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PRESSURE-DIFFERENCE BEDLOAD SAMPLER

E. J. HELLEY & W. SMITH

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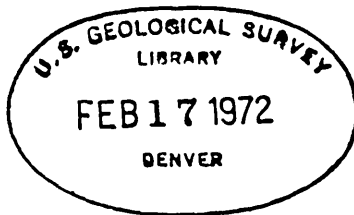
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DEVELOPMENT AND CALIBRATION OF A PRESSURE-DIFFERENCE
BEDLOAD SAMPLER

By

Edward J. Helley and Winchell Smith



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DEVELOPMENT AND CALIBRATION OF A PRESSURE-DIFFERENCE BEDLOAD SAMPLER

By Edward J. Helley and Winchell Smith

ABSTRACT

The Helley-Smith bedload sampler is a pressure-difference sampling device designed for use in natural streams carrying coarse sediments. It is of convenient size, weighing 65 pounds, and it can be handled by one man using conventional stream-gaging suspension equipment.

Extensive calibration has not yet been made, but the studies that have been possible suggest that overregistration by about 50 percent may occur when the device is used in streams carrying sand-sized material. In streams carrying coarse material, bedload transport, measured by the sampler, is in reasonable agreement with bedload transport, computed by the Meyer-Peter and Müller procedure.

Field experience with the sampler has indicated that it is a usable device which will permit a direct measurement of coarse bedload in transport in relatively high-velocity flow regimes--situations that have heretofore been beyond the range of convenient measurement.

INTRODUCTION

The need for data on bedload transport has long been apparent to both scientist and river engineer. Bedload is a significant part of the total sediment transported by many streams, yet procedures and equipment have not yet been developed to permit its direct measurement. Movement of bedload by bouncing, rolling, or sliding is largely responsible for changes in the geometry of alluvial channels. In large rivers such changes can be a navigational hazard. Short-term changes in channel geometry, known as scour or fill, are frequently responsible for damage to bridges and other structures. More recently bedload has been recognized for its influence on the disposal of wastes which may be entrained physically and (or) chemically in the moving debris.

Although several computational methods for determining bedload have been developed, none is universally applicable to all sediment sizes, bed configurations, and flow regimes. One major difficulty with these computational methods is that the true size distribution of the moving bedload is difficult to determine. Size-distribution measurements made after a flood event do not necessarily represent material in transport during the flood, and present bed-material sampling equipment is of limited value in streams carrying materials of highly variable size. Direct measurement of the bedload would provide these size distributions, as well as data on the variation in transport rate in both time and space. Direct measurement would also provide invaluable information on the hydraulic behavior of the various sizes, shapes, and densities of sediment in transport and data from which sediment sources might be identified.

This report presents information on the general details of a pressure-difference type sampler developed by the authors to meet the rather specific needs for measurement of bedload in California coastal streams. These are typically rain-fed mountain streams carrying heavy loads of coarse sediments. Bed slopes are steep; water velocities are high; and water discharges are highly variable.

Results of calibration work and field tests are included to provide a base for evaluation of the effectiveness and the potential application of this sampler in other areas. For convenience this particular sampler has been designated the Helley-Smith bedload sampler.

This report was prepared by the U.S. Geological Survey, Water Resources Division, California District, under the general supervision of R. Stanley Lord, district chief in charge of water-resources investigations in California. The continued interest and encouragement given by Luna B. Leopold, Staff Scientist, Washington, D.C., and the time-consuming and detailed flume calibration studies made by Harvey Jobson, Research Hydraulic Engineer, Fort Collins, Colo., are gratefully acknowledged.

DESIGN CRITERIA

The product desired from any sediment sampling program is a measure of the sediment in transport. Techniques and equipment for measurement of suspended material have progressed to a reasonable level of acceptability and provide a means for documentation of the load in transport from the water surface to a point about 0.3 foot above the bed. (The nozzle of typical suspended-sediment samplers is 0.3 foot above the bottom of the device.) Thus, a prime requirement for this bedload sampler is the ability to document the transport in the unmeasured zone, that is, from the bed to a point about 0.3 foot above the bed. This initial constraint dictates the approximate size of the sampler nozzle. Other constraints considered important in the design were:

1. That the sampler be hydraulically stable in velocity regimes of at least 10 fps (feet per second) and of sufficient mass to maintain its position on the bed during the sampling interval.
2. That it be of a configuration which would provide minimum disturbance to the flow regime when in place on the streambed.
3. That it be of a size and shape that can be handled by one man using the suspension equipment designed for routine stream-gaging work.
4. That provision be made for rapid and efficient retrieval of the sample collected.

THE BEDLOAD SAMPLER

Description

The configuration of the sampler is shown in figure 1. The external shape is similar to that of the sounding weights commonly used in stream gaging. The torpedo shape is outlined by three curved aluminum tubes which connect the 3- by 3-inch entrance orifice to the stabilizing tail-fin assembly. The sample is caught in a mesh bag attached to the back of the orifice assembly. The detail drawing of the brass orifice (orifice A) assembly (fig. 2) shows the entrance orifice and expanded section at the rear of the orifice. The expanded area provides the pressure difference, or velocity drop, necessary to trap the moving sediment. The entrance orifice extends up from the streambed about 3 inches, only slightly less than the lower limit to which suspended-sediment samplers, now in general use, reach. Mass of the sampler is developed by use of 1/4-inch brass in the orifice assembly and by loading the curved aluminum tubes with lead. Total weight is approximately 65 pounds which can be readily handled by one man using conventional stream-gaging equipment. Materials and fabrication techniques employed are shown in plan and side-elevation drawings, figure 3.

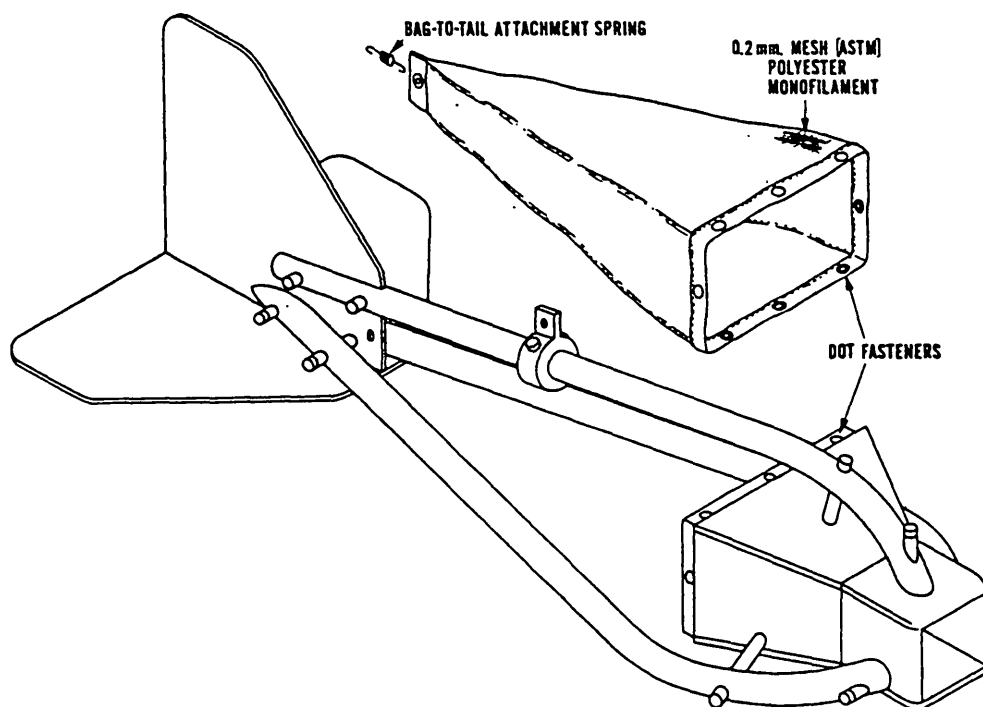


FIGURE 1.--The Helley-Smith bedload sampler.
Sampling bag attached.

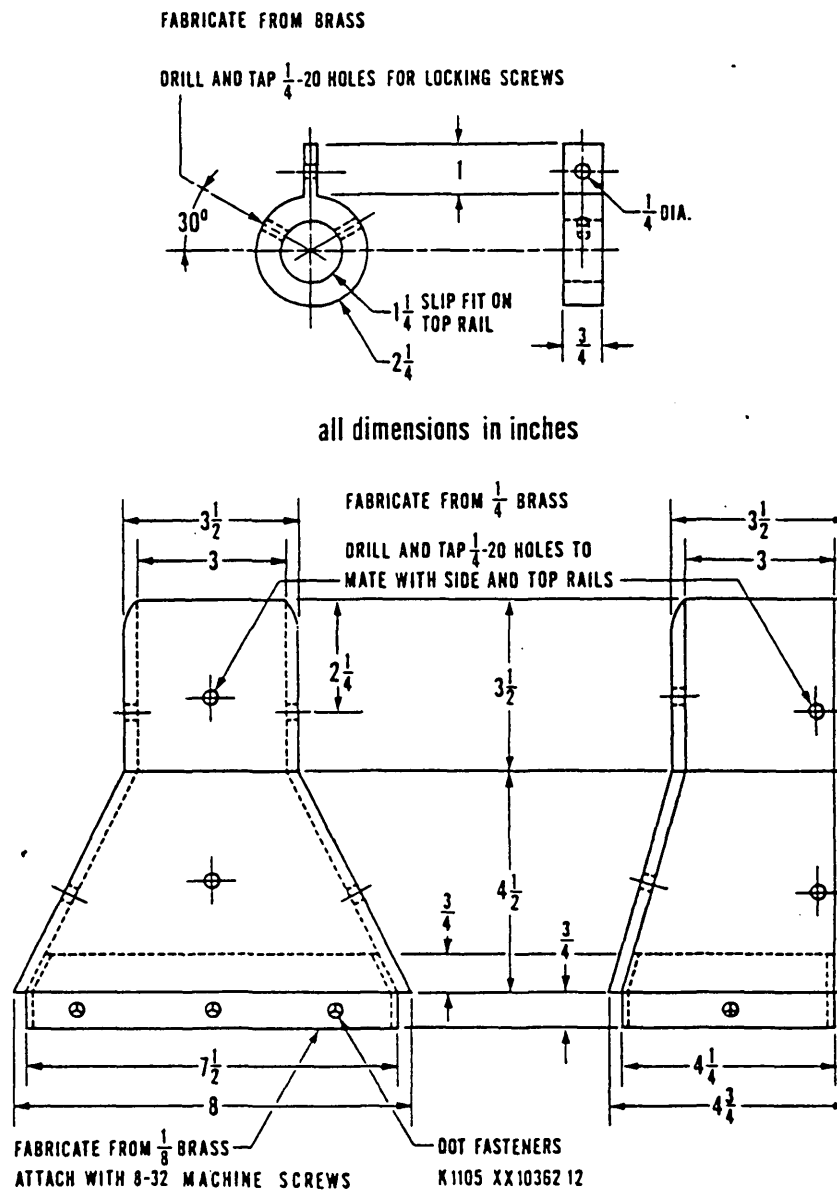


FIGURE 2.--Plan and side-elevation of orifice A.

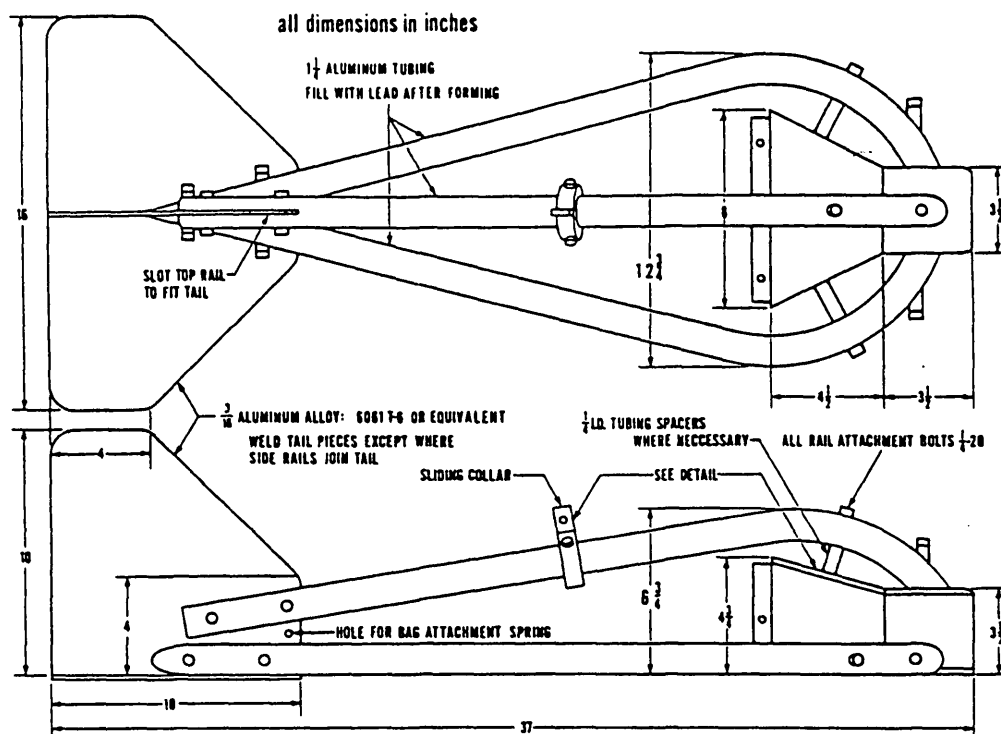


FIGURE 3.--Plan and side-elevation of Helley-Smith bedload sampler.

Material used for the collection bag is polyester monofilament mesh of 0.2 mm (millimeter) and meets ASTM (American Society for Testing Materials) standards for uniformity. It is rugged and extremely resistant to abrasion and wear and does not absorb water--it does not wet. Thus, samples, even those of fine sand, can be removed from the bag without washing. It is generally not necessary to remove the sample bag from the orifice even though the dot fasteners afford easy detachment. The sample can be quickly and efficiently removed by standing the unit on end and lightly tapping the mesh bag.

The angle at which the sampler enters the flow can be adjusted by proper positioning of the sliding collar to which the support cable is attached. The collar is set so that the sampler will touch the water tail first to aid in rapid orientation with the streamlines of flow. This suspension attitude also insures that the sampler orifice will lift up immediately when the unit is raised from the bed, thus avoiding the loss of sediment by spillage.

Hydraulic Calibration

Hydraulic calibration refers to the comparison of ambient velocities with those observed in the orifice of the sampler. Ideally, the velocity in the entrance of the orifice should be no different than that of the stream.

Preliminary tests were made in a 4- by 4- by 60-foot clear-water recirculating flume at California State College in San Jose, Calif. The purpose of these tests was to observe the performance of the prototype unit in a flowing stream and to obtain some data on hydraulic characteristics. Depth of water in the flume was stabilized at 1.25 feet with a mean velocity of about 3 fps. These conditions were maintained throughout the test period.

The sampler was suspended from a boom by a cable near the midpoint of the flume. Performance of the sampler as it was lowered to the flume bed and raised again was documented by slow-motion moving-picture photography. The sampler was also allowed to hang in the flow to observe its stability. Review of the films indicated that the sampler was quite stable in the stream under the flow conditions imposed, supporting, in general, the design decisions made as to the size and configuration of the tail assembly and mode of suspension employed.

The hydraulic characteristics were then checked by lowering the unit to the bottom and measuring the velocity distribution within the entrance nozzle at three points along a horizontal and vertical transect. These measurements were made with a Prandtl-type pitot tube with an 1/8-inch outside diameter. The ambient velocity of 2.80 fps at the elevation of the centerline of the orifice was measured by extension of the pitot tube to a point 1.0 foot in front of the orifice and by a second pitot tube outside the sampler. Velocities measured within the sampler nozzle and along the centerline of the nozzle are shown in figure 4. Velocity distribution in the horizontal was almost identical to the measured velocity in the vertical.

These data indicated that the velocities within the nozzle of the sampler were consistently higher than the ambient velocities and that acceleration of flow began about 4 inches in front of the orifice itself. Velocities measured near the sides of the entrance nozzle were, as would be expected, appreciably lower than those on the centerline. The acceleration of the flow approaching the entrance does not exceed 10 percent for distances from the nozzle greater than about 1 inch. The effect of this change in velocity on the actual catch of the sampler is conjectural, but it probably would not greatly influence the performance when coarse material is predominant.

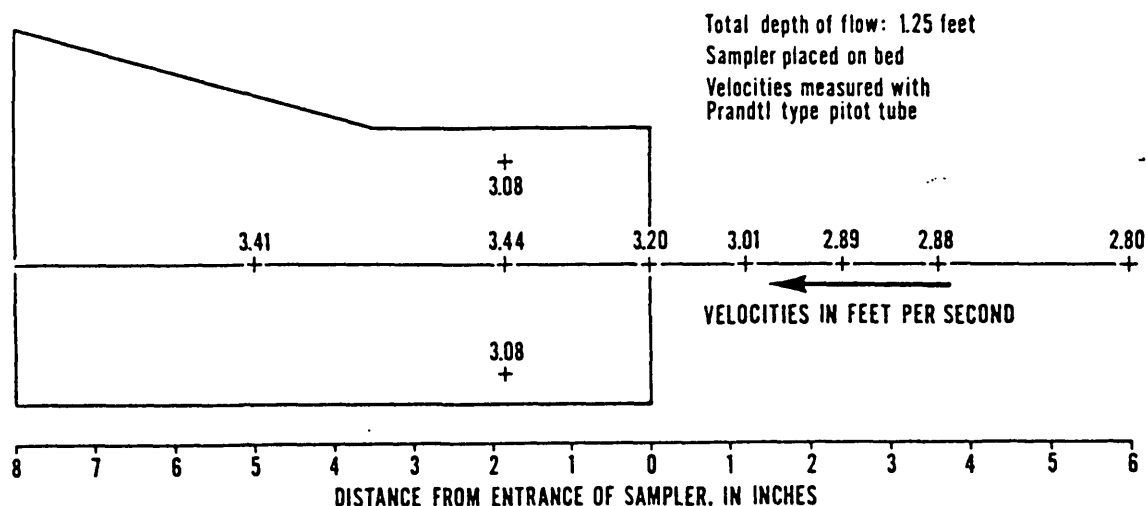


FIGURE 4.--Streamflow velocities along the centerline of the sampler orifice.

The scope of the work in the San Jose flume was limited by the range of conditions that could reasonably be imposed; therefore, a second series of tests was made February 19 and 20, 1970, in the towing tank operated by the U.S. Army Corps of Engineers at Bonneville, Oreg. (The towing-tank procedures and specifications were described by Johnson, 1966.) These tests were designed to determine the hydraulic characteristics of the sampler in velocity regimes ranging from 2 to 8 fps, to determine the effect on hydraulic efficiency of changes in the content of the sample bag, and to ascertain the effects of modifications of the geometry of the nozzle assembly. In the prototype, designated orifice A in the discussion which follows, the ratio of the area of the flared rear section to that of the entrance nozzle was 3.5:1. Two additional orifices, designated orifices B and C and having rear section to entrance section ratios of 2.5:1 and 2.0:1, were fabricated for testing along with orifice A. Conventional Geological Survey stream-gaging suspension equipment was used to simulate the stability problems that might be encountered in fast flows. At the towing tank, as at San Jose, the ambient velocities were compared with velocities measured in the nozzle by pitot tube. The towing speed was used as the ambient velocity.

Runs were made at velocities ranging from 2.0 to 6.4 fps. Orifice A was tested first and more completely than the other two. Velocities were measured in orifice A with the sample bag empty, 1/3 full, and 2/3 full of coarse sediment of about 10 mm median size. Orifices B and C were tested with the sampler bag empty and 2/3 full. Figure 5 shows the results of these tests. It is immediately evident from this plot that changes in orifice type or partial filling of the sample bag have practically no effect on the flow into the nozzle. Velocities measured at the centerline of the nozzle, V_s , are consistently higher than the ambient velocity, V_f , and conform to the equation

$$\frac{V_s}{V_f} = 1.08 V_f^{0.092}.$$

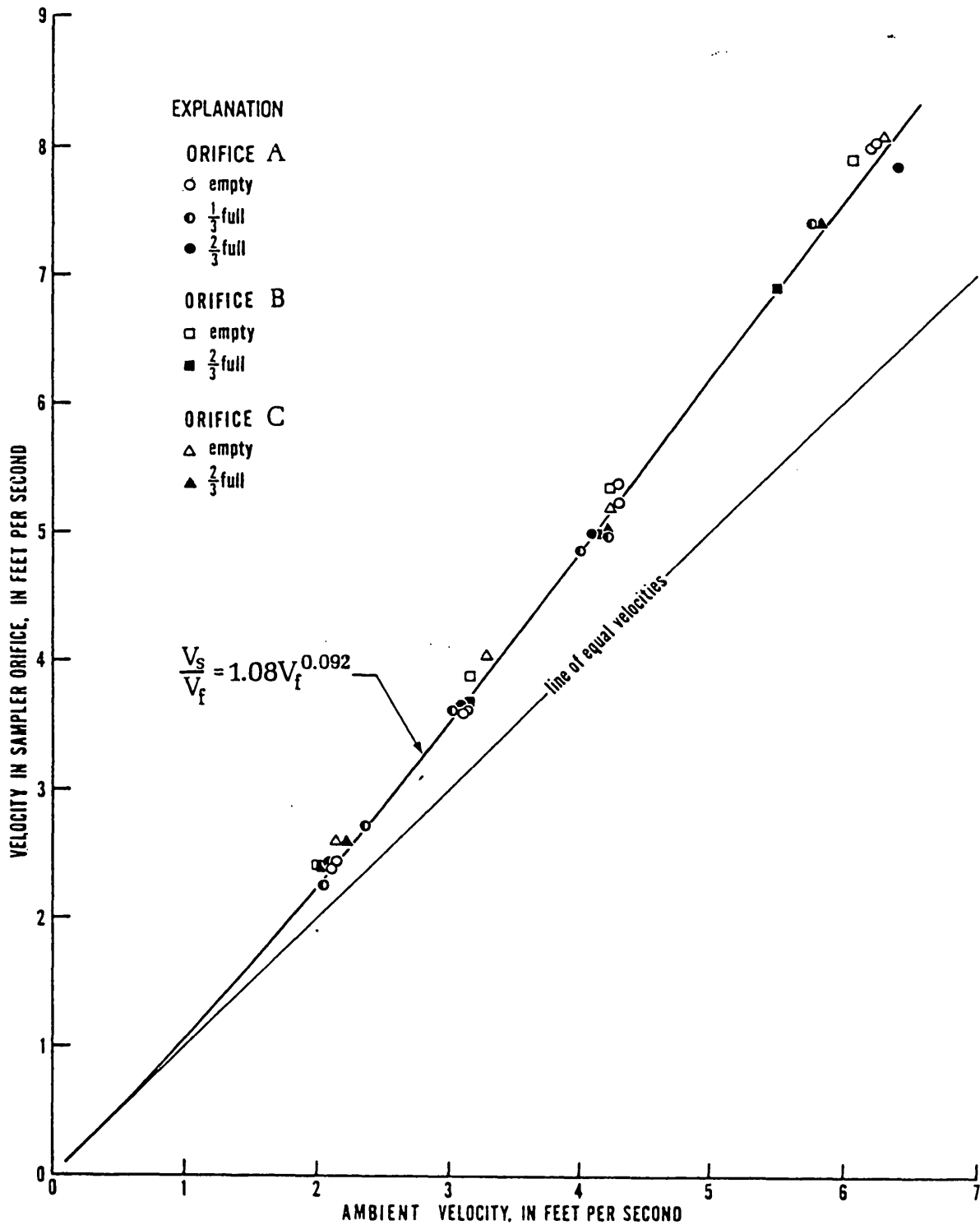


FIGURE 5.--Relation between ambient velocity and velocity in the three sampler orifices--sample bag empty, 1/3 full, and 2/3 full of sediment.

Points based on data obtained using partly filled sample bags tend to plot below those for the empty-bag condition, but differences noted are generally within the probable error in the observations.

Conclusions which can be made from these tests are:

1. That velocities in the sampler nozzle will be consistently higher than the ambient velocity, and that the percentage departure will increase as the ambient velocity increases.
2. That acceleration of flow occurs within a short distance in front of the nozzle entrance.
3. That, because velocities do increase in the approach area of the nozzle, the device should be expected to overregister rather than underregister.
4. That hydraulic characteristics of the sampler are not significantly controlled by the ratio of entrance to exit areas of the nozzle assembly.
5. That changes in sampler performance as the sample bag fills to as much as 2/3 capacity will be negligible.

Data on the hydraulic characteristics of the unit provide qualitative information about probable performance, but such data cannot be used directly to evaluate the sediment-trap efficiency of the unit. Controlled experiments are still needed to define sediment-trap efficiency.

Sediment-Trap Efficiency

Sediment-trap efficiency is defined as the ratio of the quantity of sediment trapped in the bedload sampler to the quantity of the sediment the stream is actually transporting as bedload. Determinations of this ratio are virtually impossible to make in natural streams because the true transport rate cannot be determined. Therefore, a controlled laboratory experiment was initiated using the recirculating sediment flume at Fort Collins, Colo. The tilting recirculating flume is 200 feet long, 8 feet wide, and 4 feet deep (Simons and others, 1961). Tests were conducted here under equilibrium flow conditions as an adjunct to an ongoing research program for which the flume had been filled with natural sand of a median size of 1.15 mm. The grain size of this bed material was much smaller than that for which the sampler was designed, but the testing with this size material was done because of economic necessity.

The procedure for determining trap efficiency is described by Harvey Jobson (written commun., 1971) as follows:

Before any run was started, the flow was allowed to stabilize and the flume controls were adjusted until equilibrium flow was obtained throughout the flume. After equilibrium flow had been established, the flow was maintained continuously until the end of the run. During the run, samples were collected repeatedly at equal intervals of time, either 1 hour or 6 hours.

The bedload sampler was suspended from a cable on the centerline and about 10 ft upstream from the end of the flume. The bedload sample time--the amount of time the sampler was actually on the bed--was determined by use of a stopwatch. The sand collected during each sample time was dried and weighed.

Suspended load was determined by use of a DH-48 sampler. Several verticals across the entire width of the flume were taken in order to fill each sample bottle. The volume of water in each sample bottle was determined by use of a graduated cylinder, and the sand was separated by filtration. The sand was dried and weighed to the nearest one-tenth of a milligram. The sampler nozzle occasionally came in contact with dunes in the bed, and excessive quantities of sand were scooped up. If this condition was detected at the time of sampling, the sample was discarded and another sample obtained. Otherwise, any sample containing excessive sand was omitted in computing the average.

Harvey Jobson (written commun., 1971) also says that the total-load sample was obtained by use of splitter--a device that collects all the water and sand which passes off the end of the flume, through a section 1/2-inch wide. The splitter was slowly traversed across the entire width of the flume while obtaining one sample. The weight of the water collected was determined volumetrically by use of a calibrated tank. The sand in the sample was then dried and weighed.

He further states that the water discharge was determined for each sample by use of a side-contracted orifice in the return-flow pipe. The depth was determined for each sample as the average of 32 individual depth measurements obtained at 5-foot intervals along the flume. The velocity was computed as the discharge divided by the width multiplied by depth. The values given for each run represent the average of the values obtained for each sample.

The results of these tests are summarized in table 1.

TABLE 1.--Comparison of bedload transport, computed from flume data, with bedload transport measured
by sampler

Period of test	Water discharge Q (cfs)	Average depth of water (ft)	Velocity (fps)	Sampling interval (hours)	Number of samples	Sediment transport in flume (tons per day per ft)				Sampler measurement (tons per day per ft)		Ratio $\frac{Q_f}{Q_s}$ (percent)
						Average total load	Standard deviation	Average suspended load	Average bedload (Q_f)	Average bedload (Q_s)	Standard deviation	
July 20-21, 1970	13.2	0.98	1.68	1	33	0.145	0.053	0.006	0.139	0.198	0.238	70
July 22-Aug. 7, 1970	13.4	.94	1.78	6	45	.295	.107	.0003	.295	.509	.469	58
Aug. 13-14, 1970	16.3	1.01	2.01	1	33	.913	.212	.023	.911	1.222	1.092	75
Aug. 14-28, 1970	16.4	1.02	2.01	6	55	.929	.293	.008	.921	1.125	1.092	84
Sept. 3-4, 1970	20.0	1.03	2.42	1	33	2.06	.540	.040	2.02	3.76	2.660	54
Sept. 8-18, 1970	20.0	1.05	2.39	6	37	2.20	.920	.028	2.17	2.96	2.76	74
Nov. 10-14, 1970	40.1	1.18	4.26	1	26	31.358	10.747	4.93	26.43	38.817	28.070	68
Dec. 15-18, 1970	25.0	1.03	3.02	1	32	9.150	3.950	2.325	6.825	10.550	7.975	65
Feb. 23-25, 1971	29.4	.99	3.73	1	29	14.700	5.527	4.322	10.378	27.224	22.638	38

Results of this test program are disappointing because the variance between individual samples, expressed as the standard deviation, is so high--equal in most cases to the mean value of the samples collected. Factors contributing to this wide variance are (1) that apparently the bedload transport is in fact extremely variable in time and in space, and (2) that point samples tend to reflect this variability. It is also noteworthy that total transport rates measured by the flow splitter reflect a similar but smaller variance--yielding a standard deviation of about one-third of the mean value of concentrations measured. Significant variability in measured suspended-sediment loads is also apparent. However, these factors do not fully explain the high variability in the sampler data.

Speculation by Harvey Jobson (written commun., 1971) provides additional insight.

"The sampler was quite heavy, and the bed for this sand was a little soft. Thus, the sampler tended to sink into the sand. The current pulled the sampler downstream as it was lowered to the bed. When the sampler was raised off the bed, it tended to slide upstream a small distance before it was raised from the bed. This sliding upstream would tend to scoop up additional sand. These results were obtained with only a single bed material, 1.15 mm. I [Jobson] would suspect that the performance of the sampler is very dependent on the bed-material size. For example, if the bed material was composed of coarse gravel, the sinking of the sampler into the bed would not be much of a problem. Bed forms should be small and long so that position on a dune or other bed form would be no problem, and the tendency to scoop up additional material when the sampler was lifted would be lessened."

If the flume data are accepted as providing some significance as to the sampler performance, a curve such as shown in figure 6 can be developed. This direct plot of sediment-transport rates computed from sampler data against transport rates derived from the flume data suggests that the sampler may consistently overregister by about 50 percent.

It seems reasonable to expect that the trap efficiency of the sampler will be related to the hydraulic characteristics of the device. Velocities in the entrance of the sampler are higher than ambient velocities as shown in figure 5. If a 1:1 relation held between the velocity ratio and the trap efficiency, C , then it would follow that the collected sample, Q_s , would be related to the true bedload, Q_f , by the equation:

$$C = \frac{Q_f}{Q_s} = \frac{V_f}{V_s} \quad (1)$$

and as

$$\frac{V_s}{V_f} = 1.08 V_f^{0.092} \quad (2)$$

then

$$C = \frac{Q_f}{Q_s} = \frac{1}{1.08 V_f^{0.092}} \quad (3)$$

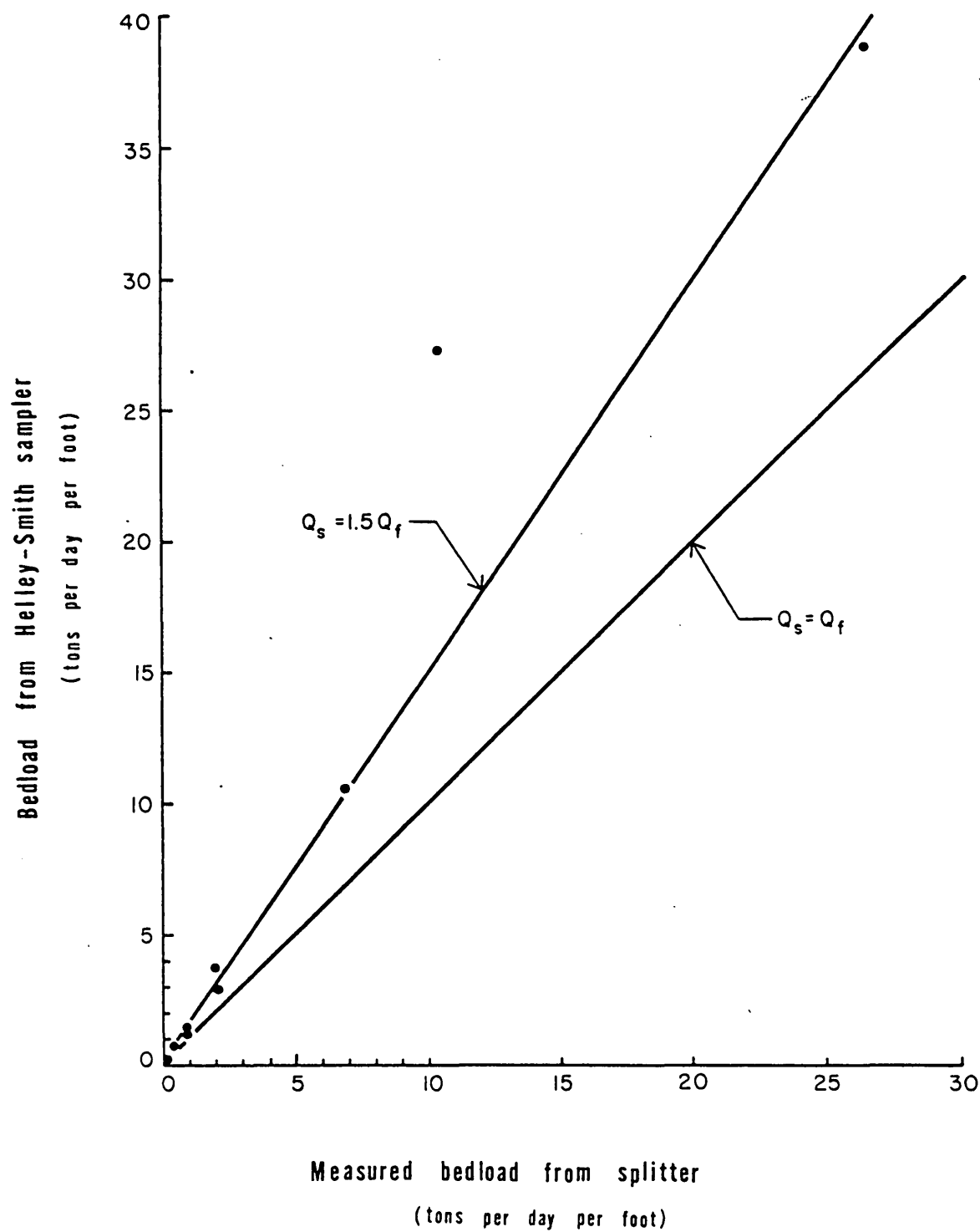


FIGURE 6.--Comparison of bedload as measured by the flow splitter and the bedload sampler.

It is also probable that a linear 1:1 relation is not to be expected, but that the effects of the hydraulic characteristics would be manifest in a higher order function such as:

$$C = \frac{Q_f}{Q_s} = \left(\frac{V_f}{V_s} \right)^2 \quad \text{or} \quad \left(\frac{V_f}{V_s} \right)^3 \quad (4)$$

Figure 7 is a plot of the trap efficiency, which is the calibration coefficient for the sampler, against the observed mean velocity in the flume. Curves drawn conform to the second- and third-power functions in equation 4. Scatter of the data is too great to permit evaluation of the correctness of either function, but the trends do confirm the probability that such a functional relation may exist. Use of a calibration equation conforming to the second-power function is recommended by the authors where transport rates are to be measured with this sampler in channels carrying material in the 1-mm median size range. Use of such an equation in regimes where larger sediments predominate is, however, highly conjectural; the flume data do not provide a base for valid recommendation.

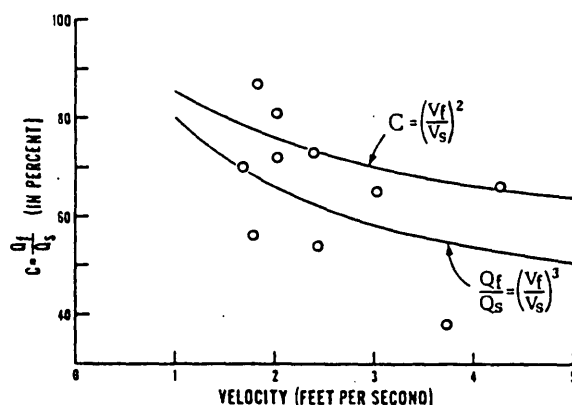


FIGURE 7.--Sampler trap efficiency, C , plotted against mean ambient velocity.

Field Testing

Field use of the Helley-Smith bedload sampler was initiated early in the development program and prior to the calibration work reported here. The design of the prototype evolved through this field use on California streams. Compatibility with the U.S. Geological Survey's existing sediment program was a primary guide in the development because the desired end result was the direct measurement of total sediment loads. Data were needed to meet the demands of current sediment-transport problems. Uniform sampling procedures were used at each field site, even though the flow regimens varied considerably.

First, a water-discharge measurement was made, and the centroids of cross-sections representing 10, 30, 50, 70, and 90 percent of the total discharge were computed. Both suspended-sediment and bedload measurements, were made at these five points in the cross section. Repeated measurements, perhaps as many as five samples at each point, were made if the water discharge remained fairly steady. The suspended-load samples were collected by standard depth-integrating samplers using techniques described by the U.S. Inter-Agency Committee on Water Resources, Subcommittee on Sedimentation (1963). Measurements with the bedload sampler were made by lowering the sampler to the streambed and leaving it in position for a measured period of time. This sampling time might range from 20 seconds to 5 minutes, depending on the transport rate. Observation time was limited to that required for a catch totaling less than half the capacity of the sample bag.

The rate of bedload transport, in tons per day per foot of width, was computed at each observation point from the dry weight of the sample and the time of observation. Total bedload transport for the stream was then computed by summation of the products of transport rates and the applicable widths. A trap efficiency of 1.00 was assumed in these computations. If the distance between sampling stations exceeded 25 feet, more than five sampling stations were used. When rapid changes in water discharge were encountered, frequent measurements at a reduced number of sampling points were made because the transport rates were considered to be more variable in time than with position in the stream. Data from three stations in California are listed in table 2. Shown also, for comparison, are bedload transport rates computed by the procedure described by Meyer-Peter and Müller (1948). These computations were based on size distributions of material retrieved with the bedload sampler.

TABLE 2.—Comparison of bedload transport, computed from sampler measurements, with bedload transport computed by Meyer-Peter and Müller procedure

Location	Date of test	Water discharge Q (cfs)	Median particle diameter d_{50} (mm)	Particle diameter at which 90 percent are smaller d_{90} (mm)	Bedload transport (tons per day)	
					Sampler measurement	Meyer-Peter and Müller procedure
San Antonio River near Lockwood, Calif.	Jan. 26, 1969	10,000	1.56	8.0	33,640	29,400
	Jan. 26, 1969	5,800	3.41	8.7	18,930	19,090
	Jan. 27, 1969	2,500	1.50	6.0	4,390	6,550
	Jan. 29, 1969	1,190	.62	5.0	460	1,120
North Fork Trinity River near Helena, Calif.	Dec. 19, 1969	1,400	16.0	36.0	216	374
	Jan. 18, 1970	2,920	9.8	32.0	661	1,070
South Fork Trinity River near Hyampom, Calif.	Dec. 18, 1970	1,550	4.5	10.0	125	168
	Feb. 21, 1970	2,900	7.7	18.0	1,060	1,600
	Apr. 23, 1970	710	1.0	5.0	2	0

The relation between measured and computed bedload transport is shown in figure 8. Transport rates computed from the sampler measurements are in reasonable agreement with rates computed by the classical procedures; the comparison does not show the overregistration characteristics indicated by the flume calibration. Significance of this should, however, not be overestimated, because validity of the Meyer-Peter and Müller procedure cannot be evaluated. The only conclusion that can be made is that transport rates computed from direct measurements made by the Helley-Smith bedload sampler are in reasonable agreement with transport rates computed by accepted theory.

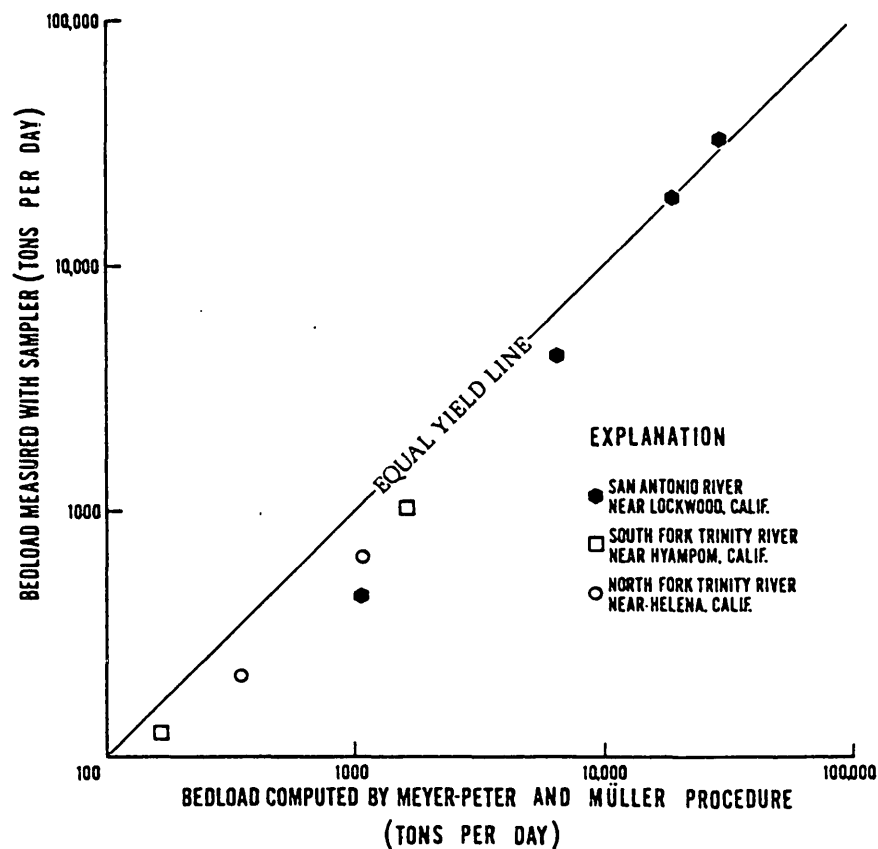


FIGURE 8.--Comparison of measured bedloads with those computed by the Meyer-Peter and Müller procedure for three stations in California.

SUMMARY AND CONCLUSIONS

The Helley-Smith bedload sampler was developed to meet the need of sedimentation studies involving the computation of total sediment loads. This sampler will meet the physical needs of the field problem. It can be inserted into high-velocity floodflows and will maintain its position on natural streambeds in velocities of as much as 10 fps.

Bedload-transport rates derived from sampler data compare favorably with those determined by classical methods in streams carrying loads of coarse material. Performance of the device in fine material is, as might be expected, subject to question. In soft material the sampler may tend to dig in and pick up material not in actual transport. Disturbances around the unit may produce scour which accentuates this problem. However, these same criticisms apply to other samplers heavy enough for use in high-flow regimes.

The hydraulic and trap-efficiency tests indicate that overregistration should be expected when the sampler is used in streams carrying sand-size material. Overregistration is likely to increase with velocity, and errors of as much as 50 percent may occur.

In spite of these deficiencies, this device offers considerable promise in meeting the need for an instrument capable of direct measurement of bedload transport. Additional calibration work is needed, however, to document performance characteristics in the regimes for which it was first designed. These are flow regimes carrying coarse materials 2-10 mm in size at velocities of as much as 10 fps.

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