TRANSPORT OF SEDIMENT BY STREAMS IN THE SIERRA MADRE, SOUTHERN WYOMING

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CONVERSION FACTORS AND VERTICAL DATUM

Multiply	By	To obtain
inch	25.4	millimeter
foot	0.3048	meter
mile	1.609	kilometer
foot per foot	1.0	meter per meter
foot per second	0.3048	meter per second
cubic foot per second	0.02832	cubic meter per second
square foot	0.09294	square meter
pound per second-foot	1.488	kilogram per second-meter
pound per cubic foot	16.02	kilogram per cubic meter
ton per day	1.102	ton per day

Sea level: In this report, "sea level" refers to the National Geodetic Vertical Datum of 1929--a geodetic datum derived from an adjustment of the first-order level nets of the United States and Canada, formerly called "Sea Level Datum of 1929."

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ABSTRACT

The power required to detach and transport sediment is defined for three streams in the mountains of southern Wyoming where the availability and mobility of sediment is limited. Unit stream power required to initiate particle movement in Battle Creek, a stream with cobbles and boulders, was an order of magnitude greater than the power required to initiate particle movement in a gravel-bed stream with smaller sized particles. Although the unit stream power and the discharges necessary to initiate movement of particles larger than 4 millimeters were about an order of magnitude greater for Battle Creek than for a gravel-bed stream, the discharge necessary to initiate the motion of the particles had nearly the same probability of being equaled or exceeded in both streams. For particle sizes smaller than 4 millimeters, all particle motion begins at a daily discharge equaled or exceeded 13 to 18 percent of the time. The authors suggest that a geomorphic equilibrium might exist for the streams; that is, the power required to initially move the available particles is in balance with particle availability and mobility. For the largest bedload particles (32 to 64 millimeters), the peak discharge required to initiate motion is about bankfull discharge (recurrence interval between 1.13 and 2.8 years; a daily discharge equaled or exceeded about 2 percent of the time).

INTRODUCTION

The Fish Creek collection system proposed by the Wyoming Water Development Commission will divert water from streams draining the western slope of the Sierra Madre in Wyoming (fig. 1). The diversion structures will be located on the headwater streams of the Little Snake River (Colorado River Basin) and will divert part of the flow of each stream to the North Platte River (Missouri River Basin)(Stone and Webster Engineering Corporation, 1986). The diversion structures and affected streams are on national forest lands.

The U.S. Forest Service is concerned that the reduction in high streamflows in the stream channels just downstream from the diversions may alter sediment-transport capacity of the streams and cause deterioration of fish habitat. The reduction in streamflow may result in smaller velocities and reduced sediment-transport capacities of the streams. This could result in deposition of materials that are now transported by the streams and cause steepened channel slopes, braided channels, and unstable channel conditions that could accelerate changes in channel morphology. Downstream from the diversions, clay, silt, and sand particles that are now flushed through the system may be deposited in the gravels of the streams, covering the substrates, decreasing fish habitat, and inhibiting fish reproduction. To address the concerns mentioned above and the potential effect of the diversions on channel morphology, the U.S. Geological Survey (USGS), in cooperation with the Wyoming Water Development Commission, collected and analyzed streamflow and sediment data in and near the area of the Fish Creek collection system.

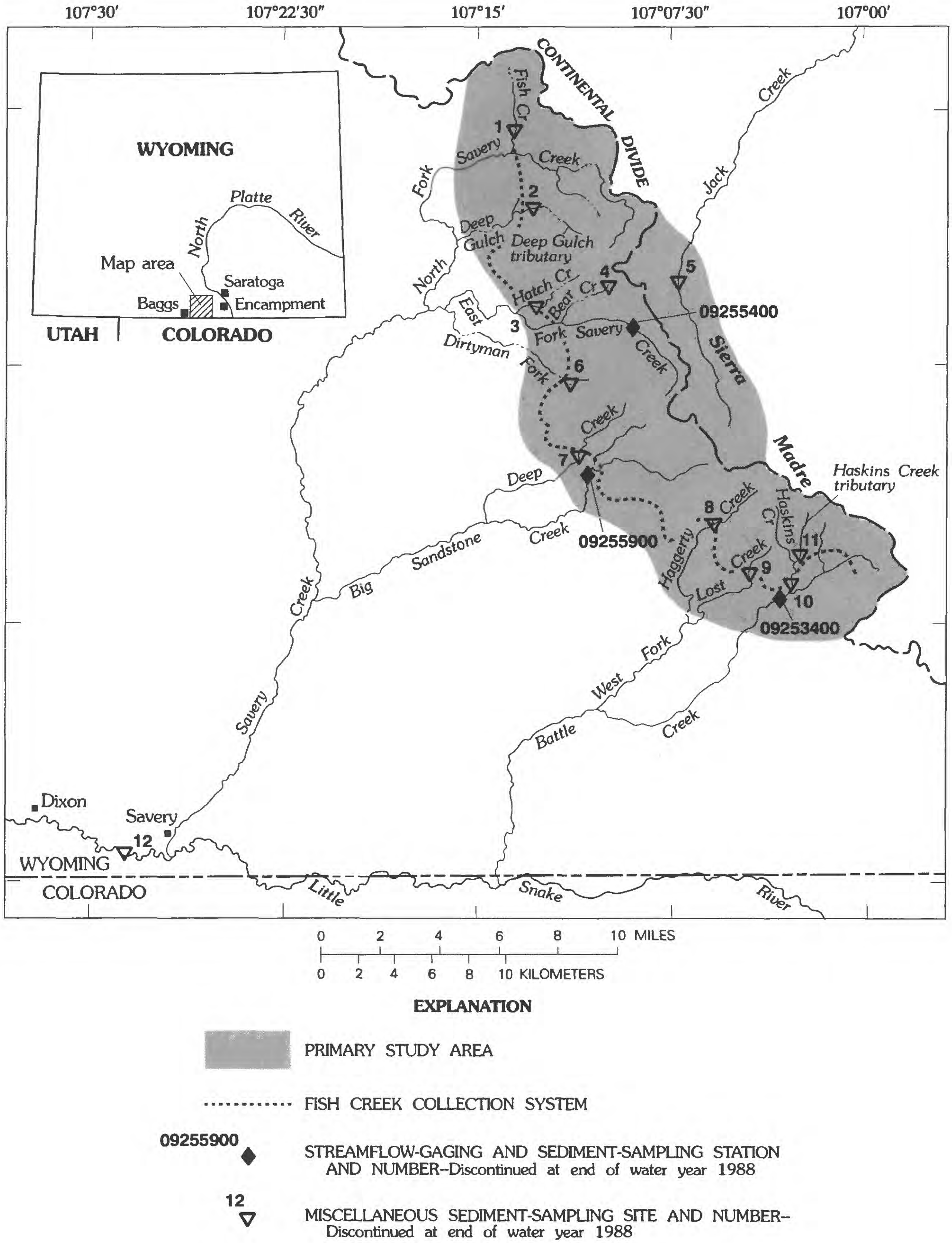

Figure 1.--Location of study area and streamflow-gaging stations and miscellaneous sediment-sampling sites used in study. (See table 2 for identification of sites.)

Purpose and Scope

The purpose of this report is (1) to describe the existing hydraulic and sediment-transport characteristics at three U.S. Geological Survey streamflow-gaging stations on the western slope of the Sierra Madre, and to describe streamflow and sediment data collected at 12 miscellaneous sites (fig. 1); (2) to identify streamflows necessary to maintain the natural channel conditions; and (3) to determine a method for evaluating the effects of reduced streamflow on the transport of sediments in streams having limited sediment supply in the Sierra Madre.

Movement and transport of bed material are emphasized in this study. Discharge, bed material, and sediment data collected at the three streamflow-gaging stations on the western slope of the Sierra Madre are used to develop relations between flow frequency, stream power, and sediment transport. Miscellaneous measurements of discharge, suspended sediment, and bedload made at 12 streams in the Sierra Madre and surrounding area are used to define areal variations of sediment transport. Data on suspended sediment are summarized in this report.

Physiography

The Sierra Madre is a rolling dissected plateau with eroded peaks and ridges. Metasedimentary and metavolcanic rocks of Precambrian age (Love and Christiansen, 1985) are exposed in most of the study area. Tertiary sedimentary rocks underlie some of the small streams in the northwestern part of the study area, and Quaternary glacial deposits underlie some of the stream valleys in the northern part of the study area.

The soils in the southern part of the study area are described as steep and are developing from residuum and transported materials from the metasedimentary and metavolcanic rocks (Young and Singleton, 1977). In the northern part of the study area, the soils are rolling to steep and are developing from residuum and transported materials from sedimentary rocks.

The vegetation is predominantly forest in most of the study area, except above timberline between 9,000 and 10,000 feet above sea level, where bedrock is exposed. The vegetation in the northern part of the study area is predominantly grasses and shrubs.

The mean annual precipitation ranges from about 25 to 40 inches per year (Martner, 1986) in the study area. About 80 percent of the precipitation is snow, which occurs between November and April. Snowmelt is the primary source of runoff, generally in May and June. Annual peak discharges of streams originating in the high elevations generally occur during June. Occasionally, an annual peak flow results from a thunderstorm or rainfall on snowpack.

All streams considered in this study originate in the Sierra Madre above an altitude of 8,000 feet above sea level. Channel-geometry characteristics of slope, width, depth, and roughness are a function of the geology and topography. Sediment is carried to the stream by overland flow, soil creep, and bank erosion. Variations in quantity and size of stream sediment are dependent on the type of bedrock and soil in the drainage basin. In general, streams in the southern part of the study area have steeper channels, coarser streambed material, and rougher channels than those in the northern part. Jack Creek in the northern part of the study area is a stream with a gravel bed, and Battle Creek in the southern part of the study area is a stream with cobble-and-boulder bed (fig. 2).

Approach

River hydraulics, channel geometry, and sediment-transport characteristics were used to develop relations between streamflow and stream morphology and to show the effects of decreased streamflow on channel morphology. Channel-hydraulics data were used to evaluate the relations between the measured bedload discharge and the power available for sediment transport.

Three U.S. Geological Survey continuous-record streamflow-gaging stations--Battle Creek near Encampment (09253400) (1956-63, 1985-88), East Fork Savery Creek near Encampment (09255400) (1956-58, 1985-88), and Big Sandstone Creek near Savery (09255900) (1956-58, 1985-88)--were operated in the study area. During 1986-88, suspended-sediment and bedload samples were collected throughout the snowmelt runoff periods. These three gaged streams are considered to be representative of perennial streams in the area.

In addition, hydrologic data were collected during the 1987 and 1988 snowmelt-runoff seasons at nine miscellaneous sites near proposed diversions for comparison to hydrologic and bedload characteristics determined for the three streamflow-gaging stations. Three other sites--Fish Creek (site 1), Jack Creek (site 5), and Little Snake River near Dixon (site 12)--in the vicinity of the Fish Creek collection system also were sampled to determine hydrologic and bedload characteristics for areas not representative of the geological formations found at the other nine sites (fig. 1).

Suspended-sediment data were collected at the three streamflow-gaging stations using depth-integrating samplers (DH-48) and automatic-pumping samplers. Procedures outlined by Guy and Norman (1970) were followed for collecting depth-integrated samples. At each station, two automatic-pumping samplers were linked together, which enabled the collection of 48 consecutive samples between site visits at a rate of 4 samples per day for 12 days. Coefficients to correct the concentration of the automatically pumped samples to the concentration of the depth-integrated samples were computed and applied. About 600 suspended-sediment samples were collected at each station.

Bedload was sampled at the three streamflow-gaging stations and at all miscellaneous sites using a 3-inch Helley-Smith bedload sampler (Emmett, 1980). The sampling procedure for this study was as follows: To determine the spatial distribution, approximately 20 vertical profiles were taken for each cross section, unless the cross section was less than 10 feet wide, in which case samples were collected every 0.5 foot. To determine the temporal distribution, two traverses were made at each sampling site (when time permitted), and the sampler was held on the bottom for 60 seconds at each vertical. Battle Creek could not be waded in the spring of 1987; therefore, bedload samples were collected at a single point near the center of flow. After a safety line had been installed, both single-point and cross-section samples were collected to determine a correction coefficient for the single-point samples. The single-point samples were corrected by a coefficient of 0.62 to obtain bedload values equivalent to the cross-section values.

Jack Creek (site 5)

Battle Creek (station 09253400)

Figure 2.--Typical stream channels in the Sierra Madre. (Jack Creek is in the northern part of the study area; Battle Creek is in the southern part.)

Particle-size distributions of bedload samples were determined using U.S. Standard Sieves; sieve diameters ranged from 0.25 to 256 millimeters. The data were adequate to determine instantaneous transport rates and particle size.

The distribution of particle sizes of streambed material was determined at each of the three streamflow-gaging stations. In-place measurements of coarse streambed material (pebble count at grid points) were made for particles larger than 8 millimeters in diameter (Wolman, 1954). At grid points where particles were smaller than 8 millimeters in diameter, material was bulk sampled and the distribution of particles finer than 8 millimeters was determined by using conventional sieve-analysis techniques. The two sets of data were combined by redistributing the weight analysis using a ratio of the number of points in the grid that had particle sizes less than 8 millimeters to the total number of points in the grid. In a study of sampling procedures for coarse fluvial materials, Kellerhals and Bray (1971) considered the results of the in-place and bulk-sampling methods to be equivalent.

Bulk bar-material samples were collected from point bars upstream from each of the streamflow-gaging stations. Each sample weighed about 1,500 grams. The samples were collected from the surface of the bar to a depth of about 200 millimeters, a depth equal to about 3 times the largest particle diameter.

Discharge and suspended-sediment data used in this study are published in the annual water-resources data reports for water years 1986-88 (U.S. Geological Survey, 1987-89). Bedload data, including size distributions of the bedload samples collected at the three streamflow-gaging stations, and discharge and suspended sediment data for all of the miscellaneous sites for water years 1986-88 are published in the annual data report for water year 1988 (U.S. Geological Survey, 1987-89). Results of the analysis of bar and bed material are presented in this report in bar graphs. Bedload-transport rates for ranges of selected particle sizes for the three streamflow-gaging stations are tabulated in the supplement of this report.

STREAMFLOW

Two streamflow characteristics are useful for this study--annual peak-discharge frequency (Interagency Advisory Committee on Water Data, 1981) and flow duration (Searcy, 1959). The frequency of the annual peak discharge was computed using log-Pearson type III distribution for each of the three streamflow-gaging stations (fig. 3). The duration of daily discharge was computed from data collected at each of the stations (fig. 4). Ten water years of discharge data were available for Battle Creek and 5 water years of discharge data were available for East Fork Savery Creek and Big Sandstone Creek.

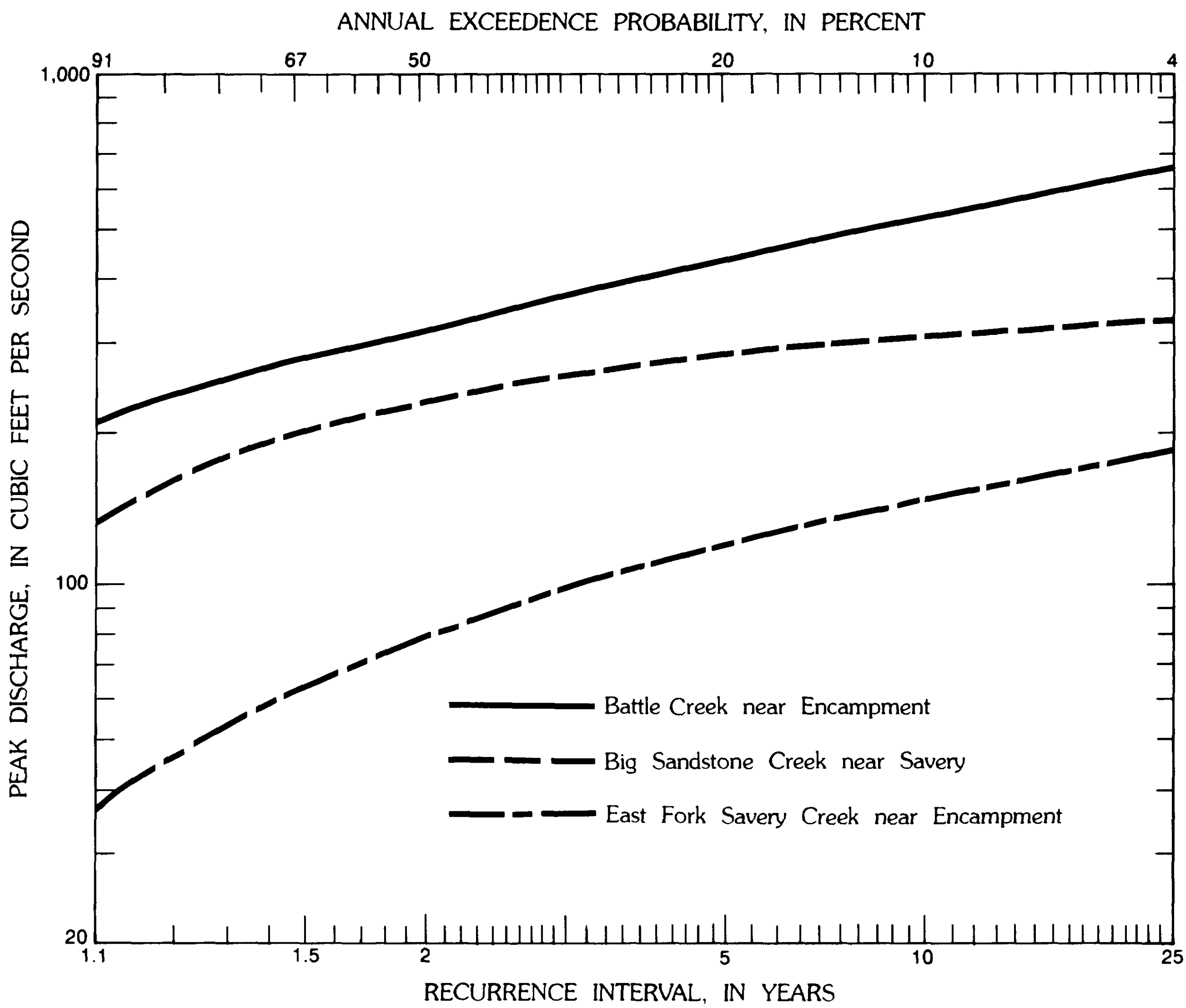

Figure 3.--Peak-discharge frequency for three streamflow-gaging stations in the Sierra Madre.

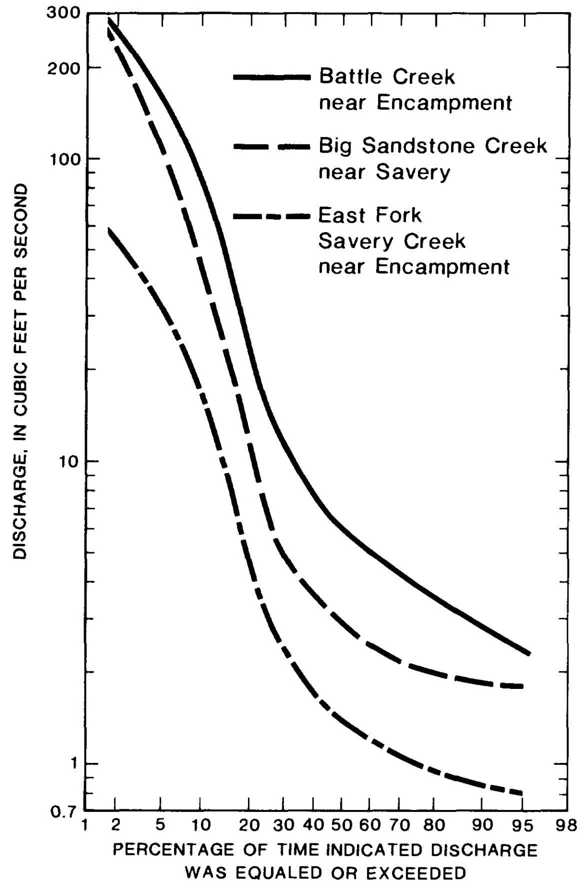

Figure 4.--Flow-duration curves for three streamflow-gaging stations in the Sierra Madre.

HYDRAULIC GEOMETRY

Hydraulic-geometry properties were computed from data listed on the discharge-measurement notes for each of the three streamflow-gaging stations (Leopold and Maddock, 1953). Width, depth, and velocity were related to the discharge using the following power equations:

$$W = aQ^b, \quad (1)$$

$$D = cQ^f, \quad (2)$$

$$V = kQ^m, \quad (3)$$

where W is width of the water surface, in feet;
D is average depth of water, in feet;
V is average velocity, in feet per second;
a, c, and k are coefficients of regression;
Q is discharge, in cubic feet per second; and
b, f, and m are exponents of regression.

Values for the coefficients and exponents of regression, along with the coefficients of determination for the three streamflow-gaging stations, are listed in table 1.

Table 1.--Regression parameters for width, depth, and velocity

Station name	Regression coefficients			Regression exponents			Coefficient of determination (percent)		
	Width a	Depth c	Velocity k	Width b	Depth f	Velocity m	Width	Depth	Velocity
Battle Creek near Encampment	12.44	0.320	0.252	0.162	0.296	0.542	73.3	91.8	96.9
East Fork Savery Creek near Encampment	7.01	.314	.454	.220	.365	.415	83.2	82.9	82.7
Big Sandstone Creek near Savery	7.69	.369	.352	.299	.231	.470	85.5	80.9	94.3

The energy gradient was computed using Manning's equation:

$$S = \left[\frac{(Q)(n)}{1.486(A)(R)^{2/3}}\right]^2 \qquad (4)$$

where Q is discharge, in cubic feet per second;
n is Manning's roughness coefficient, in feet $^{1/6}$;
A is cross-sectional area, in square feet; and
R is hydraulic radius, in feet.

Values for Manning's roughness coefficient n were selected for each site. The cross-sectional area was divided by the estimated wetted perimeter to obtain the hydraulic radius. The wetted perimeter, in feet, was estimated as the width plus one depth of the channel.

To compare the hydraulic geometry of all the streams sampled in this study, average hydraulic properties were computed from streamflow measurements made at each of the miscellaneous sites. The number of measurements and the average values for instantaneous discharge, width, average depth, slope, and unit stream power are listed in table 2. Hydraulic properties were computed for the three streamflow-gaging stations with equations 1 through 4 using the respective average of the discharges measured at the time the bedload samples were collected.

SUSPENDED SEDIMENT

Suspended-sediment samples were collected at the three streamflow-gaging stations and at the 11 miscellaneous sites in the primary study area during snowmelt runoff in water years 1986-88. The mean, maximum, and minimum concentration of sediment in samples collected at the three stations are listed in the following table:

Station name	Mean (milligrams per liter)	Maximum (milligrams per liter)	Minimum (milligrams per liter)
Battle Creek near Encampment	18	159	0
East Fork Savery Creek near Encampment	31	258	2
Big Sandstone Creek near Savery	17	114	0

The maximum suspended-sediment concentration determined in samples from the nine miscellaneous sites along the proposed diversion was 157 milligrams per liter at an instantaneous discharge of 1.8 cubic feet per second at site 3.

It is difficult to determine the source of particles of suspended sediment. During the early part of snowmelt runoff, fine sediment that has accumulated in the channel during the low-flow season will be flushed from the channel. However, during the later part of snowmelt runoff, the source of suspended sediment may be upslope areas or eroded stream banks. A sediment sample was collected to determine the concentration of suspended sediment in water flowing from a snowbank just upstream from the sampling site on Jack Creek (site 5). The suspended-sediment concentration in the overland flow was

Table 2.--Average hydraulic properties of streams in the Sierra Madre

[Average computed on the basis of all measurements]

Site or station number	Stream name	Number of measure-ments	Average instantaneous discharge (cubic feet per second)	Average width (feet)	Average depth (feet)	Energy gradient (foot per foot)	Average unit stream power (pounds per second-foot)
1	Fish Creek	2	6.30	3.7	1.23	0.0020	0.21
2	Deep Gulch tributary	3	3.47	6.8	.49	.0025	.079
3	Hatch Creek	3	2.55	4.7	.55	.0022	.074
4	Bear Creek	2	1.28	4.6	.24	.0120	.21
5	Jack Creek	6	79.2	28.2	1.09	.0036	.63
6	Dirtyman Fork	2	4.20	5.4	.54	.0066	.32
7	Deep Creek	3	12.0	9.0	.91	.0038	.32
8	Haggerty Creek	4	65.8	15.5	1.11	.0092	2.44
9	Lost Creek	4	9.32	8.2	.65	.0054	.38
10	Haskins Creek	3	12.2	9.1	.53	.0124	1.04
11	Haskins Creek tributary	2	11.7	8.6	.70	.0042	.36
12	Little Snake River near Dixon	4	2,700	115	4.65	.0012	1.75
09253400	Battle Creek near Encamp-ment	55	200	29.3	1.54	.0206	8.77
09255400	East Fork Savery Creek near Encamp-ment	47	34.0	15.2	1.14	.0040	.56
09255900	Big Sandstone Creek near Savery	39	127	32.7	1.13	.0144	3.49

15 milligrams per liter, slightly greater than the suspended-sediment concentration in Jack Creek of 11 milligrams per liter, indicating that in this example overland flow was transporting some sediment from upslope areas to the channel.

The suspended-sediment concentrations should be the same upstream and downstream from the diversion because the suspended material will be diverted with its portion of the streamflow. Therefore, reduced streamflows likely will have little impact on a stream's ability to transport suspended sediment downstream.

BEDLOAD TRANSPORT RATES

Unit stream power was used to establish the relation between the power required to move bed material and the measured bedload transport rate for Battle Creek, East Fork Savery Creek, and Big Sandstone Creek. Unit stream power is defined by Bagnold (1966) as the product of the unit weight of water, average velocity, average depth, and energy gradient as follows:

$$\omega = \gamma VDS \tag{5}$$

where ω is unit stream power, in pounds per second-foot;
γ is unit weight of water, in pounds per cubic foot;
V is average velocity, in feet per second;
D is average depth, in feet; and
S is energy gradient of the stream, in feet per foot.

The transport rate for the measured bedload was computed in pounds per second-foot. Least-squares regressions were computed for each of the three streamflow-gaging stations using the following equation:

$$Q_s = g\omega^h \tag{6}$$

where Q_s is bedload-transport rate, in pounds per second-foot; and
g and h are regression coefficients.

Results of the regression analysis of the relation of bedload-transport rate to unit stream power are presented in figures 5 through 7 and in table 3.

Prediction intervals were computed for each of the regressions relating bedload-transport rates to unit stream power. The prediction interval allows for a greater variability than the confidence interval, which represents the variability of the group's mean. The individual variability, which is greater than the group's mean, is useful when comparing bedload data collected at miscellaneous sites in the Sierra Madre to the bedload-transport relations established at the three streamflow-gaging stations.

It is hypothesized that the analysis of bedload-transport rates defines two types of stream channels in the Sierra Madre. Battle Creek requires on the average a unit stream power from 0.8 to about 20 pounds per second-foot (fig. 5) to initiate movement of sediment-particle sizes of 0.25 to 64 millimeters and transport them. East Fork Savery Creek, which has a gravel bed, on the average requires a unit stream power from 0.1 to 1.0 pounds per second-foot (fig. 6) to initiate movement and transport the same size particles found at Battle Creek. The data for Big Sandstone Creek indicate that a limited supply of fine particles, generally between 0.25 and 1.0 millimeter, are flushed from the stream early in the runoff season; however, there is not a sufficient supply of fine bed material to maintain a proportionately greater transport rate for large discharges. With these considerations, the bedload-transport rates of Big Sandstone Creek require stream powers similar to those of Battle Creek. It is concluded that the two stream-channel types can be categorized by unit stream power as (1) cobble-and-boulder bed and (2) gravel bed. This has been previously shown, but as a continuum, as d_{50} gets larger with increased flow (Leopold and Emmett, 1976).

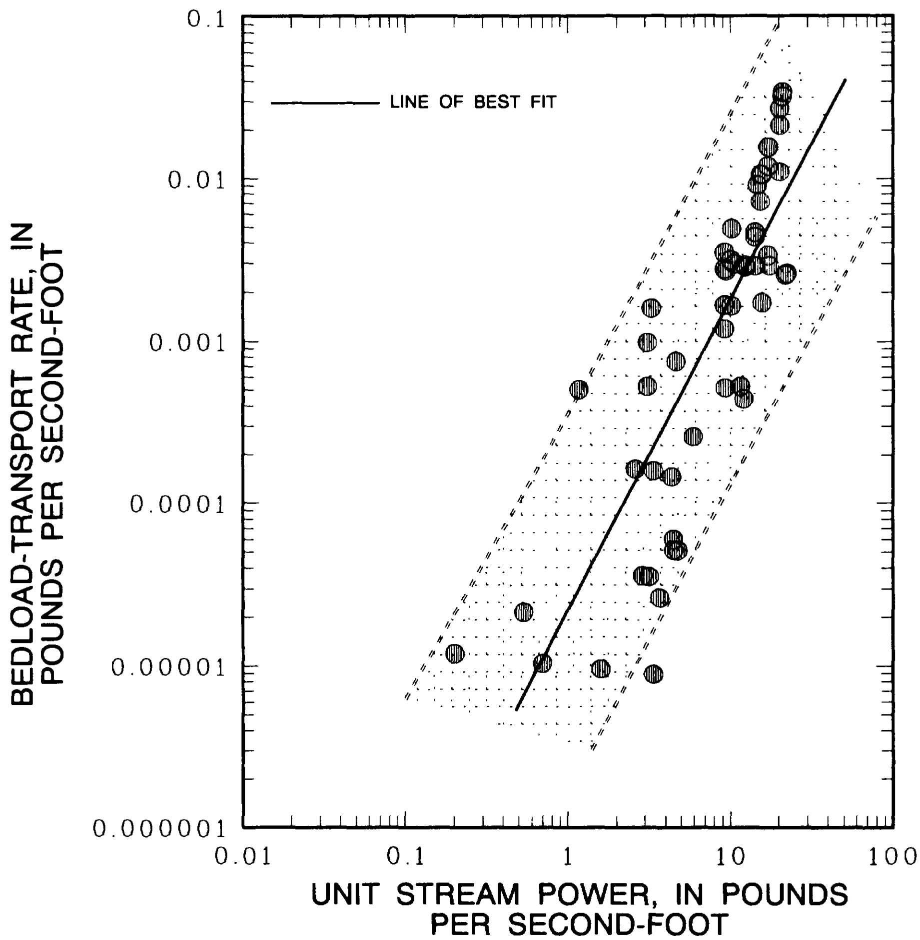

Figure 5.--Relation of bedload-transport rate to unit stream power at streamflow-gaging station, Battle Creek near Encampment. Prediction interval indicated by shaded area.

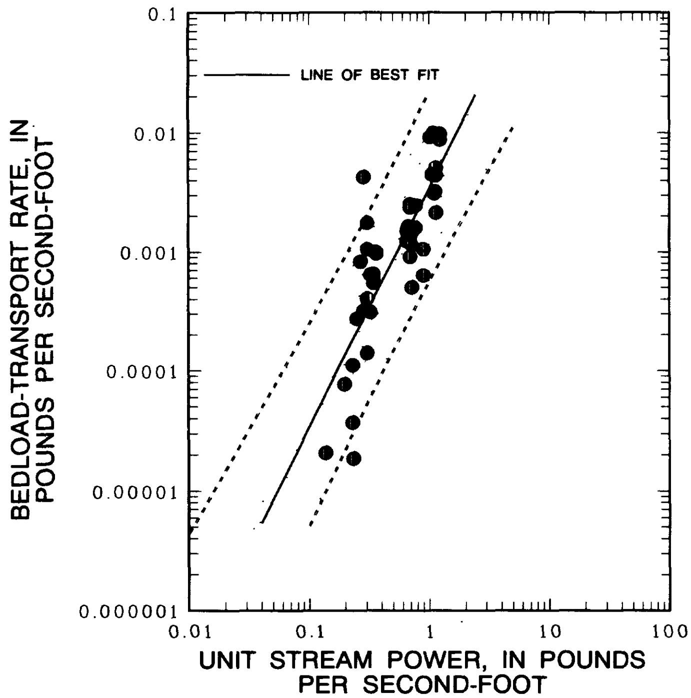

Figure 6.--Relation of bedload-transport rate to unit stream power at streamflow-gaging station, East Fork Savery Creek near Encampment. Prediction interval indicated by shaded area.

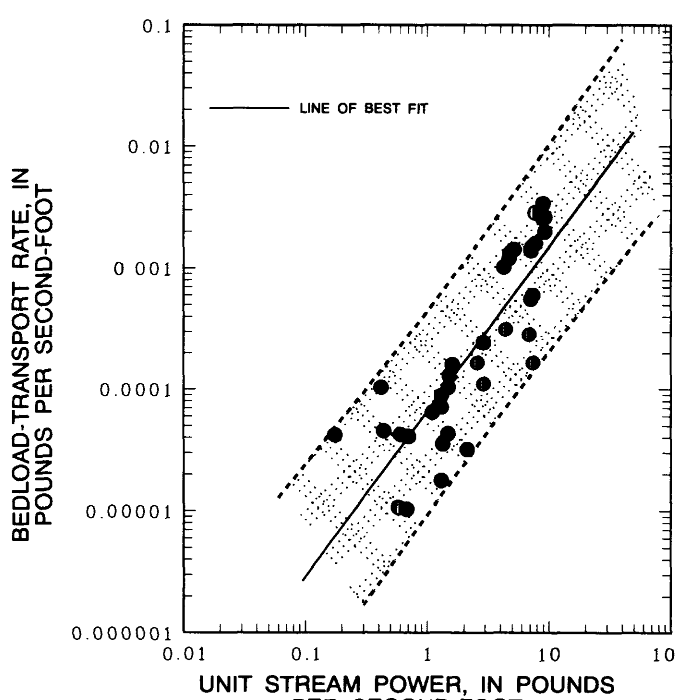

Figure 7.--Relation of bedload-transport rate to unit stream power at streamflow-gaging station, Big Sandstone Creek near Savery. Prediction interval indicated by shaded area.

Table 3.--Equations and statistics of regression analyses between bedload-transport rate and unit stream power

Station name	Regression constants g	h	Coefficient of determination (R^2) (percent)	Standard deviation (log units)	Standard error of estimate (percent) Positive	Negative
Battle Creek near Encampment	0.0000234	1.89	69.2	0.5633	266	73
East Fork Savery Creek near Encampment	.00350	1.99	65.5	.3847	124	59
Big Sandstone Creek near Savery	.0000643	1.36	71.8	.4039	153	60

An analysis of the distribution of particle sizes was made for bed material, bar material, and the average size of all bedload collected at the three streamflow-gaging stations. The percentages for each particle-size range are illustrated by bar graphs in figures 8 through 10. These particle-size analyses support the conclusion drawn from the analysis of unit stream power; that is, there are two types of stream channels found in the Sierra Madre -- cobble-and-boulder bed and gravel bed. The particle-size distributions for bed- and bar-material samples for Battle Creek indicate that large particles dominate (fig. 8), indicating a cobble-and-boulder bed. The particle-size data for East Fork Savery Creek (fig. 9) indicate that fine particles are present in all of the samples and about 70 percent of the bed material consists of gravel, ranging in size from 2 to 64 millimeters. The distribution of particles in the bedload samples for Big Sandstone Creek (fig. 10) indicates that about 30 percent by weight of the bedload particles is 2 millimeters or smaller, but neither the bed-material nor the bar-material samples explain the source of the finer material. A cut bank, which is actively eroding upstream from the study reach on Big Sandstone Creek, possibly provides some of the finer particles.

To determine the average discharge at which bed-material particles began to move, bedload-transport rates were computed for each particle-size range analyzed for the three streamflow-gaging stations. Least-squares regressions were computed using bedload-transport rates as the independent variable and discharge as the dependent variable.

$$Q = d\, Q_b^{\,p} \tag{7}$$

where Q is discharge, in cubic feet per second;
Q_b is bedload-transport rate, in tons per day for an indicated particle-size range; and
d and p are regression coefficients.

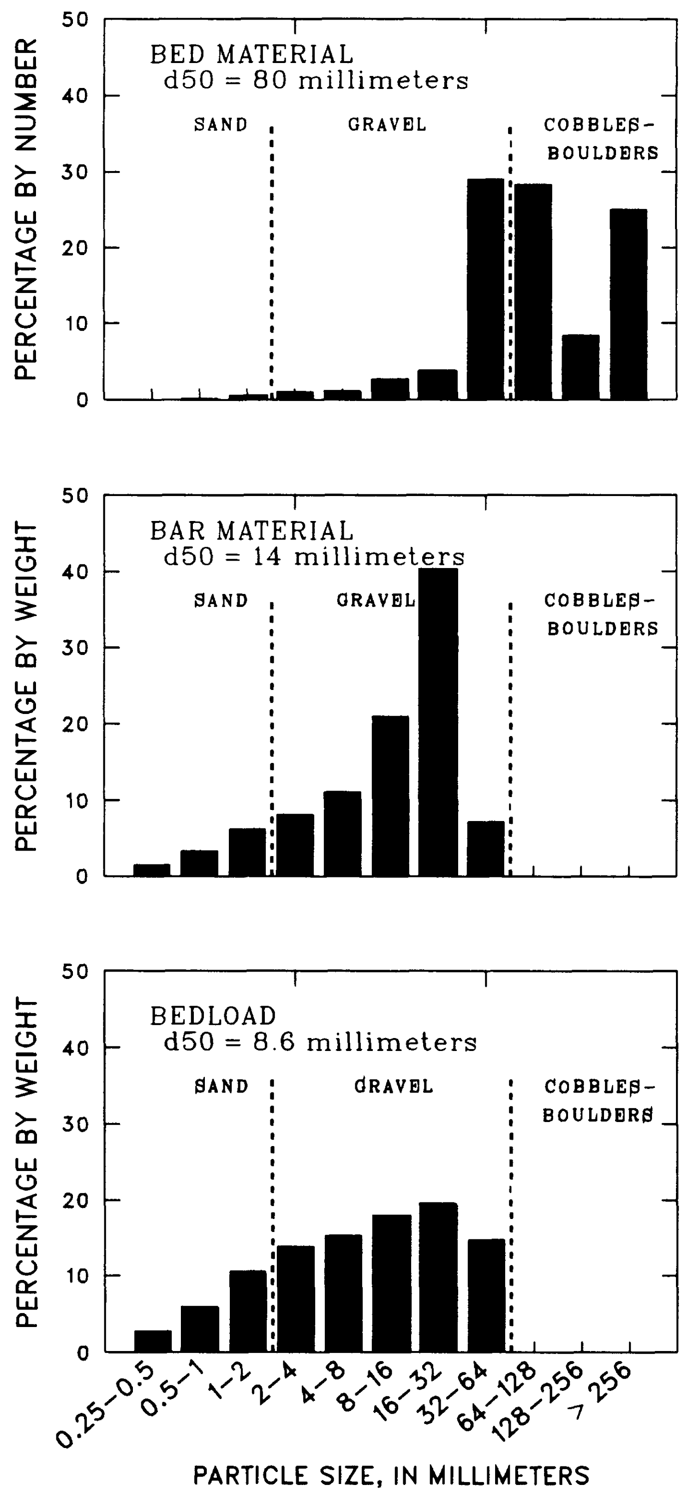

Figure 8.--Particle-size distribution for samples collected at Battle Creek near Encampment.

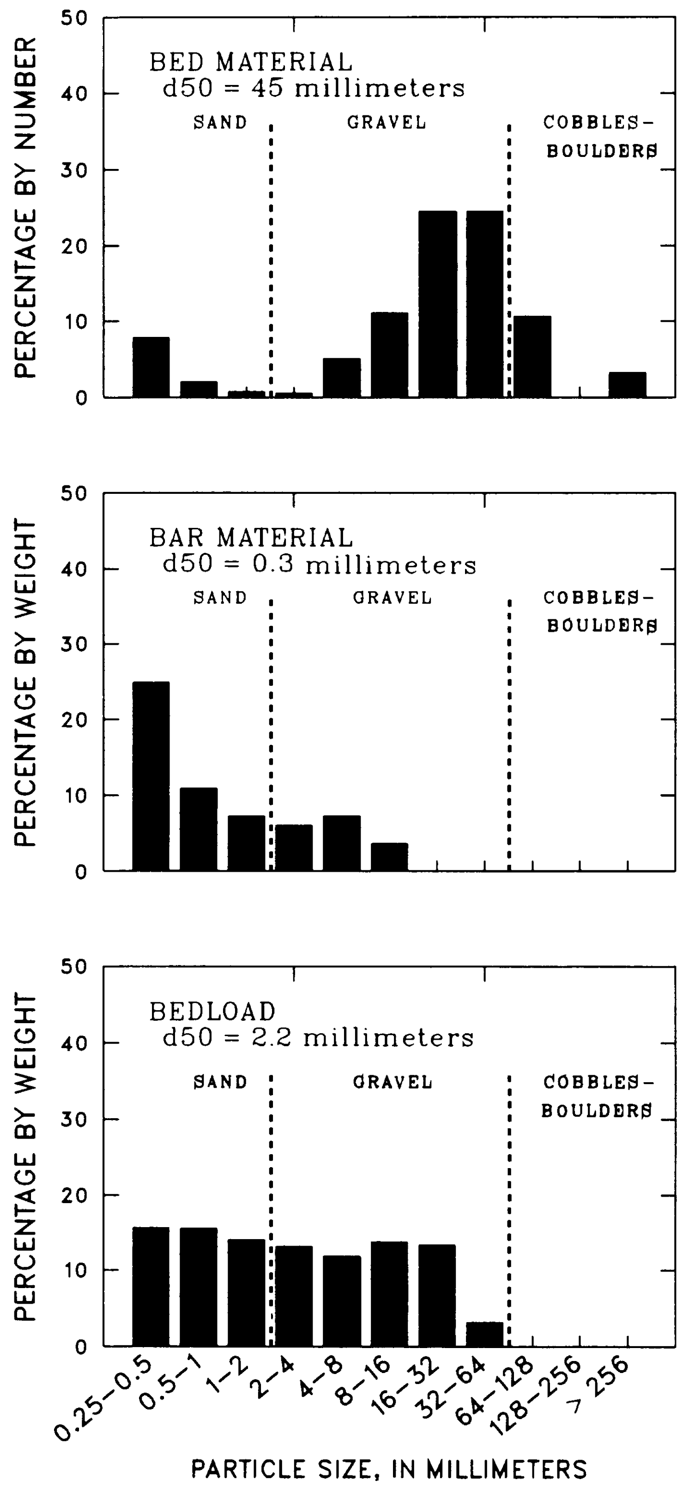

Figure 9.--Particle-size distribution for samples collected at East Fork Savery Creek near Encampment.

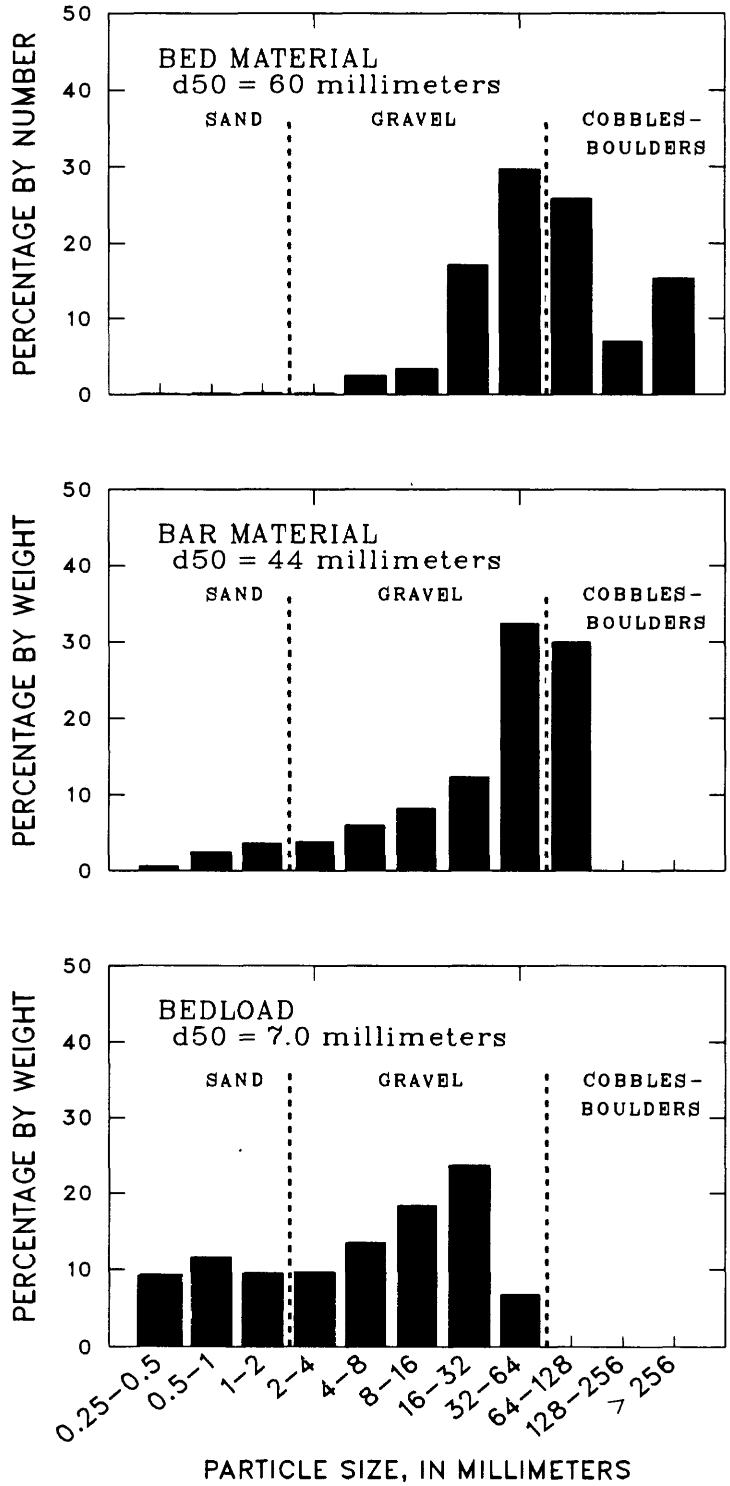

Figure 10.--Particle-size distribution for samples collected at Big Sandstone Creek near Encampment.

The bedload-transport rates, discharges, and the regression lines are presented in figures 11 through 13, and the data for the analysis are listed in the supplement of this report. Intercepts and slopes of the regressions are not presented in this report, because the equation is used only as a tool for determining the average discharge at the beginning of movement for the particle-size ranges and not as a predictive equation.

The discharge for the lowest bedload-transport rate observed was computed for all the particle sizes presented in figures 11 through 13 using equation 7. Unit stream power (eq. 5) was computed for each discharge to determine the power necessary to initiate movement of the particles. The percentage of time the computed discharge for initial movement of a selected particle size was equaled or exceeded was determined from figure 4. The discharge, unit stream power, and the percentage of time the discharge was equaled or exceeded are listed in table 4 for each range of particle sizes for the three streamflow-gaging stations.

The data in table 4 confirm the earlier hypothesis that two types of stream channels exist -- cobble-and-boulder bed and gravel bed. To initiate movement of particles in the range of 4 to 64 millimeters in Battle Creek, a unit stream power is required that is nearly an order of magnitude greater than the unit stream power required to initiate movement of the same size particles in East Fork Savery Creek. The power to initiate movement of the large particles (4 to 64 millimeters) in Big Sandstone Creek is at least twice that required to move the particles in East Fork Savery Creek. Clearly, availability and mobility are important factors in the movement of bedload in the Sierra Madre. The range in unit stream power to initiate movement of the different particle sizes for East Fork Savery Creek is much smaller than that for the other two streams, suggesting that the equal-mobility concept (all particle sizes have a tendency to move at the same discharge) described by Andrews (1983) is more applicable to that station than to the other two stations.

The percentage of time that discharge, at the time of initial particle movement, was equaled or exceeded has a similar value for all three streams for each particle-size range. Because only three data sets are available and the discharge records are short, the similarity may be a coincidence, but if it is not, then the data indicate a geomorphic equilibrium for the streams, that is, the power required to detach the available particles is in balance with the particle availability.

The data were analyzed to determine the discharges necessary to maintain natural channel conditions, or conditions prior to any diversions. The results of the analysis in table 4 indicate that to initially move particles from 0.25 to 4 millimeters in diameter, a daily mean discharge that is equaled or exceeded 13 to 18 percent of the time is required. Again, this is the discharge required to initiate movement of the particles. The probability of the discharge is approximately the value used in the Hoppe method to determine a flushing flow on the Fryingpan River in Colorado (Milhous, 1986; Kondolf and others, 1987).

Many investigators have used peak-flow frequency to quantify flood-plain formation, channel maintenance, and flushing flows in natural channels (Leopold and others, 1964; Milhous, 1986; Kondolf and others, 1987). The data collected for this study show reasonable consistency in the recurrence interval of peak flows (1.13 to 2.8 years) required to move the largest particles

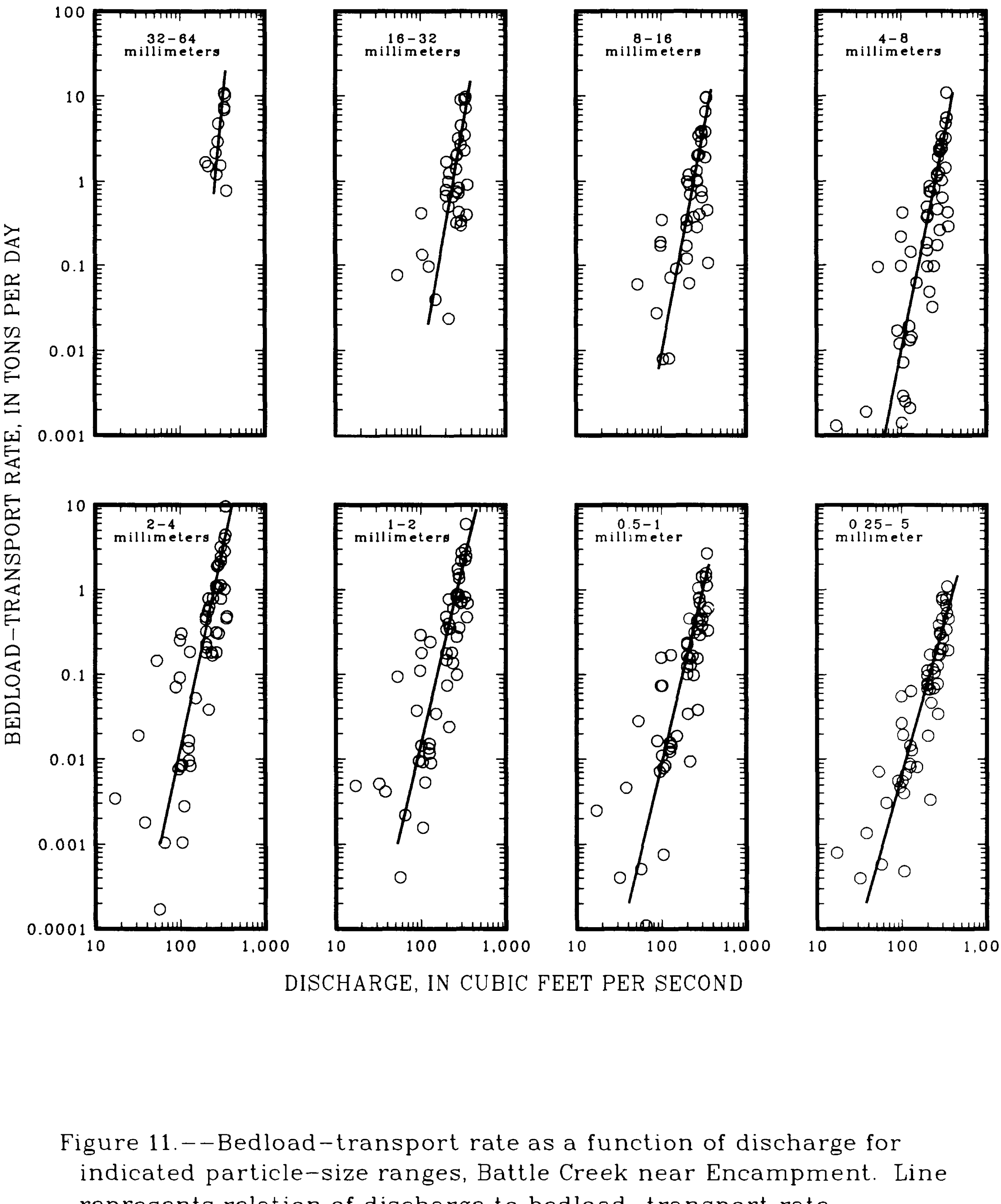

Figure 11.--Bedload-transport rate as a function of discharge for indicated particle-size ranges, Battle Creek near Encampment. Line represents relation of discharge to bedload-transport rate.

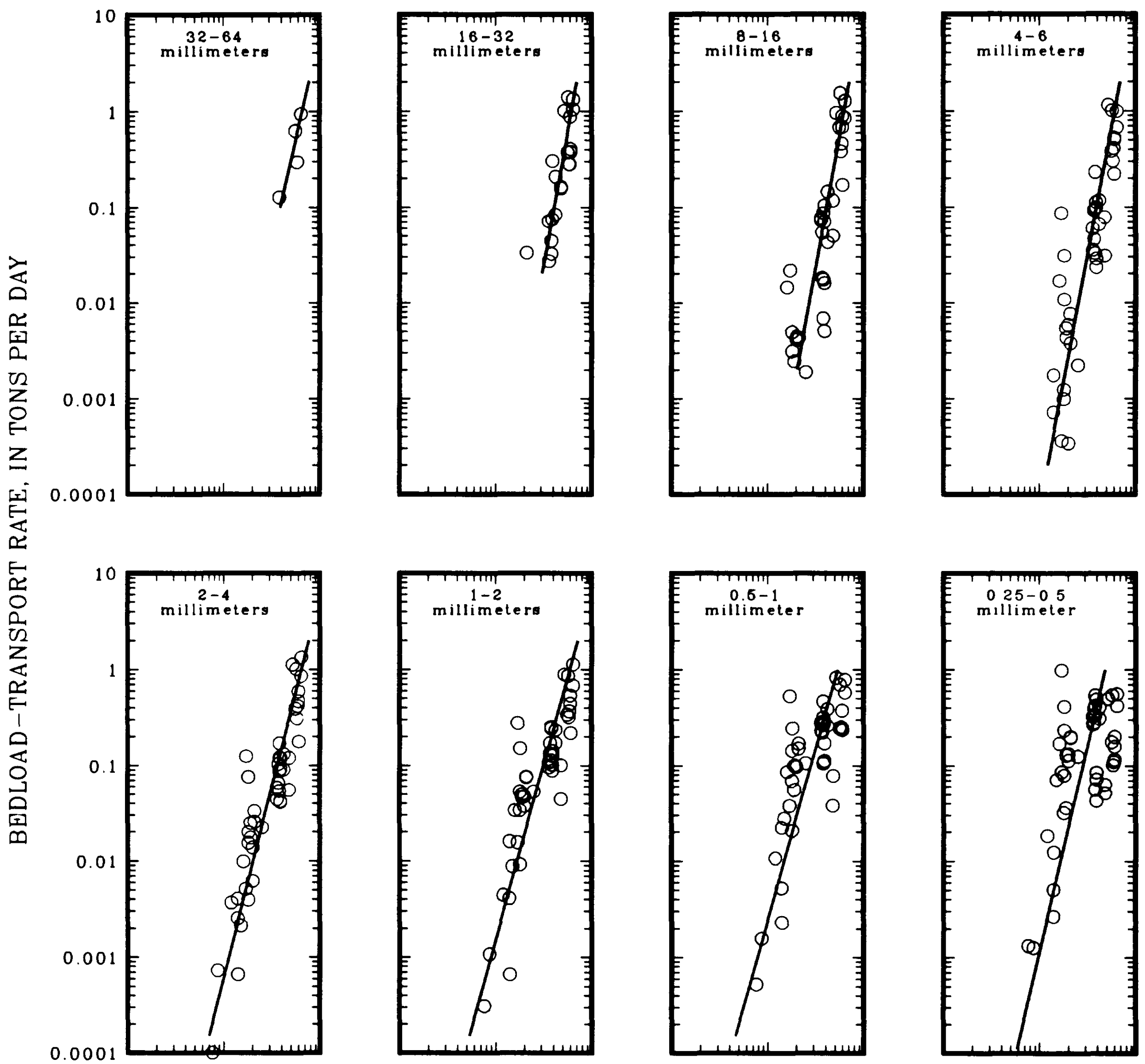

Figure 12.--Bedload-transport rate as a function of discharge for indicated particle-size ranges, East Fork Savery Creek near Encampment. Line represents relation of discharge to bedload-transport rate.

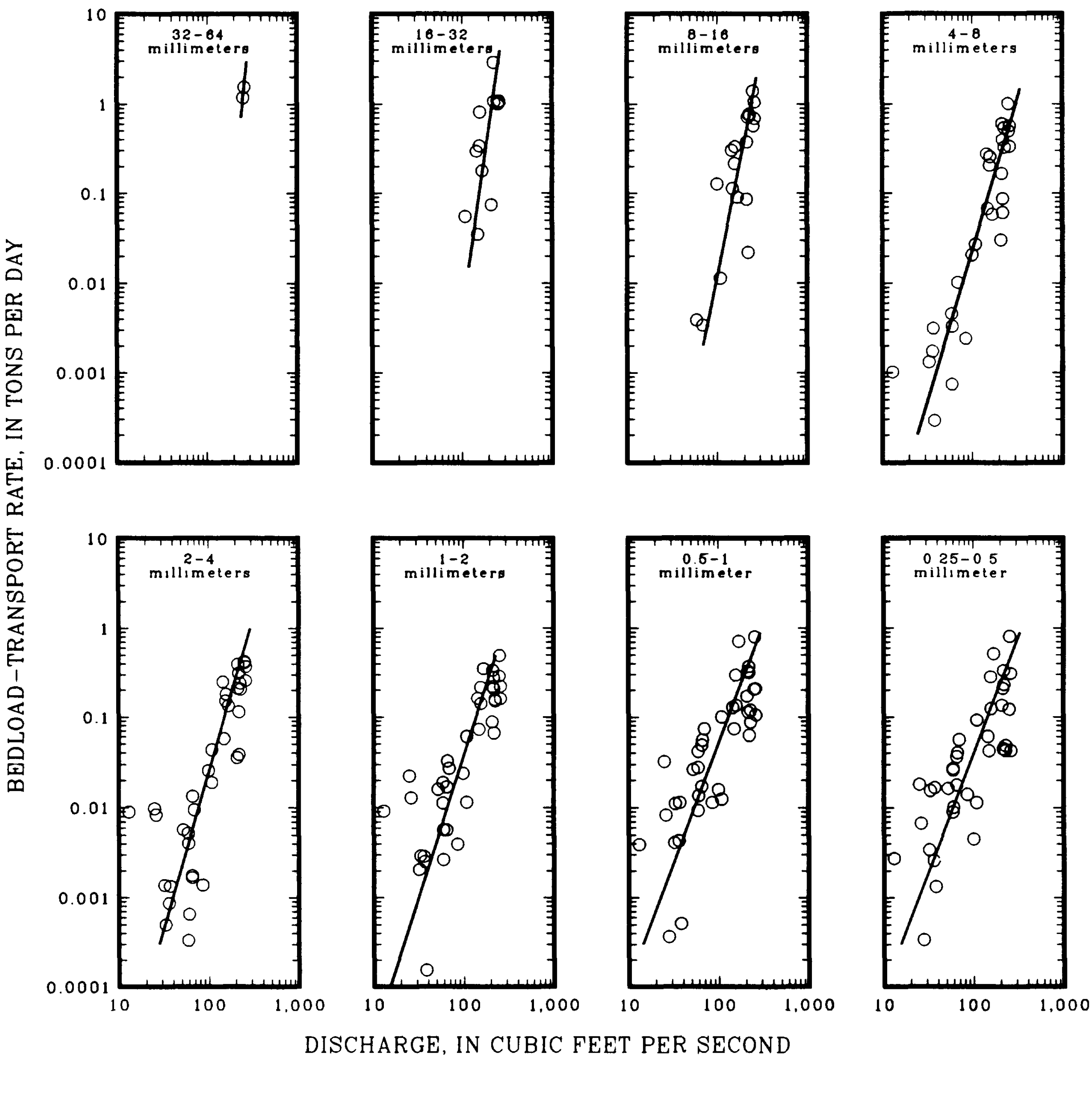

Figure 13.--Bedload-transport rate as a function of discharge for indicated particle-size ranges, Big Sandstone Creek near Savery. Line represents relation of discharge to bedload-transport rate.

Table 4.--Analysis of particle movement

Streamflow-gaging station	Range of particle sizes (millimeters)	Discharge at time of initial movement (cubic feet per second)	Unit stream power at time of initial movement (pounds per second-foot)	Percentage of time discharge was equaled or exceeded
Battle Creek near Encampment	32-64	254	13.3	2
	16-32	140	5.30	6
	8-16	98.0	3.05	9
	4-8	66.3	1.66	12
	2-4	39.5	.75	16
	1-2	42.7	.84	15
	0.5-1	35.6	.63	16
	0.25-0.5	45.8	.94	15
East Fork Savery Creek near Encampment	32-64	41.0	.77	3
	16-32	32.4	.59	5
	8-16	20.2	.35	8
	4-8	13.5	.23	11
	2-4	6.3	.10	17
	1-2	6.4	.10	17
	0.5-1	6.5	.10	17
	0.25-0.5	10.2	.17	14
Big Sandstone Creek near Savery	32-64	251	8.68	2
	16-32	133	3.75	4
	8-16	77.9	1.85	7
	4-8	27.4	.47	13
	2-4	28.7	.49	13
	1-2	14.4	.20	18
	0.5-1	15.4	.22	18
	0.25-0.5	16.3	.23	17

sampled, 32 to 64 millimeters (fig. 3 and table 4). Recurrence intervals of the flows of about 1.5 years (flow duration of about 2 percent of the time) are a commonly accepted value of recurrence for bankfull discharge (Emmett, 1975, p. A50). For movement of particles finer than 32 millimeters at the three streamflow-gaging stations, the recurrence interval of the peak flows is less than 1.1 years, indicating that the flow has greater than a 90-percent chance of being equaled or exceeded in any given year. Some large particles are likely not to move or to move only at infrequent flood stages. These large particles, mostly stationary, inhibit mobility of smaller particles such that in channels with large particles, the unit stream power necessary to move sediment of a given size is about an order of magnitude larger than the stream power necessary to move sediment in channels with much smoother beds.

To retain the geomorphic integrity of a channel downstream from a diversion, two aspects of the bedload transport problem need to be addressed. First, will particles larger than 4 millimeters remain in motion downstream from the diversion? Second, will sufficient unit stream power be available to prevent the fine particles, smaller than 4 millimeters, from accumulating in the substrate? Because the analysis of data presented in table 4 shows the power required to initiate movement of the particles in a natural channel, but not the power required to transport the material, we use inference when considering the power available to transport particles in motion below the diversion.

From table 4, it can be seen that the unit stream power required to initiate movement of large particles is nearly an order of magnitude less for East Fork Savery Creek than for Battle Creek and Big Sandstone Creek. It is hypothesized that particles in motion, 4 millimeters and larger, will remain in motion with a unit stream power of less than 0.77 pound per second-foot for all streams. The small power required to keep these particles in motion is consistent with the results of a survey of 20 channels upstream and downstream from diversion structures on mountain streams in Wyoming and Colorado (Wesche and others, 1988). Wesche and others (1988) found that there was no statistical difference in channel morphology upstream and downstream from the diversion structures. Some of the structures have reduced streamflow as much as 90 percent and have been in place from 12 to 106 years.

East Fork Savery Creek requires a unit stream power of 0.10 pound per second-foot to initiate movement of particles finer than 4 millimeters. Battle Creek requires 6 to 8 times more power to move particles finer than 4 millimeters, and Big Sandstone Creek requires 2 to 5 times more power to move particles finer than 4 millimeters than East Fork Savery Creek. The hypothesis used for coarse-grained particles also should apply for particles finer than 4 millimeters. That is, a unit stream power of 0.10 pound per second-foot required to move the finer particles at East Fork Savery Creek should transport particles finer than 4 millimeters that are in motion in all streams of the Sierra Madre.

The number of bedload samples collected at each of the miscellaneous sites is not sufficient to develop quantitative relations between bedload-transport rates and stream power. Therefore, the data were compared to the relations developed at the streamflow-gaging stations. Prediction intervals computed for Battle Creek (fig. 5) and East Fork Savery Creek (fig. 6) are plotted in figure 14. The prediction interval for Big Sandstone Creek (fig. 7) was not used because the results are similar to those for Battle Creek. All of the bedload data from miscellaneous sites, except those for Bear Creek (site 4), were plotted in figure 14. Data from Bear Creek were not included because the measurements were made on a riffle between two beaver dams, and the data were not considered representative of channels of unaltered streams.

If a value of bedload-transport rate from a miscellaneous site plots within the prediction interval of the bedload-transport rate data for a streamflow-gaging station, one can be 95-percent confident that the transport characteristics of the miscellaneous site are the same as those for the station. Bedload data for two of the miscellaneous sites, Haggerty Creek and Haskins Creek, plot within the prediction interval of Battle Creek (fig. 14), indicating cobble-and-boulder stream types. These two streams, though smaller

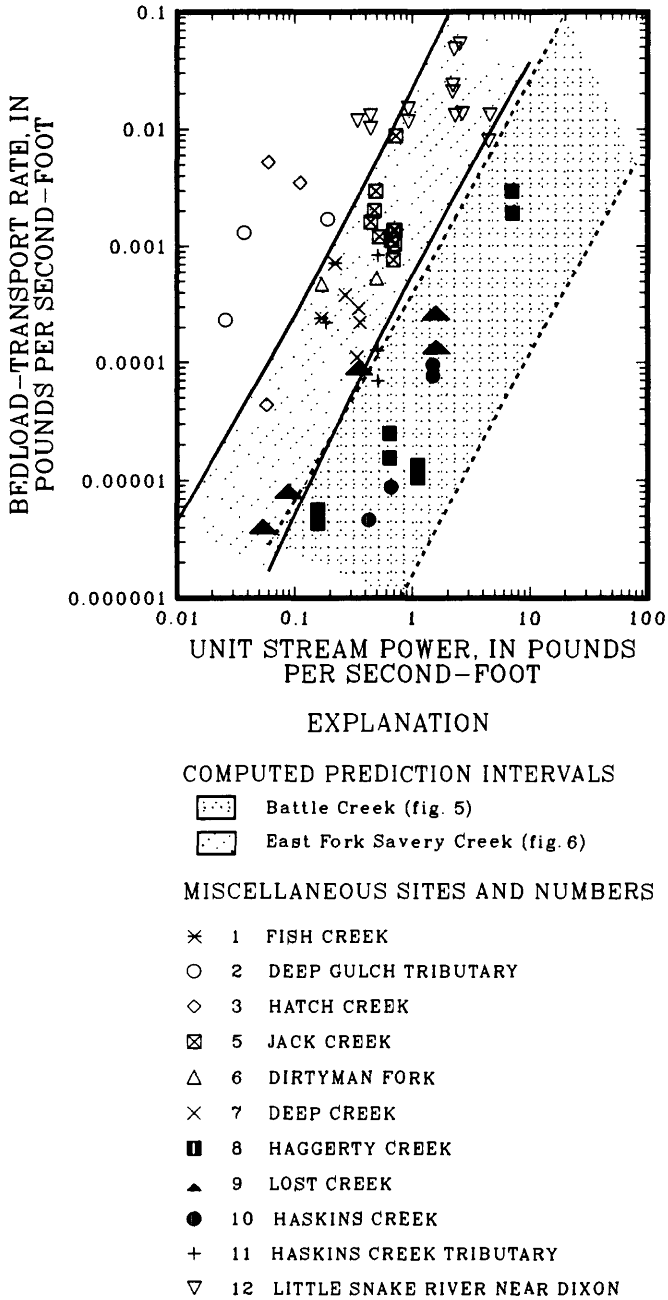

Figure 14.--Bedload-transport rate as a function of unit stream power at miscellaneous sites in the Sierra Madre.

than Battle Creek, have channels similar to that of Battle Creek, that is, steep slopes with cobbles and boulders. Haskins Creek tributary and Lost Creek are the only two streams whose data plot in the prediction intervals of both Battle Creek (a cobble-and-boulder bed) and East Fork Savery Creek (a gravel bed). The channels in the vicinity of the measurements are similar to the channel of the cobble-and-boulder-bed stream.

Bedload data for four sites--Fish Creek, Jack Creek, Dirtyman Fork, and Deep Creek--plot within the prediction interval of East Fork Savery Creek (fig. 14). Of the four sites, Fish Creek drains an area of sedimentary rocks. Hatch Creek, Deep Gulch tributary, and the Little Snake River near Dixon also drain areas of sedimentary rocks, but at least some of their data points plot to the left of the East Fork Savery Creek prediction interval (fig. 14), indicating that a stream power less than that of East Fork Savery Creek is likely to transport bedload.

The effects of vegetation encroachment, soil creep, and debris slides on the integrity of the channel downstream from a point of diversion were not addressed in this study. It should be safe to assume that the same level of power required to initiate movement of particles from the stream banks upstream from the diversions will be required to initiate movement of bank material downstream from the diversions.

CONCLUSIONS

Sediment availability and mobility are the controlling characteristics of bedload transport in mountainous areas. Bedload and streamflow data collected in the Sierra Madre clearly show the relation between sediment availability and stream power. The power required to move bedload in a cobble-and-boulder-bed stream is an order of magnitude greater than the power required to move bedload in a gravel-bed stream (figs. 5 through 7). The power required to initiate movement of selected particle sizes is nearly an order of magnitude greater in one of the cobble-and-boulder-bed streams than in the gravel-bed stream. These two factors, along with an analysis of the size distribution of bed material, bar material, and bedload, indicate that the power required to move the material through a given reach of the stream is related to the much greater unit stream power required to detach the material and initiate motion.

To maintain natural channel conditions, or conditions prior to any diversions, a daily mean discharge is required that is equaled or exceeded 13 to 18 percent of the time. Mean daily discharges in this range will initiate motion of particles from 0.25 to 4 millimeters in diameter. Movement of the largest particles sampled in this study (32 to 64 millimeters) requires a daily mean discharge about 2 percent of the time.

To maintain the channel downstream from a diversion, sufficient unit stream power must be available to keep particles larger than 4 millimeters in motion and to keep particles smaller than 4 millimeters from accumulating in the substrate. Because a unit stream power of 0.77 pound per second-foot was required to initiate and move particles larger than 4 millimeters on East Fork Savery Creek, it follows that a unit stream power of slightly less than 0.77 pound per second-foot was required to initiate and move particles larger than 4 millimeters on East Fork Savery Creek; and it also follows that a unit stream power of slightly less than 0.77 pound per second-foot will keep these particles in motion for all streams in the Sierra Madre. For particles smaller than 4 millimeters, a unit stream power of 0.10 pound per second-foot should keep the sediment from accumulating in the substrate.

Data collected at miscellaneous sites provide an overview of the power required to transport bedload material by streams on the western slope of the Sierra Madre. In general, the streams in the southern part of the study area have larger values of unit stream power for initiating particle movement and steeper channel slopes than the streams in the north. The data also show that the streams in the north are capable of transporting more sediment with less power, indicating a greater supply of fine materials.

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SUPPLEMENTAL DATA

Table 5.--Bedload-transport rates of selected particle-size ranges for three streamflow-gaging stations in the Sierra Madre, southern Wyoming

[The number of significant figures does not indicate the accuracy of bedload-transport rates, but is used to show the relative amount in each particle-size range]

Date	Discharge (cubic feet per second)	Bedload-transport rate, in tons per day, for indicated range of particle sizes, in millimeters							
		32-64	16-32	8-16	4-8	2-4	1-2	0.5-1	0.25-0.5
		09253400 Battle Creek near Encampment, Wyoming							
4/30/86	17				0.0013	0.00343	0.00488	0.00250	0.00080
5/12/86	38				.0019	.00181	.00415	.00461	.00137
5/21/86	129			0.0713	.1431	.18416	.24202	.17005	.06386
6/02/86	300		2.6992	3.8272	2.7184	2.16320	2.19040	1.42720	.81280
6/02/86	300		9.0184	2.9138	2.4048	2.42607	2.18964	1.42923	.76041
6/02/86	342	10.1904	9.6888	9.6184	5.5924	4.47040	2.48160	1.12200	.53680
6/02/86	342		7.2427	9.4895	10.8878	9.70752	5.93448	2.68758	1.09494
6/03/86	357		.9050	.1060	.2900	.48616	.69094	.60967	.45752
6/03/86	352	.7738	.3975	.4511	.4250	.45996	.47337	.33147	.19486
6/03/86	300		.2961	.7634	1.0265	1.13090	.69518	.37426	.20476
6/03/86	304		.3353	.6422	.6356	.78617	.73326	.45202	.27035
6/11/86	266	2.1736	.3191	.2839	.1728	.31267	.27856	.15501	.07807
6/11/86	266		1.3817	1.0329	1.1481	1.05681	.87843	.42603	.17409
6/11/86	266		.7479	1.3222	1.1867	1.10111	.81421	.34190	.12757
6/12/86	221		1.2396	.6931	.7438	.62592	.34944	.12902	.04646
6/12/86	214		.9805	.9076	.8680	.56430	.39838	.15523	.06692
6/12/86	201	1.6889	.7837	.2855	.3695	.44642	.47913	.23559	.11227
6/12/86	201			.3426	.4948	.48257	.48150	.22470	.09694
6/12/86	201		.6687	.1191	.1503	.18270	.17865	.12315	.06765
6/12/86	201			.1693	.1836	.32106	.34087	.16497	.07810
6/20/86	204		1.6929	.9856	.3926	.20965	.07421	.03420	.01915
7/01/86	105				.0029	.00105	.00158	.00076	.00048
4/29/87	53		.0764	.0587	.0948	.14556	.09405	.02809	.00720
5/08/87	126				.0131	.01650	.01517	.01227	.00811
5/08/87	131				.0143	.00837	.00901	.01440	.01271
5/09/87	101				.0014	.00826	.01446	.01102	.00551
5/09/87	95				.0120	.00763	.00953	.00714	.00469
5/09/87	126				.0021	.00962	.01169	.01581	.01444
5/09/87	124		.0965	.0080	.0192	.01363	.01342	.01335	.00878
5/10/87	111				.0025	.00279	.00536	.00838	.00658
5/10/87	105		.1329	.0079	.0072	.00856	.00922	.00789	.00396
5/19/87	151		.0391	.0908	.0617	.05268	.03426	.01876	.00807
5/28/87	65					.00104	.00220	.00011	.00307
6/10/87	57					.00017	.00041	.00051	.00058
5/13/88	32					.01905	.00515	.00040	.00040
5/17/88	89			.0273	.0171	.07087	.03710	.01645	.00560
5/25/88	99			.1702	.2173	.25300	.29210	.15870	.05520
5/25/88	99			.1882	.0973	.09145	.11092	.07375	.02655
5/28/88	233				.0321	.18236	.18031	.16597	.11748

Table 5.--Bedload-transport rates of selected particle-size ranges for three streamflow-gaging stations in the Sierra Madre, southern Wyoming--Continued

Date	Discharge (cubic feet per second)	Bedload-transport rate, in tons per day, for indicated range of particle sizes, in millimeters							
		32-64	16-32	8-16	4-8	2-4	1-2	0.5-1	0.25-0.5
		09253400 Battle Creek near Encampment, Wyoming--continued							
5/28/88	280		3.1824	3.4272	2.3664	1.94480	1.50960	.80240	.31280
5/28/88	284	4.7905	.8294	2.0449	2.2451	1.98770	1.35850	.70070	.30030
5/28/88	284		.4271	.4023	.2622	.30510	.35482	.29380	.20114
5/28/88	267		1.9888	1.0020	.4610	.18288	.09906	.03810	.03429
5/28/88	240				.0971	.16844	.13647	.09821	.06909
5/29/88	202				.0966	.22855	.14823	.10056	.07509
6/06/88	215		.0235	.0605	.0485	.03827	.02413	.00936	.00333
6/06/88	215	1.513	.4982	1.1808	.7503	.78720	.77490	.45510	.17220
6/06/88	272	1.205	2.0664	1.9926	1.9188	1.89420	1.74660	1.04550	.38130
6/06/88	302	1.547	4.5144	3.6784	3.3440	3.19770	2.69610	1.42120	.45980
6/06/88	334	10.839	3.4892	3.8038	3.2032	2.86000	2.23080	1.40140	.65780
6/06/88	334	7.385	9.1385	6.5275	4.7744	4.02840	2.94670	1.56660	.78330
6/06/88	334	6.961	2.3100	1.9096	1.4322	1.01640	.81620	.55440	.33880
6/07/88	280	2.945	.7148	2.0204	1.2675	1.06736	.86723	.45744	.17154
6/07/88	244		.6533	.3743	.8184	.79272	.60188	.31195	.10643
6/22/88	103		.4154	.3450	.4171	.30272	.18128	.07392	.01936
		09255400 East Fork Savery Creek near Encampment, Wyoming							
4/30/86	8.6					.00073	.00108	.00159	.00127
5/12/86	14.0				.0018	.00254	.00412	.00524	.00508
5/21/86	39.0		.3043	0.1046	.1130	.11966	.12671	.11260	.07164
5/21/86	38.0				.2322	.08741	.11291	.10516	.05630
6/01/86	54.0		1.0090	.9598	1.1525	1.12828	.88901	.82228	.49741
6/01/86	57.0		1.3968	1.5282	1.0114	1.01439	.86025	.69657	.54316
6/01/86	64.0	.9426	1.3286	.8514	.6742	.85269	.68215	.57639	.41974
6/01/86	64.0		1.0494	1.2740	.9940	1.32946	1.12845	.78186	.55648
6/01/86	60.0		.3788	.1717	.2221	.18031	.22000	.23814	.15779
6/02/86	60.0		.8781	.6849	.5284	.46948	.53676	.37460	.19958
6/02/86	60.0		.4060	.8899	.5076	.59220	.44053	.23392	.11614
6/02/86	59.0		.2811	.4629	.4107	.41854	.36782	.25193	.10997
6/02/86	58.0	.2972	.2831	.3832	.3038	.31073	.31947	.23690	.10166
6/02/86	56.0	.6279	.3764	.6795	.3840	.39257	.33961	.24560	.17609
6/12/86	48.0		.1578	.0501	.0308	.05548	.04482	.03812	.05148
6/12/86	48.0		.1634	.1177	.0780	.12037	.10087	.07800	.06322
6/19/86	39.0		.0745	.0704	.0991	.09251	.14196	.17043	.08494
6/19/86	39.0			.0159	.0286	.04230	.08843	.10911	.04294
7/02/86	14.0					.00067	.00067	.00233	.00267
4/29/87	15.0					.00214	.00888	.02782	.07107
4/29/87	16.0			.0145	.0168	.00989	.03390	.08620	.16946
5/08/87	17.0				.0004	.00513	.01559	.03780	.08606
5/08/87	18.0			.0049	.0109	.01998	.05322	.14316	.23346

Table 5.--Bedload-transport rates of selected particle-size ranges for three streamflow-gaging stations in the Sierra Madre, southern Wyoming--Continued

Date	Discharge (cubic feet per second)	Bedload-transport rate, in tons per day, for indicated range of particle sizes, in millimeters							
		32-64	16-32	8-16	4-8	2-4	1-2	0.5-1	0.25-0.5
		09255400 East Fork Savery Creek near Encampment, Wyoming--continued							
5/08/87	20.0			.0041	.0003	.00623	.04742	.09705	.13182
5/09/87	19.0				.0054	.02483	.04999	.10016	.12854
5/09/87	18.0				.0012	.01539	.03397	.06900	.07926
5/09/87	18.0				.0010	.00397	.00926	.02066	.03206
5/09/87	20.0			.0044	.0059	.01379	.03754	.09754	.11328
5/09/87	21.0			.0043	.0038	.02561	.07540	.16974	.19930
5/09/87	21.0		.0332		.0076	.03323	.07672	.15059	.19551
5/10/87	20.0			.0019	.0022	.02240	.05309	.10636	.12526
5/20/87	19.0			.0024	.0043	.01748	.04660	.05549	.03618
5/29/87	14.0				.0007	.00406	.01601	.02223	.01243
6/11/87	7.6					.00010	.00031	.00052	.00133
5/13/88	17.0			.0216	.0864	.12480	.27840	.53280	.98400
5/13/88	18.0			.0031	.0312	.07592	.15288	.24544	.41184
5/17/88	37.0			.0180	.0920	.10400	.17100	.22100	.28100
5/17/88	38.0	.1280	.0442	.0174	.0964	.17064	.25122	.31758	.42186
5/25/88	37.0			.0539	.0462	.06600	.13310	.28380	.39490
5/25/88	38.0		.0323	.0867	.0952	.12070	.24310	.46580	.53890
5/25/88	42.0		.2086	.1454	.1180	.13167	.23427	.38817	.40698
5/25/88	42.0		.0836	.0429	.0660	.09130	.17160	.26180	.31020
5/25/88	39.0			.0050	.0232	.04141	.10201	.28785	.48884
5/25/88	38.0			.0069	.0327	.05418	.11266	.26488	.33454
5/26/88	36.0		.0711	.0731	.0597	.05871	.10815	.27707	.32754
5/26/88	36.0		.0271	.0763	.0353	.04428	.09594	.22878	.26978
6/21/88	12.0					.00370	.00445	.01076	.01856
		09255900 Big Sandstone Creek near Savery, Wyoming							
5/21/86	99			.1274	.0207	.02561	.02387	.01580	.00455
5/21/86	108		.0552	.0114	.0271	.01888	.01140	.01246	.01140
6/02/86	212			.3754	.6049	.39721	.33741	.33143	.20953
6/02/86	216			.7172	.3985	.31322	.27999	.37250	.33356
6/02/86	252	1.1856	1.0442	.5714	.4990	.41521	.49480	.80190	.80962
6/02/86	259		1.0847	1.0554	.3340	.25841	.16042	.20838	.30981
6/02/86	259	1.5474	1.0621	.6918	.5726	.37213	.22133	.10579	.04269
6/02/86	250		1.0039	1.3986	1.0116	.42615	.29070	.20565	.12240
6/03/86	227		1.0674	.7501	.3267	.20529	.15115	.11953	.04851
6/03/86	225		2.9017	.7706	.5431	.24086	.15660	.08758	.04284
6/03/86	218			.0222	.0869	.11460	.20890	.31790	.23110
6/03/86	218				.0608	.03870	.06630	.06264	.04421
6/03/86	212		.0745	.0856	.1658	.21040	.21979	.11362	.04471
6/03/86	207				.0301	.03572	.08836	.17108	.13536
6/11/86	155		.3393	.2145	.2051	.15155	.21595	.29768	.28298

Table 5.--Bedload-transport rates of selected particle-size ranges for three streamflow-gaging stations in the Sierra Madre, southern Wyoming--Continued

Date	Discharge (cubic feet per second)	Bedload-transport rate, in tons per day, for indicated range of particle sizes, in millimeters							
		32-64	16-32	8-16	4-8	2-4	1-2	0.5-1	0.25-0.5
		09255900 Big Sandstone Creek near Savery, Wyoming--continued							
6/11/86	157		.8185	.3316	.2555	.18050	.14170	.13507	.12442
6/19/86	144		.2950	.3023	.2743	.24913	.16211	.12784	.06094
6/19/86	148		.0351	.1129	.0674	.05734	.07280	.07384	.04249
7/02/86	36				.0017	.00087	.00289	.00433	.00260
4/22/87	13				.0010	.00894	.00918	.00393	.00274
4/29/87	33				.0013	.00050	.00295	.01112	.01545
4/29/87	37				.0031	.00134	.00253	.01141	.01663
5/07/87	59				.0046	.00526	.01122	.02770	.02703
5/08/87	52					.00575	.01590	.02639	.01624
5/08/87	65					.00177	.01693	.04893	.03649
5/09/87	59			.0039	.0008	.00404	.01885	.04173	.02599
5/09/87	60				.0033	.00065	.00574	.01356	.01016
5/09/87	69			.0034	.0102	.00949	.02715	.07364	.05599
5/09/87	65					.00168	.00571	.01712	.01779
5/10/87	59					.00033	.00267	.00933	.00900
5/19/87	85				.0024	.00138	.00395	.01141	.01403
5/29/87	38				.0003		.00015	.00052	.00133
6/10/87	28						.00009	.00037	.00034
5/13/88	25					.00977	.02253	.03238	.01804
5/13/88	26					.00832	.01284	.00832	.00680
5/17/88	66					.01347	.03271	.05535	.04040
5/25/88	108					.04336	.06064	.10008	.09258
5/29/88	167		.1784	.0903	.0580	.13330	.35260	.72025	.51815
6/22/88	32					.00138	.00207	.00412	.00343

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