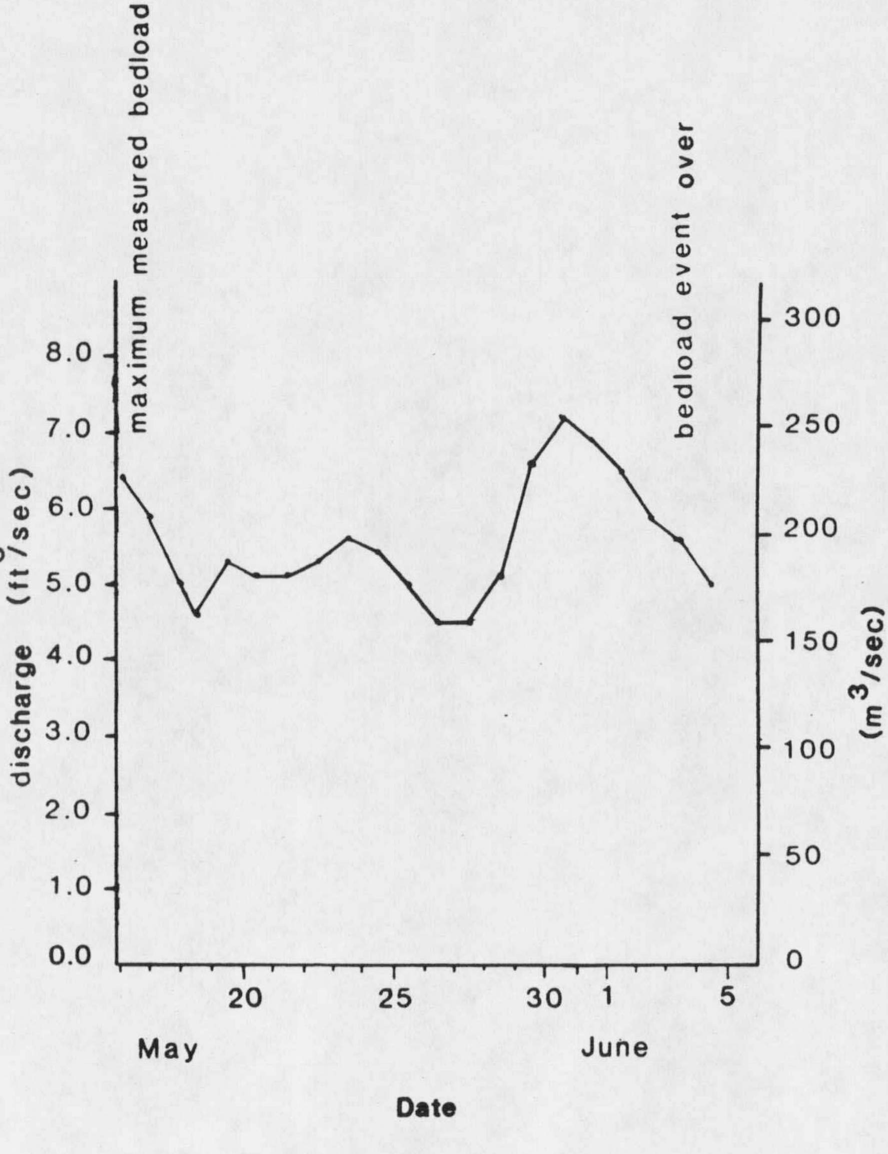

Figure 7. 1984 hydrograph during bedload event.

Much of the bedload transport observed was related to release of channel storage. On 28 May 1983 the author and two field assistants were completing installation of the slope survey lines on the study reach of Squaw Creek. At 18:45 we were finishing supper at our tent camp about 70 m from the bridge. It was evening, the gathering darkness was closing in around our camp. All of a sudden, we heard a tremendous, "BOOM", as if a stick of dynamite had exploded at the stream. Huge amounts of debris were then observed floating down the creek. It became clear that a log jam, which had been emplaced just upstream of the study reach at least two years earlier, had just burst.

We hurriedly completed installation and began sampling through the night. A reconnaissance of the reach revealed a tremendous bedload event was taking place. Along the right bank, directly across from where the jam had been, fist-sized and larger cobbles were bouncing a foot above the water surface. Having never witnessed a catastrophic bedload event on Squaw Creek, no one knew how long it would continue at this intensity.

While relating the events of the previous evening to another student the following morning, a row of cobbles was observed protruding above the water surface upstream (Figure 16). Yet the staff gauge showed that stage was rising - aggradation of cobble-sized material was taking place before our eyes!

The dispersal of this log jam triggered the most significant bedload transport event observed in three years of study. Changes in channel morphology were recorded by plane table mapping (Figures 8, 9, and 10) and aerial (Figures 11 and 12) and ground photo survey (Figures 13 and 14). The log jam acted as both a temporary sediment storage area and local base level. Its dispersal released loose sediment into the sediment deficient stream. Much of this sediment was deposited in the right channel. After this sediment deposition the stream shifted its course and incised its channel as it graded to a new base level (Figure 14). This incision resulted in the breaking of the armor layer and release of additional sediment. The dispersal of this log jam had greater effect on bedload transport at Squaw Creek than any other factor studied.

The bedforms identified at Squaw Creek were dunes and cluster bedforms. Bedforms caused spatial and temporal variations in bedload, affecting both predictions and measurements.

The bedload event at Squaw Creek lasted about 21 days in 1983 and 1984 with great variability in particle size and mass of material in transport. Total measured bedload, as presented in Table 2 above, was 727 tons in 1983 and 522 tons in 1984. Bedload moved during this period both as continuous, long duration events and as sporadic, discontinuous bursts.

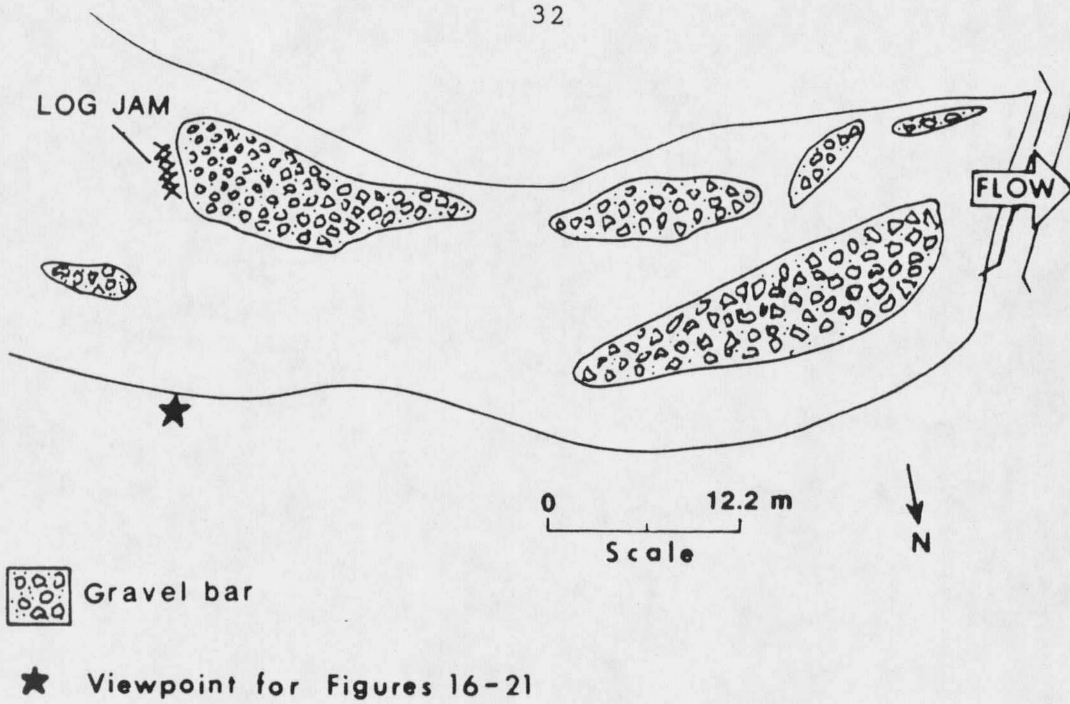

Figure 8. Study reach prior to dispersal of log jam (prior to 28 May 1983).

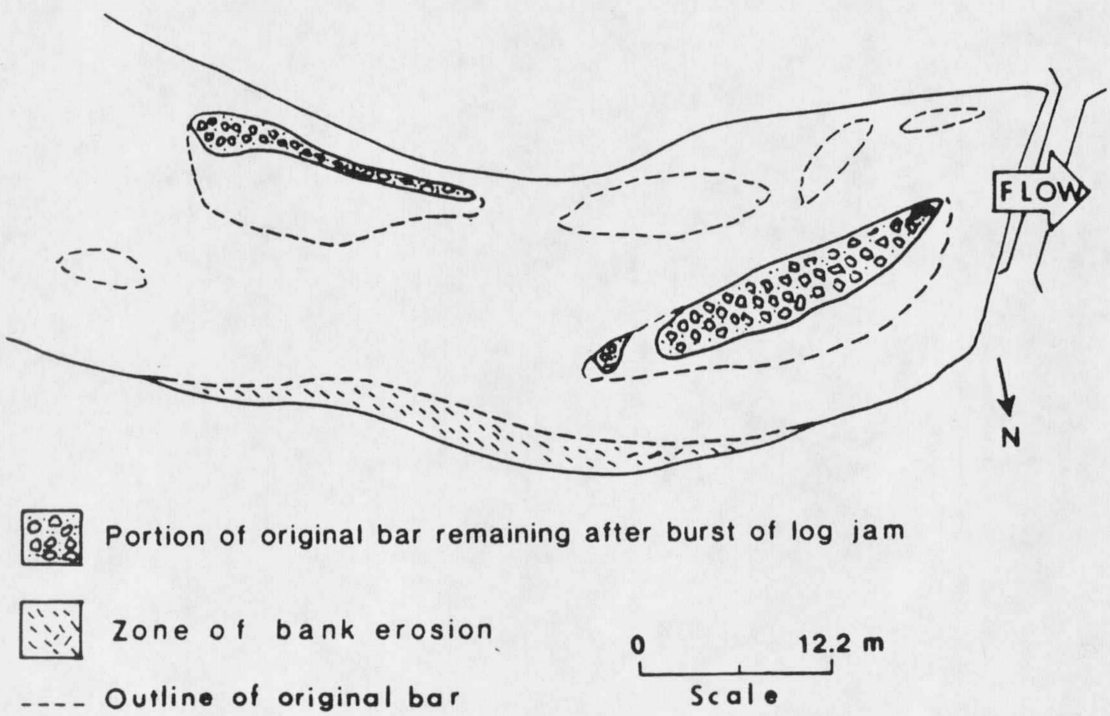

Figure 9. Study reach after dispersal of log jam and prior to channel incision (prior to 5 June 1983).

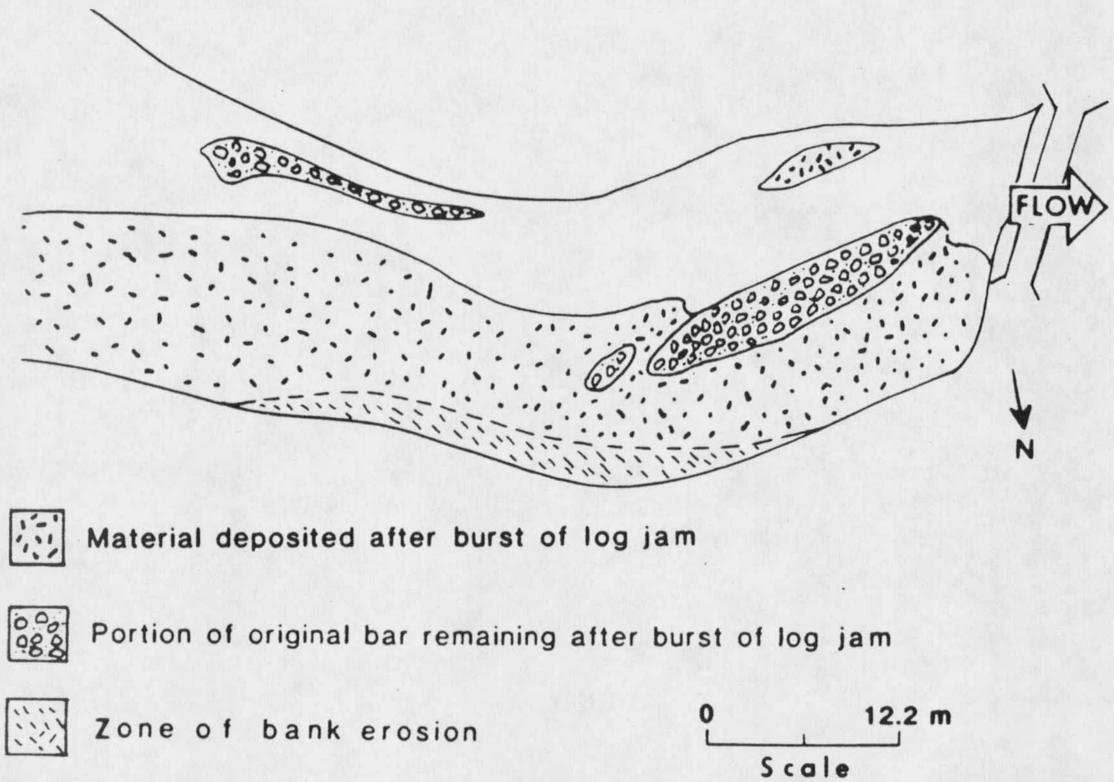

Figure 10. Study reach after deposition of new bars, shift of flow to left bank and channel incision (after 5 June 1983). All legend material same as Figure 9 unless otherwise noted.

Figure 11. Aerial photo of study reach prior to 28 May, 1983.

Figure 12. Aerial photo of study reach after 19 June, 1983.

Figure 13. View looking upstream prior to 28 May, 1983 showing flow along right bank.

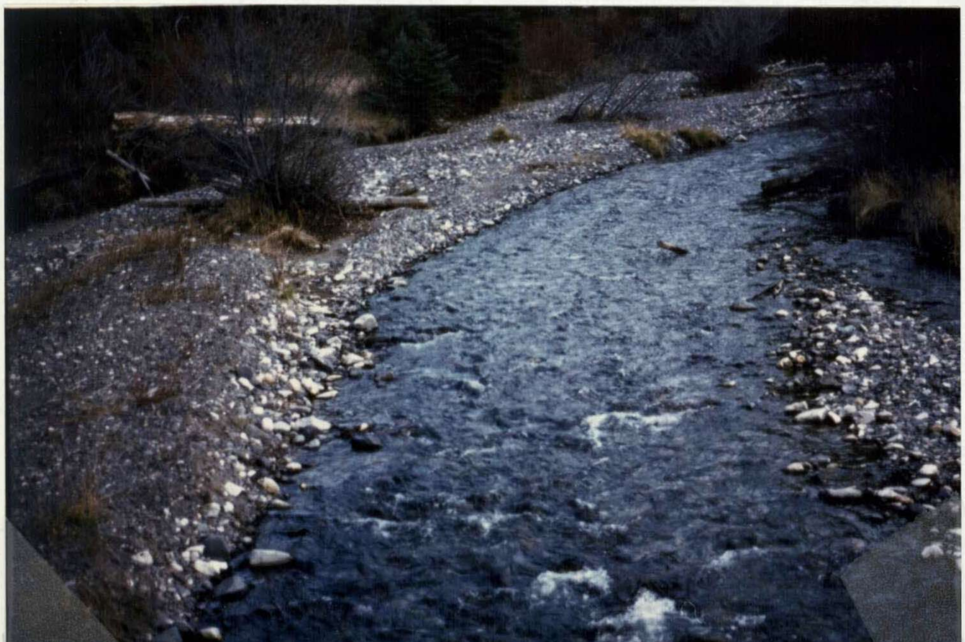

Figure 14. View looking upstream after 19 June, 1983 showing deposition along right bank and channel incision.

CHAPTER 4

DISCUSSION

Introduction

All three of the formulas tested predicted much more bedload transport in Squaw Creek than was measured (Table 2). The Schoklitsch (1934) formula prediction was the closest to measured bedload, being two orders of magnitude high. The stream power and Meyer-Peter and Müller formulas both predicted quantities 196% higher than Schoklitsch, on the average, for 1983 and averaged 280% higher in 1984. Similar results have been found by Ergenzinger (personal communication) in other high gradient mountain streams. Stall, Rupani, and Kandaway (1958) checked three formulas on a lower gradient stream with smaller particle size and also found the Schoklitsch (1934) formula the best at 31% high. They found the Einstein (1950) formula 225% high and the Duboys (1879) formula 776% high.

The overprediction of the formulas in this study can be considered in two parts - measurement error, and inability of the formulas to account for several important factors: spatial variation in bedload transport; variations in sediment supply and storage; and temporal variations in bedload transport.

Overprediction Due to Error

Measurement Error

The first of these sources of error (measurement) occurs both in measurement of the parameters used in the predictive formulas and in the sampling done to quantify bedload. First consider the error in measurement of the formula parameters.

Error in Slope Measurement. The slope measurement technique used provided very consistent results. Measurements made on a dry channel give an indication of the accuracy and consistency of the technique. Six measurements at one point on the upstream datum line taken over a 14-day period vary by less than 1mm or 0.2%. Measurements made at the water surface (see Figure 4) in flowing water were more difficult due to turbulence. Even allowing for 10 times the error of dry measurement, error is still less than 5%.

These measurements do not lend themselves well to statistical analysis because each measurement is at a different discharge and, therefore, at a different depth. If measurements were taken at the same discharge, the standard deviation could be determined for each measurement. This was not done because of time considerations - the number of parameters which were being measured simultaneously allowed very little time for measurement replication to obtain statistical populations.

An additional source of error in the slope measurements was introduced in 1983 when the catastrophic dispersal of an upstream log jam twice washed out upstream datum line stakes. Fortunately, each time this occurred one of the pair of stakes remained in its original position allowing the replacement stake to be referenced to it. The datum line was releveled using a Brunton hand-transit during the field season. At the end of the season the datum line was resurveyed level by plane table and adjustments were made to the data based upon this more accurate survey. Although great care was exercised each time in relocating the datum line, it is probable that there was some deviation introduced. For this reason the 1983 slope data is less certain. The 1984 data was not subject to this error.

Error in Water Density Measurement. Variation in water density was measured to determine if it significantly affected stream power on Squaw Creek. It was thought that the forest litter, algae, and fine sediments which had accumulated since the previous flood event, combined with water temperature effects, might increase the effective specific gravity of the water in the first flood of the water year. If so, the stream power might be affected by this density variation.

To determine the effective specific gravity, suspended load and water temperature were measured simultaneous to the collection of data on the other study parameters. Water density was then calculated as the mass of a unit volume of water at the measured water temperature plus the mass of the suspended load, this quantity was then divided by a unit volume of water.

Water density was found to vary about 0.01% during Squaw Creek's bedload transport season, thus not significantly affecting stream power. Density differences were also discounted as a significant factor in bedload events by Nanson (1974), working on a stream similar to Squaw Creek. If suspended sediment sampling and analysis and temperature measurement were off by a factor of 100, error would still be less than 5%. A 5% variation in water density would change stream power (ω) by only 0.5%, an insignificant amount. Since water density was found to vary negligibly, the remaining functional parameter of stream power is discharge.

Error in Discharge Measurement. One possible source of error in discharge measurement was the method of stream velocity measurement. The study discharge data was obtained from the catwalk mounted immediately upstream of the bridge. Here the flow was constrained on either bank by the bridge abutments and on the bed by the log upon which the magnetic detectors were mounted. There was some concern as to whether this location would yield statistically comparable discharge measurements as compared to the U.S.F.S. site, which was downstream of the bridge across the natural channel. Two stage/discharge rating curves were compared with like data, obtained by the U.S.F.S., for the same streamflows of Squaw Creek. The two pairs of data were compared using the U.S.F.S. regression RATER computer program. The data were found to have r^2 values of 0.996 for 1983 and 0.987 for 1984. Discharge measurement at the bridge, from the catwalk, was not influenced by the location at which the measurement was taken. This indicates that, where possible, discharge can be measured without the inconvenience and danger of wading the stream. Discharge measurement, having been shown to be accurate, was assigned a typical measurement error of 5%, a realistic value for measurements shown to possess a high degree of accuracy. The effect on stream power, of the probable error in discharge, density, and slope measurements can be determined.

Table 4 shows the percentage change in bedload predictions by each formula when error in the variables has been introduced. One variable is at the maximum probable error value used in this study and the other variables are held constant. The values used to compute the tables are from data measured 01:41, 28 May 1983 on Squaw Creek. Also shown is the worst possible case, when all the variables in the formula are at their maximum error value. The Schoklitsch 1934 formula prediction is least affected by this error as can be seen in Table 4, being ±16% in 1983 and ±8% in 1984. The most complex formula, the MPM, was affected the most by this possible error yielding values ±52% in 1983 and ±31% in 1984. This amount of deviation, while great, does not approach the two orders of magnitude difference between the formulas' predictions and sampled bedload. The difference between the predicted and measured values cannot be accounted for by measurement error alone.

Error in Bedload Sampling. Sampler error did affect both formula predictions and sampled bedload rate. This was not due to the Helley-Smith sampler design, but rather the sampling efficiency of the 76.2 mm nozzle in Squaw Creek. Emmett (1980) found sampler efficiency to be near 100% when median particle diameter was 1/5 nozzle size. This means the sampler used was 100% efficient when median particle diameter was 16 mm or less. It was possible to check sampler efficiency on Squaw Creek with a high degree of confidence.

In 1983 the author was fortunate enough to witness and record a catastrophic bedload event. During this event the hand-held Helley-Smith sampler was used to sample the bedload as new channel bars were forming. Cumulative grain size distributions were computer plotted for 42 in-channel Helley-Smith samples and 8 new channel bar samples. The curves assume a variety of shapes depending on the bedload transport event being sampled. Figure 15 shows three of the curves. The curves from the Helley-Smith channel samples taken while the bars were forming and those from the newly formed bars are nearly identical, as can be seen on the two curves to the left in Figure 15. This characteristic shape of the grain size distribution curves is a "signature" identifying the two samples as having been in transport during the same bedload event. The 18 April 1984 plot is a sieve analysis of a sample taken from a channel bar deposited during the 28 May, 1983 bedload event. The shape of the curves or "signature" of the two samples, 18:28, 28 May, 1983 and New bar (Sample 3, APPENDIX D) is unmistakable as compared to the other curve representing a sample taken earlier the same day prior to this bedload transport event. Note, however, that the 18:28, 28 May curve has slightly less coarse material and slightly more fine material than the curve from New Bar #3, which was being deposited during this event. This is exactly what one would expect if the sampler nozzle were too small. This interpretation is supported by the fact that in the two years of sampling the nozzle would often be completely blocked by a single large cobble wedged into the orifice. Alternatively it could be held that the bedload being sampled was finer than that being deposited. Because

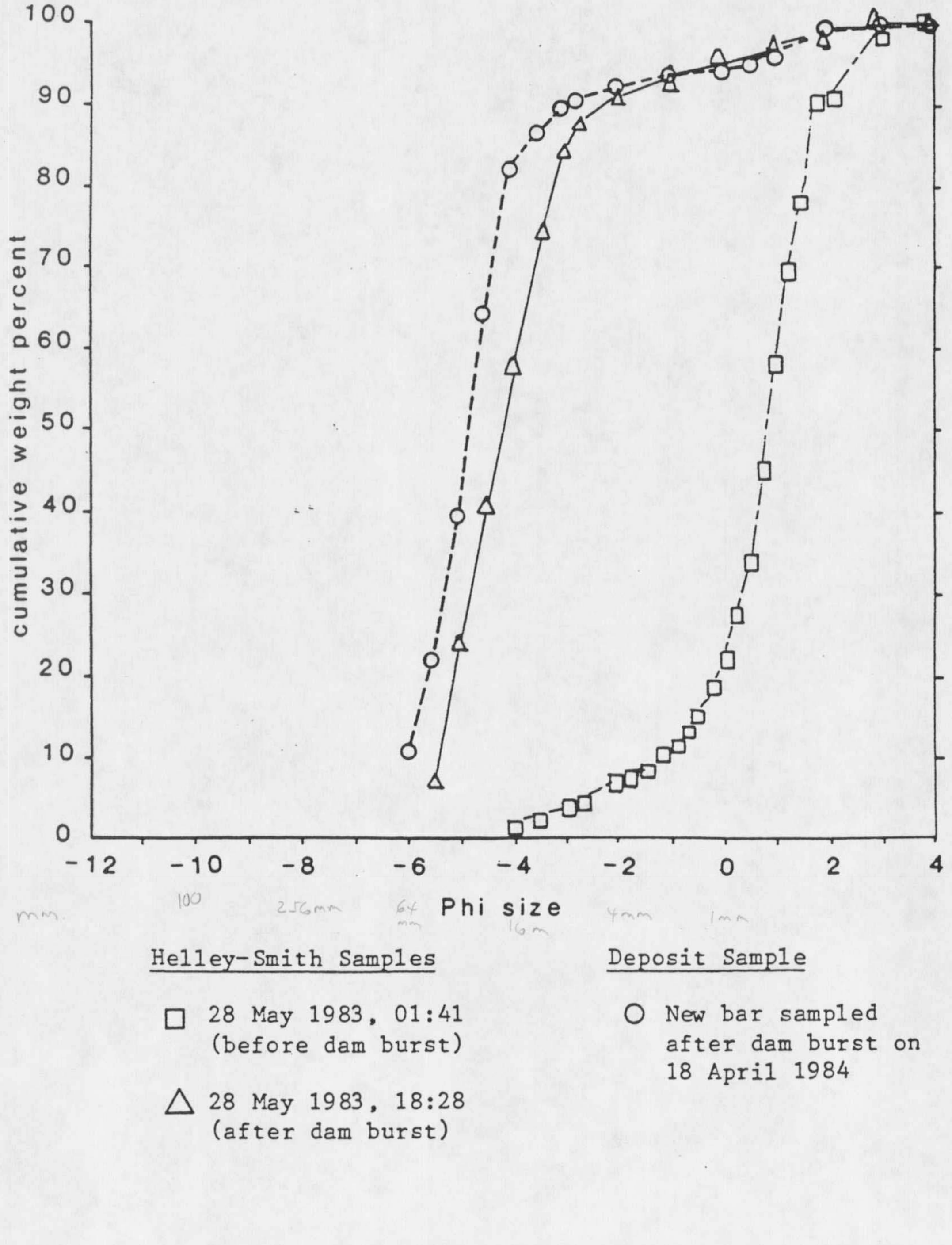

Figure 15. Cumulative grain size distribution for three bedload samples.

the Helley-Smith has been shown to function near 100% efficiency when sampler size is correctly matched to bedload (Emmett, 1980) and because the nozzle was often blocked by a single cobble, the interpretation that the sampler was too small and so did not sample all the material in transport is believed correct.

The samples taken from the gravel bar after the event had an average median particle size, or d_{50} of 43 mm, much larger than the 16 mm size necessary for 100% sampler efficiency. Appendix D contains additional sieve data. The data in Figure 15 are representative of the general size and distribution of the bed material. This 30% difference between actual bedload d_{50}, as obtained from the freshly deposited bar gravel after the event, and sampled d_{50} has a great effect on both the formula's predictions and sampled bedload. If the sampler is inefficient, then the total measured transport rate will be smaller than it should be. If the d_{50} obtained from the sampler is too small, then the Schoklitsch formula will predict too much transport and the Meyer-Peter and Müller formula will predict too little transport. Table 4 shows how the sampler bias of 30% increases the Schoklitsch formula error and decreases the MPM error. This bias is always a negative bias, that is, the 76.2 mm Helley-Smith samples are always 30% smaller than actual bedload on Squaw Creek. Compensating for this sampler error shifts the predictions by formulas with grain size parameters. Measured bedload quantity, when adjusted for this 30% sampler bias, increases. The sampler bias affected bedload measurements and bedload predictions by the Schoklitsch and MPM formulas.

Effect of Measurement Error on Formula Predictions. When applied to both the formulas and sampled bedload, these corrections account for one order of magnitude in discrepancy between predicted bedload and measured bedload, as can be seen from the new k-values in Table 5. Column three of Table 5 shows the range of possible predicted bedload transport calculated by adding and subtracting the worst possible per cent error from Table 4 to or from the predicted bedload values in Table 2. The fourth column of Table 5 shows the increase in mass of measured bedload resulting from a 30% increase in particle diameter. This value was estimated considering the particle to be spherical in shape. Although diameter increased by a factor of 0.3 (30%), volume increased by a factor of 3 (300%) because volume is calculated by raising the radius to the third power. Mass is calculated as the product of volume and density. Since average particle density is constant (2.94 g/cm^3 on the study reach), mass increases by the factor of 3 (300%) due to the 30% increase in particle diameter. Measured bedload values are subject to analytic error as well as this sampler bias.

Column five adds a 10% analysis error to the 30% sampler bias. A 10% analysis error was chosen to represent the worst possible case. These values represent the maximum probable error in measured bedload obtained with the 76.2 mm hand-held Helley-Smith sampler used in the study.

The new k-values in the sixth column of Table 5 are calculated by dividing the measured bedload values adjusted to maximum probable error (column five) by the predicted bedload from the low end of the error range in column three. These values, reflecting the maximum probable error due to measurement error and sampler error, vary one order of magnitude from the k-values in Table 2.

Table 5. Range of possible predicted bedload based on probable errors.

		Range of possible predicted bedload (metric tons dry)	Bedload when 30% H-S bias is accounted for (metric tons dry)	Bedload when 30% H-S bias + 10% analysis error is accounted for (metric tons dry)	k-values adjusted for 30% H-S bias and 10% analysis error
Stream	1983 b_ω	207,418 - 280,625	3323	3656	1.8×10^{-2}
power	1984 b_ω	175,702 - 214,747	2834	2622	1.5×10^{-2}
Schoklitsch	1983 G_1	57,376* - 215,843	3323	3656	6.4×10^{-2}
	1984 G_1	32,403* - 200,817	2384	2622	3.6×10^{-2}
MPM	1983 G''_1	230,892 - 353,644	3323	3656	1.6×10^{-2}
MPM	1984 G''_1	166,663 - 178,395	2384	2622	1.6×10^{-2}

*More likely variation.

Helley-Smith samples taken on the Clearwater River (Bagnold, 1977) in 1974 with a 152.4 mm sampler were also one order of magnitude greater than those taken in 1972 with a 76.2 mm sampler.

Measurement error and sampler error can explain one order of magnitude of the formulas' overprediction. The remaining order of magnitude overprediction must be attributable to factors not considered in the formulas.

Overprediction Due to Formula Inadequacies

Spatial Variation

The model implied in many bedload formulas is that of particles at rest on the streambed until stream power reaches a minimum value (threshold) necessary to entrain them. When such a stream power is attained they are entrained, smaller sizes first, progressively larger, until, at some stream power, the entire bed is in motion in a kind of "moving carpet" (Duboys, 1879; Shields, 1936; Einstein, 1950). Such behavior has been observed in flumes with equal diameter spheres and sand size particles and may also be correct for sandbed streams.

Some workers acknowledge that instream flow is not steady, but fluctuates and have tried to duplicate these conditions in flumes. Griffiths and Sutherland (1977) suggest steady flow bedload formulas could work if adjusted for these peaks and sediment supply conditions. Working with particle sizes as large as 7 and 25 mm Yalin (1963) found that fluctuations in velocity were responsible for entrainment and that "critical tractive force is non-existent" (1963, p. 223).

In Squaw Creek bedload was not observed to be spatially continuous. Nanson (1974), working in a small, steep mountain stream very similar to Squaw Creek, found bedload consistently greatest at the left bank and center of the stream. Using pressure sensitive devices mounted in the streambed, Brayshaw, Frostick and Reid (1983) also found bedload did not occur evenly across the width of the bed. Bagnold (1977) recognized that channel shape, channel cross section, and diverging and converging flow are not constant in natural rivers, so ideas based on flume observations are "not necessarily applicable to rivers" (1977, p. 305). He suggested that "streams of solids wander at random laterally over the bed" (1977, p. 307).

At Squaw Creek bedload was consistently greatest in early 1983 in a zone 1.3 m wide and centered 5.8 m from the left bank. As an example of this, in one sample traverse eight 30-second samples had filled only about 10 cm of the Helley-Smith sample bag. When the point 5.8 m from the left bank was reached the remainder of the bag and the entire sampler nozzle completely filled in 30 seconds.

As the right channel upstream of the bridge began to fill in, about 5 June 1983, bedload shifted towards a point 3.7 m from the left bank where the greatest volume continued to flow in 1984 and 1985. Custer and others (1987) also show that bedload is not laterally continuous across the stream, but is confined largely to this point.

If then, bedload is not laterally continuous across the total stream width, bedload predictions based on multiplying unit stream power by total stream width will be in error. They will overpredict by the ratio of total width to actual bedload zone. At Squaw Creek only about 83% of the entire stream width is actively involved in sediment transport as bedload. This value was determined by observation of quantity of bedload obtained at marked 0.3 m intervals on the catwalk across the stream width during 1983 and 1984. Multiplying predicted bedload transport rates $\left[\frac{kg}{m\text{-}s}\right]$ by total width will overpredict by about 17% on Squaw Creek. Leopold and Emmett also used only part of the stream width in their East Fork River study (1976) recognizing that only a portion of the stream width is involved in bedload transport.

Variations in Sediment Supply and Storage

Sediment supply and storage will also affect predictions of sediment yield based on the formulas. If rate of sediment supply or release from storage is less than transport rate, sampled bedload will be less than predicted. Sediment can be supplied to high mountain streams such as Squaw Creek from extra-channel sources including landslides, debris flows, avalanches and streambank failure. Sediment can be stored within the channel by bed armor, pool storage, log jams and bedforms. The effect of extra-channel sediment supply on bedload transport predictions on Squaw Creek will be discussed first.

Landslides, Debris Flows, Avalanches, Streambank Failure. Workers in drainage basins very similar to Squaw Creek have noted that sediment production in these basins occurs at limited sites by landslides, debris flows and avalanches (Griffiths, 1980), mudflows (McPherson, 1970) and streambank failure (Griffiths, 1980; Laronne and Carson, 1976). The geologic map of the Squaw Creek basin (McMannis and Chadwick, 1964) shows five Quaternary landslide units which are cut by Squaw Creek or its tributary streams. Two large avalanche chutes on Garnet Mountain terminate their runout zones abruptly at Squaw Creek. A field check of these sediment supply sites shows that the streams have done most of their work moving the new material and adjusting their courses prior to the period of this study. Load from extra-channel sources was introduced into Squaw Creek during the study primarily by bank failure. The riparian zone is well established along Squaw Creek contributing to bank stability. Thus the extra channel sediment supply rate into Squaw Creek may be less than the potential transport rate accounting for some of the apparent overprediction of the formulas. It should be noted that the formulas overpredicted by similar amounts, as can be seen by the k factors in Table 2, in both 1983 when the log jam burst and in 1984 when no such event occurred on the study reach. This shows that while the bursting of the log jam was an important event, the amount of sediment stored behind the jam was not great enough to compensate for the lack of steady extra-channel sediment supply and bring measured transport rate up to the predicted levels. Perhaps the greater significance of the log jam burst is that it demonstrates a mechanism by which a sediment deficient stream can initiate the break up of bed armor and the release of sediment stored there.

Since the supply of extra-channel sediment load to Squaw Creek appears to be limited, the bedload which does move must be stored from event to event within the stream channel. At Squaw Creek several intra-channel storage areas can be identified: the bed armor, pools and log jams, and bedforms.

Bed Armor. Other workers in gravel bed streams have noted that bed armor holds sediment beyond calculated threshold values of stream power (Yalin, 1972; Milhous and Klingeman, 1973; LaRonne and Carson, 1976; Parker and others, 1982; Bridge and Jarvis, 1982; Griffiths, 1980). These researchers are in agreement that when the pavement is in place, bedload is governed by sediment availability from other sources. Parker and others, (1982) have found that the coarse surface pavement has typically 1.5 to 3 times the mean particle size of the subpavement. They have found the subpavement d_{50} to be characteristic of most of the bedload the stream transports.

This relationship is seen at Squaw Creek where the bed armor has a d_{50} value of 94 mm, versus the subpavement value of 43 mm, a ratio of 2.2:1. Bed armoring can account for predicted values of bedload at least one order of magnitude above measured values (Milhous and Klingeman, 1973; Parker and others, 1982). This effect was demonstrated when painted stones thrown into a stream moved before the same size material in the bed armor in an experiment performed by LaRonne and Carson (1976). Once the armor layer is broken bedload is again governed by hydraulics. Milhous and Klingeman (1973) attributed the difference in discharge on the rising and falling limbs of the hydrograph necessary to attain a given bedload to these armor layer effects. Nanson (1974) discounted this armor layer effect because he observed less bedload during post-peak discharges.

To determine if such an armor layer effect was present on Squaw Creek an analysis of bed slope, predicted bedload, stream power (ω) versus measured bedload, and field observations was undertaken. If such an armor layer effect was present, stream power and predicted bedload should be very high compared to measured bedload until the armor was broken, at which time bedload should occur at much lower values of stream power. When the armor breaks, the sediment deficient stream should begin to incise its channel. Since channel erosion is headward, the effect on a reach scale would be to lower bed slope. The bed should change from a hard, cohesive pavement capable of supporting a persons weight while wading, to a soft, non-cohesive mush like a freshly graveled driveway.

In making the slope measurements, the stream was traversed. Field notes show observation of the bed being loose twice. On 28 May 1983 a soft bottom was noted 6.4 to 7.0 m from the left bank. This observation is attributable to sediment filling a scour hole that was at that location in 1982, 1983, and 1984 - not to the armor breaking. The second observation occurred on 5 June 1983 when the author sank into the bed approximately 5 cm with each step across the entire channel width. At this time the armor was broken, this observation being supported by the bed slope data.

The analysis of bed slope data for this period, 28 May - 5 June 1983 is shown in Table 6. The data is for two longitudinal bed slope profiles, 5-3 and 4-2 (see Appendix C). Note the distinct break in bed slope values between 5 June and 11 June 1983. There are two probable explanations for the change in slope. One is that the armor was broken at about 5 June 1983 and the slope changed in response to this event. A second has to do with the erosion and resetting of the upstream slope datum line stake.

As mentioned earlier, an upstream datum line stake was washed into the stream twice and on each occasion the line was resurveyed level. The possibility exists that error in releveling the datum line could account for the break in bed slope values. The first resetting of the line was on 31 May 1983 and the second in the period 5-11 June 1983. Each time the line was reset it was checked several times for level. Although, as mentioned earlier in the error discussion,

Table 6. Bed slope values for streamwise profiles 5-3 and 4-2. Note decrease in slope at about 5 June 1983 when stream incised and broke bed armor.

Date	Slope Profile 5-3 (%)		Slope Profile 4-2 (%)	
28 May 1983	2.91	$\sigma_{5-3} = 0.15$	4.52	$\sigma_{4-2} = 0.45$
29 May 1983	2.86	Range $2\sigma_{5-3}$	4.10	Range $2\sigma_{4-2}$
30 May 1983	2.70	= 2.45-3.05	3.98	= 2.90-4.70
30 May 1983	2.55		3.81	
31 May 1983	2.63		3.57	
5 June 1983	2.87		3.39	
11 June 1983	Not wadable		3.20	
12 June 1983	0.75	$\sigma_{5-3} = 0.06$	2.94	$\sigma_{4-2} = 0.13$
18 June 1983	0.89	Range $2\sigma_{5-3}$	2.79	Range $2\sigma_{4-2}$
19 June 1983	0.83	= 0.70-0.94	2.70	= 2.48-3.00
19 June 1983	0.76		2.65	
25 June 1983	0.86		2.62	

resetting the datum lines contributed to less certainty in the 1983 slope data, slope values from 30 May, 31 May and 5 June show no significant statistical variation (see Table 6).

Further confirmation that this change in bed slope is due to the stream breaking its channel armor and incising and not due to error in resetting the datum line can be found in Table 6. Note that the variation in slope profile 4-2 is -0.45% from 5 June to 12 June. From 12 June to the end of the study season point 4, the upstream datum point, was on a dry bar and measured the same elevation each day. The decrease in slope along profile 4-2 is due to aggradation at point 2. During the period 5 June to 12 June the variation in slope profile 5-3 is -2.12%, or nearly five times as great as at profile 4-2. This difference occurred when point 4 measurements could be used as a control and proved constant. Clearly the data supports that lowering of bed slope occurred along profile 5-3 around 5 June 1983.

Prior to 5 June 1983 the right channel completely filled with bedload, much of which had been stored behind a log jam. (When referring to bank and channel, the terms right and left are used here, in accordance with hydrologic convention, to mean right and left to an observer facing downstream.) The catastrophic dispersal of this log jam, which was described earlier and which triggered a major bedload event, will be described in more detail in a separate section. When the sediment stored by the log jam was moved and deposited in the right channel, Squaw Creek was again deficient in sediment. Discharge now shifted entirely to the left channel, that is, the stream straightened its course and began to incise and entrain bedload. The process just described was also recorded in a series of time lapse photographs (see Figures 16-21). Figures 16-18 photographically record the process which was represented earlier as plane table maps in Figures 8 and 9. Figures 19-21 record the process resulting in the channel configuration mapped in Figure 10. The process can be more clearly understood by comparing the photographs with the plane table maps. Note that the main process occurring in Figures 16-18 is aggradation of material along the right channel. This material was initially derived from storage behind the log jam and was supplemented by material from a zone of bank collapse and from upstream. Figures 19-21 show the entire flow forced to the left bank and the stream incising into the armor after the right channel has filled. This breaking of the armor, triggered by the log jam event, caused

Figure 16. 13:35, 29 May, 1983. Bar aggradation beginning. View from right bank toward log jam location. View point for photos in Figures 16-21 is identical. See Figure 8 for view point location.

Figure 17. Indefinite time between 18:40, 29 May and 11:26, 30 May, 1983. Bar aggradation continues with rising discharge.

Figure 18. 11:26, 30 May, 1983. Discharge is still rising. Aggradation is filling right channel.

Figure 19. 11:00, 11 June, 1983. Right channel filled. Discharge is waning and incision has begun.

Figure 20. 13:29, 12 June, 1983. Flow confined to left bank. Compare lower level of wetted gravel at stream's edge with higher level of new bar. New bar material is drying and appears lighter in color.

Figure 21. 14:15, 19 June, 1983. Bedload transport event has ended.

significant bedload to be released from instream storage from 5 June - 19 June 1983. This reaction of a stream to non-equilibrium transport conditions was observed by Griffiths and Sutherland (1977) working in a flume with d_{50} = 4 mm particles.

If this interpretation is correct, a graph of stream power versus measured bedload should show high stream power relative to measured bedload until the armor is broken, at which time bedload should increase relative to stream power. Comparison of a graph of predicted bedload transport rate versus time and a graph of measured bedload transport rate versus time confirms this interpretation (Figure 4). Initially, from 28 May - 29 May 1983, as stream power rises, measured bedload follows. This is due to the instantaneous release of stored sediment from the log jam. As material fills the right channel, from 29 May - 5 June 1983, stream power values remain high, but measured bedload drops as the armor remains intact and little new sediment is supplied. Then on 5 June, as the armor begins to break, measured bedload increases while stream power decreases, giving less discrepancy between stream power and measured bedload as expected.

Alternatively, the divergence of stream power from measured bedload could be explained in terms of a new wave of sediment supply arriving from upstream. Figure 4 does show what Nanson (1974) reported; less bedload after peak stream power, but this hypothesis does not explain the observed channel shift, measured incision, measured bed slope change and subjective judgment that the armor had become non-cohesive. Figure 5, for the 1984 runoff, also shows less bedload after peak stream power, but here measured bedload follows stream power through the entire runoff. The armor was not broken in the study reach in 1984 and bedload behaved as Nanson observed, perhaps offering an explanation for his observation.

In addition to armor, pools and log jams are a second category of instream sediment storage. The distinction is made between them because, although log jams form pools and retain sediment, they do not fill and empty by hydraulic control alone. The release of sediment stored by a log jam is also controlled by the structural integrity of the log jam.

Pool Storage. The pool-riffle sequence of a coarse-particle mountain stream is well known. There are 5-7 channel widths between successive riffles, water surface slope decreases with increasing discharge over the riffles and the riffles generally consist of coarser material than that which fills the pools (Dunne and Leopold, 1978).

The study reach at Squaw Creek measured 5.2 channel widths from riffle to riffle. Plots of water surface slope versus discharge over the study reach for the study periods of 1983 and 1984 show a decrease in slope with increasing discharge, consistent with riffle sequence hydraulics.

Pools tend to be scoured of their fine material during rising stage (Bagnold, 1977). After this sediment has moved through a reach, bedload drops markedly until another sediment input (Griffiths, 1980). This is the behavior observed on Squaw Creek. Comparison of data in Appendices A and D for the periods 22 - 30 May 1983 and 28 May - 2 June 1984 shows this behavior. During the rising limbs of each major flood event the proportion of fines relative to coarse increased. After 1-2 days this fine material was much less evident and total bedload also dropped, even though stream power remained high (see Figures 4 and 5), indicating little new sediment input and removal of sediment stored in pools within the channel.

Log Jams. A log jam both stores sediment and acts as a temporary local base level to which the stream grades. Although log jams are similar to pools in that they both store sediment, they should perhaps more properly be considered separately. This is because of their ability to effect instantaneous, catastrophic changes in stream power variables and sediment supply. That local channel gradient significantly affects particle mobility in gravel bed streams was also recognized by Laronne and Carson (1976). How the dispersal of a log jam caused an instantaneous change in local base level resulting in breaking of the armor, incision and release of intra-channel storage was discussed earlier in the section on intra-channel storage in bed armor. It should be noted that the log jam released the sediment that was stored in its pool and which contributed to blockage of the right channel seven days prior to the breaking of the armor. Log jams can thus produce combined effects on bedload transport which are not produced by pool storage. In three years of field research at Squaw Creek the largest, most significant bedload event observed by the author was triggered by the catastrophic dispersal of a log jam immediately upstream of the study reach. This event provides an excellent example of the significance of log jams in effecting variations in sediment supply and storage.

The significance of the log jam can be determined by calculating the bedload transport directly attributable to the changes triggered by its dispersal. The series of time-lapse photographs (Figures 16-21) was begun at the time of log jam dispersal to record the changes in channel morphology. Prior to the event the channel had been accurately mapped by plane table (Figure 6), and recorded on aerial and ground photographs. These records were used to determine the surface area of freshly deposited sediment by the cut and weigh method. Thickness of the fresh sediment was determined by stratigraphic relationships between new material and old bar and channel material (Figures 22-23). New material was easily identifiable by lack of fine grained matrix and by freshly washed particle surfaces typical of the Helley-Smith sediment transport samples. Having determined thickness and area of the new bar material it was a simple matter to calculate total volume of bedload deposited during this event, and from this and the average density of the sediment to determine mass of bedload.

For example, Figure 22 shows bar material aggrading in an arc from the bush at the upper left to the lower right. The dog in Figure 23 is standing near the right bank at about the point of the lower right corner of Figure 22, which was viewed from a different angle in Figure 20. All the bar material behind the dog was deposited in an eleven day period from 30 May 1983 to 11 June 1983. In Figure 23 the dog's front paws are about half way down the thickness of newly deposited material. The thickness of this newly deposited material was multiplied by the mapped surface area of the new bar to obtain the

Figure 22. Aggradation of bar along right bank during 1983 bedload event.

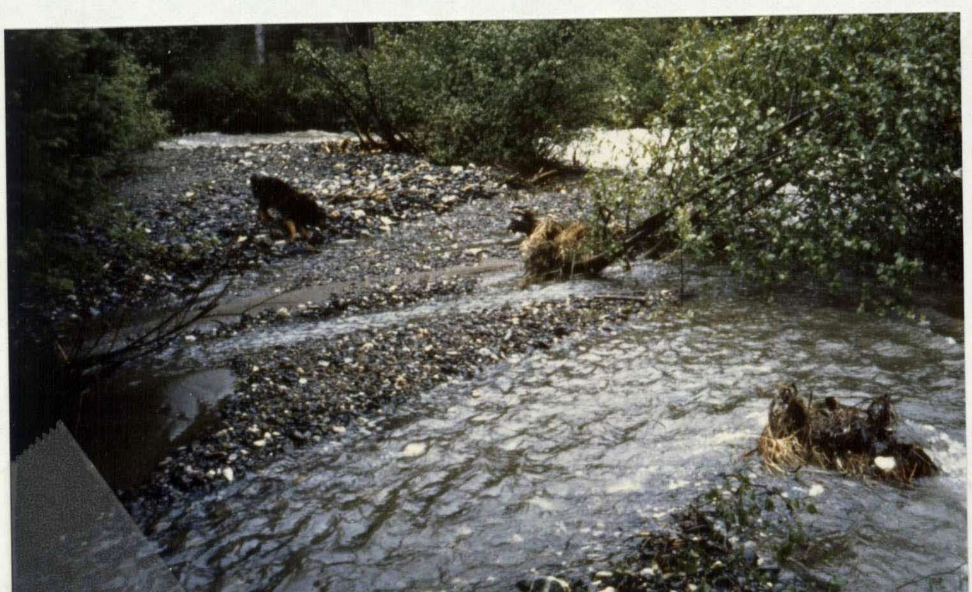

Figure 23. Bar material deposited during 1983 event over older channel material. View upstream along right bank.

volume of newly deposited sediment. New bar material was then sampled to obtain an estimate of its bulk density. The bar material was solidly packed in an armor and had an average particle density of 2.94 due to the preponderance of magnetite bearing andesite pebbles and cobbles. A bulk density of 2.1 was assumed to be realistic considering the nature of the material and deposit. This bulk density value was multiplied by the bar volume to yield the weight of newly deposited sediment in this bar.

This mass of freshly deposited material provides a known lower limit to bedload for the 1983 season. During the 7-day period from 28 May to 5 June 1983, 50 metric tons of coarse bedload was deposited in the study reach, by 19 June, an additional 23 metric tons added for a total of 73 metric tons during this 22-day period.

An examination of Figures 4 and 5 shows the highest measured transport rate during the 1983 and 1984 seasons occurred when the log jam burst. Peak bedload was measured then even though the stream power at burst (ω=13 kg/m-s), was exceeded for most of the remaining 21 days of bedload event in 1983 and exceeded or equaled for 2 1/2 days in 1984. Multiplying the graphic daily mean transport rate values from Figure 4 by the number of seconds in the day and the stream width yields the daily measured bedload. Assuming that only the initial three days of bedload, 28 - 30 May 1983, are directly attributable to the burst of the log jam, we can say that this event accounted for 221 metric tons of bedload. This is 30% of the total measured 1983 bedload. Greater stream power than that which transported this bedload was measured in 1983 and 1984, but without the log jam dispersal bedload transport was far less. The log jam was very significant in effecting variation in sediment supply and storage.

The ways that the log jam effected variations in sediment supply and storage may be summarized as follows. The catastrophic dispersal of the log jam simultaneously increased sediment supply and changed the local channel gradient of the study reach. The subsequent adjustment of bed slope to the new base level caused the armor to be broken about 5 June 1983 again increasing sediment load. These changes had more effect on bedload transport and channel morphology than any other factor studied. For these reasons it may be prudent to consider the presence or absence of log jams as a significant factor in bedload predictive formulas for high-gradient mountain streams.

Bedforms. Bedforms were identified as another source of variation in sediment supply and storage in Squaw Creek. The existence of bedforms in coarse-sediment alluvial channels has traditionally been denied. As late as 1982 Parker, Klingeman and McClean asserted that the low relative shear stresses in gravel bed streams meant that bedforms could not be created. Few will argue that the ripples and antidunes seen in fine-sediment alluvial channels are present in coarser grained channels.

A growing number of workers are identifying different bedforms characteristic of coarse-sediment alluvial channels which may have significant impact on bedload and predictive bedload formulas by causing variations in sediment supply and storage. Working in a flume with gravel size sediment (d_{50}=4 mm) Griffiths and Sutherland (1977) saw the formation of dunes up to 0.2 m in height and 1.25 m long. Six different bed structures were identified by Laronne and Carson (1976) in a stream with 90-150 mm mean particle size bar material and slopes varying locally from 0.021-0.086 - a stream very similar to Squaw Creek. Cluster bedforms were identified by Brayshaw, Frostick and Reid (1983). Are these bedforms present in Squaw Creek and, if so, how do they affect bedload there?

On Squaw Creek the previously described bed slope measurements recorded the passage of a "dune" type form or slug of bedload through the study reach following the dispersal of the log jam. The term slug might be preferred by some as the coarse particle size and scale of the bedform reduce the resolution of the bedform and may thus lead to confusion to those accustomed to visualizing sand size particle dune bedforms. The electromagnetic cobble detectors at Squaw Creek also recorded the passage of long-duration, continuous bedload (Custer and others, 1987). The term "dune" in quotations shall be used to distinguish its application here to a coarse bedload stream from the more familiar usage in sand-bed streams.

The passage of "dunes" of bedload affects both predictive measurements and quantitative sampling. Measurements of bed height or water depth taken on the crest of a "dune" will be anomalous, as will water surface slope measurements taken near a passing "dune" when water depth does not greatly exceed "dune" height (Dunne and Leopold, 1978). Bedload samples taken during the passage of a "dune" will be very high as compared to those taken in a trough. The passage of a "dune" may well explain the long duration, continuous bedload events recorded by the magnetic cobble detector.

As mentioned earlier, several other types of bedforms have been identified in coarse bedload streams. Bedforms similar to those identified by Laronne and Carson (1976) and Brayshaw, Frostick and Reid (1983) were observed in Squaw Creek, although these were not classified. Some of the bed structures identified by Laronne and Carson (1976), such as "tight structures" and "imbricate structures" function to pack bed particles more tightly together and thus increase armor layer effects, causing over-prediction by bedload formulas based on loose sediment. The cluster forms studied by Brayshaw, Frostick and Reid (1983) and the remainder of Laronne and Carson's (1976) structures are very similar. These cluster type structures have a storage function similar to armoring in that they retain sediment at stream powers greater than those at which bedload formulas predict movement. Reid and Frostick working at Turkey Brook with D_{50}=11 mm bedload, concluded that "... the most significant causes of this mismatch between bedload and water discharges include the effects of pebble clusters and other bed microforms on entrainment..." (1987, p. 15). Laronne and Carson (1976) state that threshold forces for the initiation of movement of particles in closed structures are definitely larger than those commonly assumed in most hydraulic formulae. They also report that cluster forms tend to retain the largest and finest grain sizes imparting the greatest mobility to medium-sized particles. Bedload formulas using a grain size parameter as typical of sediment in transport will therefore obtain different values using identical hydraulic parameters depending on the presence or absence of cluster forms.

Recent workers are in agreement that variation in in-channel sediment supply and storage has a variety of effects on bedload which can cause errors greater than one order of magnitude in bedload predictions based on the study formulas (Milhous and Klingeman, 1973), (Parker and others, 1982) and observations during this study suggest that many of these effects operate on bedload in Squaw Creek.

Temporal Variation

Another source of overprediction by predictive formulas is temporal variation. Formulas incorporating exponential values derived from plots of field data synthesize a variety of stream effects to produce an averaged value, but this averaged value will by its very nature cause overprediction on some streams and underprediction on others. The formulas make no provision for adjustment in stream to stream variation in timing and duration of bedload events. The "large and inconsistent variability in time and space" noted by (Laronne and Carson (1976, p. 71), of hydraulic parameters does have some identifiable features.

In coarse sediment load high mountain streams bedload is confined to a very short period in the water year coincident with the peak flood. McPherson's (1970) measurements in Two O'Clock Creek in the Rocky Mountains of Canada show that 65% of the bedload occurred in a seven day period and 79% in thirteen days. On Squaw Creek most bedload occurred in 23 days in 1983 and 19 days in 1984. If sampling to determine formula parameters is done outside this small and variable period, bedload predictions will be in error.

Bedload events also vary temporally in much smaller units of time than days. The electromagnetic detectors on Squaw Creek also demonstrated that bedload does not occur as a continuous moving carpet over the whole width of the stream, but rather as discontinuous bursts of short and long duration. Pulses of bedload were also observed by Reid and Frostick (1987) who suggested this discontinuous nature of coarse bedload transport may be a major difference between bedload transport processes in sand-bed and gravel-bed streams.

There is some controversy as to whether bedload is greater on the rising or falling limb of the hydrograph. It is important that this problem be considered when sampling bedload so that samples will reflect the true character of bedload throughout a stream's hydrograph. Milhous and Klingeman (1973) found bedload on Oak Creek to be greater on the falling limb. Nanson (1974) found less bedload on the falling limb, a condition he attributed to lower sediment availability later in the season. Working in a flume, Griffiths and Sutherland (1977) found no difference in bedload on the rising and falling limbs and that bedload was distributed symmetrically about the peak. It is likely that real differences within the reaches studied gave rise to these different observations.

The flume work by Griffiths and Sutherland (1977), was based on an unconsolidated bed. Bedload responded directly to hydraulics. It has been shown in the section on variations in sediment supply and storage that the release of sediment stored in an armored bed is not governed by simple hydraulics. It is important to realize that because an armor layer can cause these variations, it can also affect the timing of bedload events. Beyond the mere presence of an armor layer one must also consider the condition of this layer. The larger and more infrequent a flood event is, the more stable will be the resultant bed surface (Laronne and Carson, 1976). This effect of the armor explains the common observation that anomalously high stream powers are often necessary to produce the first major bedload event of a flood hydrograph. In order to obtain representative samples, sampling should be done considering whether or not the bed is consolidated, and if so, the period of time elapsed since the last event.

Cluster bedforms also may affect temporal variation in bedload as a result of their sediment storage function. These bedforms create lift forces between them as water flows over them causing particle entrainment at some discharge. The lift exerted on bed particles in a coarse alluvial channel was found to vary as a function of the spacing of the coarsest neighboring particles (Brayshaw, Frostick and Reid, 1983). As particles are removed the packing around the central, large particle of the cluster is removed and it also becomes entrained. When this cluster has been removed the spacing relationship between the adjacent clusters is changed, causing clusters to entrain in a sporadic manner, rather than a "domino" type sequence. Entrainment of bedload in this manner might explain some of the short duration discontinuous events recorded by the magnetic detector (Custer and others, 1987). Reid and Frostick (1987) also suggest that particle release is a function of particle position within the bedform and contributes to temporal variation in bedload transport.

Temporal variations also affect bedload sampling. Samples taken during the passage of a dune crest will be anomalously high in bedload as compared to those taken later in the trough between dunes. Samples taken after the dispersal of a log jam or injection of new sediment by bank collapse, debris flow, avalanche, will also be anomalous in quantity and sorting. Bagnold (1977) has found bedload to vary over 4 or 5 magnitudes and stream power "over a 100 fold range" (1977, p. 304). If anomalous particle size distributions result from these temporal variations, then problems will result in formulas requiring data on a specific particle size.

Workers on other streams have reported degrees of temporal variation in grain size distribution. On the Platte River in Nebraska, Eschner and Kircher (1984) found little variation in grain size distribution with discharge. Contrasting this is the findings of Bridge and Jarvis (1982) that streams adjust to variation in shear stress by changing grain size and not sediment transport rate. Milhous and Klingeman (1973) found that fines are released from the armor at extremely high flows, quite in contrast to the idea of particle size entrainment being directly proportional to discharge. Milhous and Klingeman (1973) also noted that when significant shear stress is reached for sediment entrainment, only 1/3 of the sizes are in motion. Parker, Klingeman, and McClean (1982) seem to contradict this idea when they state that once the armor is broken all sizes are of equal transportability. The differences in results may be attributed to the characteristics of the stream bed being discussed. It does seem that on most streams workers do find that grain size varies with time. This temporal variation of particle size was also observed at Squaw Creek.

At Squaw Creek the most dramatic example of this phenomena was in the hours preceding the burst of the log jam. In the two days preceding the burst, mean particle size was 2-4 mm. Abruptly, at 01:41 28 May, 1983, particle size dropped to 0.58 mm. One and one-half hours later mean particle size was up to 5mm and 16 hours after that, just two hours prior to the burst, d_{50} was up to 17 mm. In the space of 16.5 hours d_{50} had increased 34 times! Grain size also varies with time in some streams and therefore requires careful sampling if data is to be used in a predictive formula incorporating some grain size parameters.

CHAPTER 5

CONCLUSIONS

The formulas tested all overpredicted bedload transport on Squaw Creek. The Schoklitsch (1934) formula yielded predictions closest to measured values in 1983 and 1984, but still overpredicted bedload by two orders of magnitude. The stream power and Meyer-Peter and Müller (1948) formulas yielded very similar results for both years averaging 196% higher than the Schoklitsch prediction in 1983 and 280% higher than the Schoklitsch prediction in 1984. Error in parameter measurement and sampler bias could account for one order of magnitude of the over-prediction. This still leaves one order of magnitude overprediction by the formulas tested.

The remaining discrepancy between predicted bedload and measured bedload may be accounted for by inability of the formulas to account for variance in sediment supply, sediment storage and spatial and temporal variations in bedload transport which occurred at Squaw Creek and which may be characteristic of coarse-bedload high-gradient streams.

Squaw Creek was deficient in extra-channel sediment load during the period of the study and thus produced less bedload transport than the formulas which assume supply is not a limiting factor. Sediment stored under bed armor could not be released during most stream flows in the study period. Sediment stored in pools, log jams, and bedforms was not released in a uniform, continuous manner, but sporadically and not in direct response to discharge.

Bedload occurred over only 83% of the stream width accounting for 17% overprediction by formulas in which unit stream power is multiplied by total bed width to yield total bedload.

Bedload was not temporally constant once initiated. Bedload occurred during a very short period of the water year - 3 weeks. Sampling to determine formula parameters must be done throughout this short and variable period to yield accurate predictions. This temporal variation created a problem in the use of grain size data in predictive formulas. A bedload sample may represent the release of fines from a pool or log jam, the passage of a coarse wave of sediment, the dispersal of a cluster bedform, or a period of lapse in bedload, each of which will yield different particle size distribution data, altering predictions of formulas incorporating such data.

The catastrophic dispersal of a log jam had greater effect on bedload than any of the parameters used in the formulas. The log jam dispersal functioned as a trigger which caused instantaneous changes in the factors affecting bedload transport. This event accounted for 30% of the 1983 bedload. Even during this event the formulas overpredicted bedload transport on Squaw Creek.

The complex mathematical manipulations of the Meyer-Peter and Muller formula intended to increase predictive accuracy by accounting for form resistance, grain size effects, bed roughness, and critical tractive force did not improve accuracy as compared to the simplest theoretical expression, the stream power expression. Bedload predictive formulas of the form ω = abcqS, where a, b, and c represent empirically quantified coefficients for factors such as sediment supply and presence or absence of an armor layer, log jams, or bed forms, may yield better results for coarse bedload, high-gradient mountain streams.

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APPENDICES

APPENDIX A

DISCHARGE DATA

Table 7. Squaw Creek discharge and stage data for 1983 and 1984 bedload transport events.

Date	Time (hours)	Stage (ft)	Discharge, Q (ft^3/s)	(m^3/s)
22 May 1983	16:00	0.68	71	2.0
23 May 1983	00:00	0.68	71	2.0
	08:00	0.67	68	1.9
	16:00	0.75	86	2.4
24 May 1983	00:00	0.66	66	1.9
	08:00	0.66	66	1.9
	16:00	0.73	81	2.3
25 May 1983	00:00	1.00	154	4.4
	08:00	1.07	177	5.0
	16:00	1.18	216	6.1
26 May 1983	00:00	0.99	151	4.3
	08:00	0.96	142	4.0
	16:00	0.96	142	4.0
27 May 1983	00:00	1.11	191	5.3
	08:00	0.91	127	3.6
	16:00	1.06	174	4.9
28 May 1983	00:00	1.17	212	5.9
	08:00	0.91	127	3.6
	16:00	0.95	139	3.9
29 May 1983	00:00	1.06	174	4.9
	08:00	1.20	223	6.2
	16:00	1.12	194	5.4
30 May 1983	00:00	1.10	187	5.2
	08:00	1.23	235	6.6
	16:00	1.32	271	7.6
31 May 1983	00:00	1.29	258	7.2
	08:00	1.27	250	7.0
	16:00	1.25	242	6.8
01 June 1983	00:00	1.30	263	7.4
	08:00	1.15	205	5.7
	16:00	1.13	198	5.5

Table 7. Continued.

Date	Time (hours)	Stage (ft)	Discharge, Q (ft^3/s)	(m^3/s)
02 June 1983	00:00	1.28	254	7.1
	08:00	1.26	246	6.9
	16:00	1.24	240	6.7
03 June 1983	00:00	1.20	223	6.2
	08:00	1.29	258	7.2
	16:00	1.27	250	7.0
04 June 1983	00:00	1.29	258	7.2
	08:00	1.28	254	7.1
	16:00	1.24	240	6.7
05 June 1983	00:00	1.14	201	5.6
	08:00	1.13	198	5.5
	16:00	1.11	191	5.3
06 June 1983	00:00	1.09	184	5.1
	08:00	1.08	180	5.0
	16:00	1.08	180	5.0
07 June 1983	00:00	1.16	208	5.8
	08:00	1.15	205	5.7
	16:00	1.11	191	5.3
08 June 1983	00:00	1.14	201	5.6
	08:00	1.13	198	5.5
	16:00	1.13	198	5.5
09 June 1983	00:00	1.09	184	5.1
	08:00	0.94	136	3.8
	16:00	1.06	174	4.9
10 June 1983	00:00	1.09	184	5.1
	08:00	1.13	198	5.5
	16:00	1.09	184	5.1
11 June 1983	00:00	1.13	198	5.5
	08:00	1.17	212	5.9
	16:00	1.15E	205	5.7
12 June 1983	00:00	1.15E	175	4.9
	08:00	1.24E	175	4.9
	16:00	1.27	190	5.3

E = Estimated value

Table 7. Continued.

Date	Time (hours)	Stage (ft)	Discharge, Q (ft^3/s)	(m^3/s)
13 June 1983	00:00	1.30	200	5.6
	08:00	1.31	205	5.7
	16:00	1.30	200	5.6
14 June 1983	00:00	1.30	200	5.6
	08:00	1.27	191	5.3
	16:00	1.28	194	5.4
15 June 1983	00:00	1.27	190	5.3
	08:00	1.26	188	5.3
	16:00	1.26	188	5.3
16 June 1983	00:00	1.35	215	6.0
	08:00	1.31	205	5.7
	16:00	1.31	205	5.7
17 June 1983	00:00	1.30	200	5.6
	08:00	1.30	200	5.6
	16:00	1.31	205	5.7
18 June 1983	00:00	1.30	200	5.7
	08:00	1.29	195	5.5
	16:00	1.30	200	5.7
19 June 1983	00:00	1.30	200	5.7
	08:00	1.30	200	5.7
	16:00	1.28	192	5.4
16 May 1984	00:00	1.32	228	6.4
	08:00	1.35	241	6.7
	16:00	1.34	237	6.6
17 May 1984	00:00	1.28	212	5.9
	08:00	1.23	193	5.4
	16:00	1.19	178	5.0
18 May 1984	00:00	1.19	178	5.0
	08:00	1.16	168	4.7
	16:00	1.12	154	4.3
19 May 1984	00:00	1.15	164	4.6
	08:00	1.12	154	4.3
	16:00	1.10	148	4.1

Table 7. Continued.

Date	Time (hours)	Stage (ft)	Discharge, Q (ft^3/s)	(m^3/s)
20 May 1984	00:00	1.22	189	5.3
	08:00	1.21	186	5.2
	16:00	1.23	193	5.4
21 May 1984	00:00	1.20	182	5.1
	08:00	1.21	186	5.2
	16:00	1.19	178	5.0
22 May 1984	00:00	1.20	182	5.1
	08:00	1.19	178	5.0
	16:00	1.16	168	4.7
23 May 1984	00:00	1.22	189	5.3
	08:00	1.21	186	5.2
	16:00	1.21	186	5.2
24 May 1984	00:00	1.25	201	5.6
	08:00	1.25	201	5.6
	16:00	1.24	197	5.5
25 May 1984	00:00	1.23	193	5.4
	08:00	1.21	186	5.2
	16:00	1.19	178	5.0
26 May 1984	00:00	1.19	178	5.0
	08:00	1.17	171	4.8
	16:00	1.15	164	4.6
27 May 1984	00:00	1.14	161	4.5
	08:00	1.15	164	4.6
	16:00	1.13	158	4.4
28 May 1984	00:00	1.14	161	4.5
	08:00	1.12	154	4.3
	16:00	1.12	154	4.3
29 May 1984	00:00	1.20	182	5.1
	08:00	1.17	171	4.8
	16:00	1.16	168	4.7
30 May 1984	00:00	1.34	237	6.6
	08:00	1.32	228	6.4
	16:00	1.33	233	6.3

Table 7. Concluded.

Date	Time (hours)	Stage (ft)	Discharge, Q (ft^3/s)	Discharge, Q (m^3/s)
31 May 1984	00:00	1.39	258	7.2
	08:00	1.35	241	6.8
	16:00	1.40	263	7.6
01 June 1984	00:00	1.36	245	6.9
	08:00	1.36	245	6.9
	16:00	1.34	234	6.6
02 June 1984	00:00	1.33	233	6.5
	08:00	1.29	216	6.1
	16:00	1.28	212	5.9
03 June 1984	00:00	1.28	212	5.9
	08:00	1.25	201	5.6
	16:00	1.23	193	5.4
04 June 1984	00:00	1.25	201	5.6
	08:00	1.23	193	5.4
	16:00	1.21	186	5.2
05 June 1984	00:00	1.19	178	5.0
	08:00	1.20	182	5.1
	16:00	1.19	178	5.0

APPENDIX B

WATER DENSITY DATA

Table 8. Total suspended solids and water temperature data for 1983 and 1984 bedload transport events.

Date	Time (hours)	Total Suspended Solids (mg/1)	Water Temperature (°C)
22 May 1983	16:38	10.37	10.8
27 May 1983	12:00	115.69	5.0
28 May 1983	01:20	260.00	4.8
28 May 1983	15:00	286.04	4.6
28 May 1983	18:40	113.28	4.4
28 May 1983	22:00	680.24	4.5
29 May 1983	12:34	405.86	7.7
29 May 1983	21:40	699.86	6.0
30 May 1983	11:56	508.14	5.6
31 May 1983	21:58	167.15	5.8
05 June 1983	18:00	16.31	7.6
11 June 1983	11:17	105.62	6.0
12 June 1983	13:45	62.93	5.1
18 June 1983	20:57	22.52	7.3
19 June 1983	14:50	22.84	7.5
19 June 1983	16:44	10.87	7.5
25 June 1983	18:50	3.65	12.0
30 June 1983	18:07	338.65	--

Table 8. Concluded.

Date	Time (hours)	Total Suspended Solids (mg/l)	Water Temperature (°C)
16 May 1984	17:15	245.79	4.3
17 May 1984	20:00	87.30	5.5
19 May 1984	11:15	10.94	5.4
20 May 1984	10:30	53.42	5.0
22 May 1984	12:00	11.67	6.0
23 May 1984	15:00	12.57	6.5
27 May 1984	13:30	16.95	7.0
28 May 1984	11:50	19.37	7.0
29 May 1984	11:40	10.96	7.5
29 May 1984	23:00	205.90	6.0
30 May 1984	21:10	163.31	6.5
31 May 1984	23:34	265.96	5.0
01 June 1984	13:00	174.59	6.5
02 June 1984	12:00	100.59	6.0
02 June 1984	24:00	112.39	5.0
03 June 1984	21:40	42.60	6.0

APPENDIX C

SLOPE DATA

Table 9. Bedslope and water surface slope data for longitudinal profiles through study reach for 1983 and 1984.

Distances Between Slope Datum Lines

Profile	(ft)
1-1	129.4
2-1	124.8
3-1	122.8
4-2	123.1
K-3	123.8
5-3	122.0

Date (time)	Profile slope	Difference (y_2-y_1) in bed elevation (ft)	Difference (y_2-y_1) water surface elevation (ft)	Bed slope (%)	Water surface slope (%)
28 May 1983	4-2	5.56	2.18	4.52	1.77
(22:00)	5-3	3.55	1.84	2.91	1.51
29 May 1983	4-2	5.05	2.57	4.10	2.09
(13:50)	5-3	3.49	2.70	2.86	2.21
30 May 1983	4-2	4.90	2.16	3.98	1.75
(11:30)	5-3	3.30	2.55	2.70	2.09
(17:39)	4-2	4.69	1.97	3.81	1.60
	5-3	3.11	1.56	2.55	1.28
31 May 1983	1-1	4.35	4.07	3.36	3.15
(20:30)	1-2	3.83	3.60	3.07	2.88
	1-3	3.27	3.61	2.66	2.94
	4-2	4.40	2.41	3.57	1.96
	5-3	3.21	2.58	2.63	2.11
05 June 1983	1-1	3.48	2.20	2.68	1.70
(17:52)	1-2	4.29	2.31	3.44	1.85
	1-3	4.43	3.41	3.61	2.78
	4-2	4.17	3.37	3.39	2.74
	5-3	3.50	3.44	2.87	2.82
11 June 1983	1-1	3.42	1.76	2.64	1.36
(11:00)	1-2	3.56	2.08	2.85	1.67
	1-3	3.00	1.38	2.44	1.12
	4-2	3.94	2.28	3.20	1.85
	5-3	Not Available			1.85E

E = Estimated value

Table 9. Continued.

Date (time)	Profile slope	Difference (y_2-y_1) in bed elevation (ft)	Difference (y_2-y_1) water surface elevation (ft)	Bed slope (%)	Water surface slope (%)
12 June 1983	1-1	3.40	1.54	2.63	1.19
(13:30)	1-2	3.11	1.57	2.49	1.26
	1-3	2.68	1.24	2.18	1.01
	4-2	3.62	2.04	2.94	1.66
	5-3	0.92	1.60	0.75	1.31
18 June 1983	1-1	3.21		2.48	
(21:00)	1-2	2.92		2.37	
	1-3	2.68		2.18	
	4-2	3.43		2.79	
	5-3	1.08	1.97	0.89	1.61
19 June 1983	1-1	3.32		2.57	
(14:05)	1-2	2.81		2.25	
	1-3	2.75		2.24	
	4-2	3.32		2.70	
	5-3	1.01	1.79	0.83	1.47
(16:40)	1-1	3.41		2.64	
	1-2	2.75		2.20	
	1-3	2.67		2.17	
	4-2	3.26		2.65	
	5-3	0.93	1.79	0.76	1.47
25 June 1983	1-1	3.39		2.62	
(17:55)	1-2	2.71		2.17	
	1-3	2.69		2.19	
	4-2	3.22		2.62	
	5-3	1.05	1.86	0.86	1.52
27 May 1984	1-1	3.14	1.19	2.43	0.92
(13:30)	2-1	4.40	2.41	3.53	1.93
	3-1	3.90	1.91	3.18	1.56
	4-2	3.04	1.94	2.47	1.58
	5-3	2.00	2.00	1.64	1.64
28 May 1984	1-1	3.07	1.24	2.37	0.96
(12:00)	2-1	4.32	2.46	3.46	1.97
	3-1	3.76	1.90	3.06	1.55
	4-2	2.89	1.95	2.35	1.58
	5-3	1.93	1.95	1.58	1.60

Table 9. Continued.

Date (time)	Profile slope	Difference (y_2-y_1) in bed elevation (ft)	Difference (y_2-y_1) water surface elevation (ft)	Bed slope (%)	Water surface slope (%)
29 May 1984 (12:00)	1-1	2.80	1.28	2.16	0.99
	2-1	4.17	2.47	3.34	1.98
	3-1	3.68	1.98	3.00	1.61
	4-2	3.08	1.97	2.50	1.60
(23:45)	1-1	2.71	0.41	2.09	0.32
	2-1	4.01	1.53	3.21	1.23
	3-1	3.48	1.27	2.83	1.03
	4-2	3.00	1.92	2.44	1.56
	5-3	0.61	2.20	0.50	1.80
31 May 1984 (00:00)	1-1	2.92	0.42	2.26	0.32
	2-1	4.20	1.60	3.37	1.28
	3-1	3.70	1.41	3.01	1.15
	4-2	2.94	1.48	2.39	1.20
	K-3	2.34	1.18	1.89	1.53
01 June 1984 (13:00)	1-1	2.91	0.63	2.25	0.49
	2-1	4.02	1.66	3.22	1.33
	3-1	3.64	1.70	2.96	1.38
	4-2	3.13	2.05	2.54	1.67
02 June 1984 (12:15)	1-1	2.94	0.90	2.27	0.70
	2-1	4.04	1.94	3.24	1.55
	3-1	3.68	1.87	3.00	1.52
	4-2	2.61	0.83	2.12	0.67
	K-3	2.32	2.06	1.87	1.66
03 June 1984 (00:15)	1-1	2.86	0.78	2.21	0.60
	2-1	3.96	1.74	3.17	1.39
	3-1	4.34	1.76	3.53	1.43
	4-2	2.89	1.93	2.35	1.57
	K-3	2.66	2.18	2.15	1.76
(17:00)	1-1	2.92	0.99	2.26	0.77
	2-1	4.02	1.96	3.22	1.57
	3-1	3.78	1.91	3.08	1.56
	4-2	2.88	2.08	2.34	1.69
	K-3	2.53	2.17	2.04	1.75

Table 9. Concluded.

Date (time)	Profile slope	Difference (y_2-y_1) in bed elevation (ft)	Difference (y_2-y_1) water surface elevation (ft)	Bed slope (%)	Water surface slope (%)
*03 June 1984 (2150)	1-1			2.23	0.69
	2-1			3.28	1.58
	3-1			3.03	1.48
	4-2			2.43	1.67
	K-3			2.00	1.76
	5-3			2.02	1.77
05 June 1984 (14:30)	1-1			2.26	0.74
	2-1			3.23	1.59
	3-1			3.01	1.49
	4-2			2.40	1.62
	K-3			1.91	1.79
#12 June 1984 (20:05)	1-1			2.29	1.17
	2-1			3.33	2.07
	3-1			3.04	1.78
	4-2			2.48	1.86
	K-3			2.55	2.25
	5-3			2.22	1.78

*Water surface slope at 3-1 and 4-2 measured 3.42% by water level method.
#Water surface slope at 3-1 and 4-2 measured 2.66% by water level method.

APPENDIX D

PARTICLE SIZE DATA

Table 10. Sieve analyses (Folk, 1980) of instantaneous Helley-Smith bedload transport samples and bar and channel material samples.

E.C. = Sample integrated across entire channel width.

A5.8 = Point sample taken 5.8 meters from left bank.

Date	Time	Type of Sample	Cumulative weight percent coarser than (Phi) 95	84	75	50	25	16	5
18 May 1983	17:00	E.C.	0.25	-1.65	-3.75	-5.20	-5.50	-5.75	-5.90
22 May 1983	16:25	E.C.	0.95	0.30	-0.65	-2.30	-3.95	-4.30	-4.75
	20:00	E.C.	0.85	-0.50	-1.95	-4.00	-5.30	-5.50	-5.90
24 May 1983	22:00	E.C.	1.80	1.60	1.05	-0.45	-3.15	-3.70	-4.25
25 May 1983	20:34	E.C.	1.70	1.40	0.90	-2.60	-4.60	-5.10	-5.75
27 May 1983	11:30	E.C.	1.70	1.45	1.05	-0.45	-4.25	-4.60	-5.25
28 May 1983	01:41	E.C.	2.55	1.70	1.50	0.90	0.20	-0.35	-2.65
	02:54	E.C.	1.85	1.35	0.85	-3.25	-4.90	-5.25	-5.75
	18:28	E.C.	0.05	-2.95	-3.45	-4.20	-4.95	-5.20	-5.50
	22:25	A5.8	1.35	-0.20	-1.95	-3.65	-4.75	-5.25	-6.10
29 May 1983	14:13	E.C.	0.80	-1.60	-3.20	-4.60	-5.30	-5.50	-5.85
	14:02	A5.8	1.00	-0.60	-2.20	-3.50	-4.40	-4.70	-5.30
30 May 1983	12:15	E.C.	1.30	0.25	-1.15	-3.25	-4.75	-5.00	-5.65
	12:10	A5.8	0.70	-0.55	-1.95	-3.45	-4.50	-4.80	-6.00
	18:23	E.C.	1.75	1.35	0.85	-2.90	-4.55	-4.85	-5.25
05 June 1983	18:35	E.C.	1.50	0.90	-0.15	-1.85	-3.10	-3.45	-3.90
	18:35	A5.8	1.45	0.45	-0.50	-2.15	-4.60	-5.10	-5.70
11 June 1983	11:40	E.C.	1.50	0.75	-0.40	-2.85	-4.30	-5.00	-6.00
	11:35	A6.1	1.00	0.35	-0.80	-3.55	-4.55	-4.80	-5.75
12 June 1983	15:00	E.C.	1.35	0.15	-1.30	-3.70	-5.80	-6.00	-6.30
18 June 1983	21:50	E.C.	1.05	0.25	-0.55	-2.00	-3.30	-3.65	-4.10
	21:41	A5.8	-0.55	-2.10	-2.75	-3.75	-4.55	-5.00	-5.65
19 June 1983	15:00	E.C.	1.15	0.35	-0.50	-2.10	-3.55	-4.25	-5.35
	15:00	A5.8	1.15	0.85	0.20	-1.40	-3.20	-3.75	-4.50

Table 10. Concluded.

Date	Time	Type of Sample	Cumulative weight percent coarser than (Phi) 95	84	75	50	25	16	5
14 May 1984	20:23	E.C.	2.15	1.85	1.45	0.30	-1.95	-3.05	-4.50
16 May 1984	17:40	E.C.	1.05	-2.45	-3.45	-4.40	-5.10	-5.50	-5.90
17 May 1984	17:40	E.C.	1.85	0.90	0.30	-1.50	-3.10	-3.95	-5.00
27 May 1984	14:00	E.C.	1.20	0.00	-1.70	-4.00	-4.80	-5.15	-5.70
	14:10	A5.8	1.60	1.05	0.50	-1.55	-4.10	-4.40	-9.85
28 May 1984	12:00	E.C.	-3.50	-4.95	-5.10	-5.35	-5.65	-5.75	-6.00
	12:15	A5.8	1.90	1.50	1.20	0.70	0.00	-0.55	-2.30
29 May 1984	23:15	E.C.	1.80	1.35	0.90	-1.30	-4.15	-4.80	-5.60
	23:25	A5.8	1.80	1.35	0.90	-3.10	-5.45	-5.65	-5.90
30 May 1984	21:05	E.C.	1.50	0.85	-0.25	-1.85	-3.20	-3.70	-4.80
	21:05	A5.2	1.80	1.45	1.10	0.50	-1.60	-2.30	-3.45
31 May 1984	23:45	E.C.	1.75	1.20	0.70	-1.15	-3.50	-5.00	-5.70
	23:45	A5.8	1.80	1.60	1.20	0.50	-0.90	-1.90	-4.10
02 June 1984	01:00	E.C.	1.50	0.40	-1.30	-3.90	-4.55	-5.35	-5.90
	02:00	A5.2	1.50	0.25	-3.20	-5.10	-5.70	-5.95	-6.35
03 June 1984	21:15	E.C.	1.60	1.10	0.30	-1.50	-3.30	-3.85	-4.75
	21:20	A5.2	1.85	1.45	0.90	-0.80	-3.00	-3.25	-3.80

Table 11. Sieve analyses of samples taken from deposits formed by Squaw Creek.

Post 19 June 1983

Sample #	Location	Cumulative weight percent coarser than (Phi) 95	84	75	50	25	16	5
1	Right bank channel lower end of main bar above bridge	0.90	-1.70	-4.20	-7.00	-7.50	-7.70	-7.95
2	Upstream end of main bar above bridge	-2.60	-4.60	-6.20	-6.80	-7.20	-7.30	-7.50
3	Right bank channel at head of main bar above bridge	0.25	-3.60	-4.20	-4.75	-5.40	-5.70	-6.20
4	Upstream end of bar below bridge at right bank	1.60	-1.95	-3.35	-4.55	-5.30	-5.65	-6.30
5	Channel along right bank at lower end of Sample #4 bar	1.70	-0.70	-3.30	-4.60	-5.35	-5.70	-6.30
6	Upstream end of bar below old log jam	-2.80	-5.20	-5.95	-7.00	-7.50	-7.65	-7.95
7	Downstream end of bar below old log jam	-4.60	-5.00	-5.35	-5.90	-6.45	-6.70	-7.00
8	Upstream end of bar at mouth of Squaw Creek	0.75	-1.95	-3.45	-4.80	-5.90	-6.20	-6.70
9	Bed armour (Leopold)	-6.50	-7.25	-7.55	-8.10	-8.50	-8.65	-8.90