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INFLUENCES OF INCREASED SAND DELIVERY ON THE MORPHOLOGY OF SAND AND GRAVEL CHANNELS[1]

William L. Jackson and Robert L. Beschta[2]

ABSTRACT: A flume study was conducted to examine (1) changes in the particle-size distribution of sediments in riffles due to the proportion of sand in transport and the total rate of bedload transport at the time the riffle is deposited and (2) the effect of high sand transport rates on the stability of gravel riffles. The median particle size of sediment deposited in the riffle was larger than that of the sediment in transport. Small but significant ($\alpha = 0.05$) decreases in the median particle size of riffle sediments resulted as the sand-to-gravel ratio of sediment in transport varied from 1:1 to 5:1. Gravel deposition efficiency decreased linearly as a function of the sand-to-gravel ratio. Increased concentrations of sand in transport caused previously stable gravel riffles to undergo scour. These results, in combination with information from other studies, suggest that an alluvial channel with pool-riffle sequences and with sand and gravel beds may respond to an increased delivery of sand by reducing form roughness. Form roughness can be reduced by degrading riffles and filling pools. Subsequent responses may be increases in width-to-depth ratio and slope.
(KEY TERMS: riffles; alluvial channels; streambed; bedload sediment; scour and deposition; channel morphology.)

INTRODUCTION

A strong interdependency exists between flow conditions and sediment transport, and the associated streambed composition and form (Schumm, 1971). An alluvial channel which has reached a balance among slope, channel characteristics and discharge is said to be "graded" if its resulting hydraulic characteristics are the minimum required to transport the sediment load delivered to the channel (Leopold and Maddock, 1953). If watershed conditions change and an increased supply of sand-sized sediments to a sand- and gravel-bed channel occurs, we hypothesize that a channel's initial morphologic response will be to reduce form roughness to permit increases in flow velocity and bedload transport capacity. Form roughness caused by gravel bars has been shown to account for approximately 50 to 75 percent of the total flow resistance in gravel bed streams with high width/depth ratios and low sinuosities (Prestegaard, 1983).

Form roughness may be reduced by filling pools and degrading riffles. Pools fill when transported sediments deposit in them at a higher rate than they are being removed. Usually at discharges less than bankfull, most sediments will tend to deposit in pools because sediment transport capacities are generally less than over riffles (Keller, 1971; Lisle, 1979).

Riffle degradation may occur as the result of reduced riffle stability. Reductions in riffle stability may be caused by decreases in the particle-size distribution of riffle sediments resulting from less sorting of sediment sizes during riffle deposition, or by increases in the capacity of the flow-sediment mixture to transport riffle sediments. Several researchers have suggested that increased concentrations of sediment in suspension near the streambed increase the ability of the flow to transport bed sediments (Vanoni, 1941; Einstein, 1944; Leopold and Maddock, 1953; Colby, 1964a). Initial reductions in form roughness would encourage subsequent adjustments in channel width, depth, and slope.

The objective of this research was to identify responses of alluvial sand- and gravel-bed channels to increases in sand delivery. Two flume experiments tested the effects of increased sand transport on the stability, size, and particle-size composition of gravel riffles. Results of the flume experiments, in combination with evidence in the literature, provided a basis for proposing a series of responses including degradation of riffles and filling of pools (decreases in bedform roughness), and increases in width-to-depth ratio and channel slope.

The discussion is intended to relate to general response tendencies. The actual nature and degree of response for specific channels will be dependent upon initial conditions, the magnitude of increased sand deliveries, and the magnitude and frequency of flow events which transport bedload sediments.

BACKGROUND

Graded channels are dynamic during periods of high flow. Sand- and gravel-bed stream channels with sequences of pools and riffles have nonuniform cross-sections in the downstream direction. Thus, hydraulic characteristics and bedload transport capacity are also nonuniform in the downstream direction and localized episodes of streambed scour and fill are normal

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channel processes during discrete runoff events (Colby, 1964b; Dietrich and Dunne, 1978; Jackson and Beschta, 1982; Andrews, 1982). Jackson and Beschta (1982) describe a model of bed material routing in sand- and gravel-bed channels where, at discharges less than bankfull, bedload transport consists primarily of sand-sized materials being routed over stable gravel riffles. At higher discharges, riffle gravel materials are also transported downstream. However, because of nonuniform channel geometries, bedload transport rates are unsteady and one or more sequences of partial riffle sour and fill may occur during high discharges. Upon the recession of high flows, a final riffle deposition and a natural sorting of particle sizes occur. The bed material composition of riffles is considerably more coarse than that of the bedload sediment in transport at the time riffle sediments are deposited. "Left-over" sand-sizes bed material must therefore deposit elsewhere in the stream channel. The sorting of sediments by particle size and the long-term maintenance of pool-riffle sequences are the result of nonuniform downstream distributions in bottom velocities and average bed shear stress, and relative differences in the rate of increase of average bed shear stress with discharge in pools and over riffles (Keller, 1971; Lisle, 1979). We did not find research results which described the effects of varying amounts of sand in transport on the relative degree of sorting of bed materials by particle size.

Scour and fill processes, operating over a range of flow regimes, provide a means by which alluvial channels can undergo morphologic adjustments to changes in sediment regime. In addition to affecting channel depth, scour and fill may influence changes in channel width (Andrews, 1982) and the particle-size composition of channel beds (Kellerhals, 1967; Beschta and Jackson, 1979). While much information is available concerning the hydraulics of streambed scour (e.g., Vanoni, 1975), there is a lack of research pertaining to the deposition process. This is particularly true with regard to the sediment size distribution of depositional features and how these distributions are affected by the flow conditions and sediment transport conditions which exist during deposition (Bagnold, 1968). There is a similar lack of information on the effects of high concentrations of sediment in flow on bed stability, although Colby (1964a), Simons, *et al.* (1963), and Yalin and Finlayson (1972) have discussed general implications of high sediment concentrations on fluid viscosity and density and, in turn, the implications for increased sediment transport.

Schumm (1971) analyzed various hydraulic geometry relationships and developed a generalized relationship to describe the response of an alluvial channel to increased sediment discharge. In that relationship, channel width, slope and meander wavelength vary directly whereas channel depth and sinuosity are inversely proportional with bed material transport. Alluvial channels may respond to increased sediment delivery by filling pools (Lisle, 1982), smothering of gravel features (Platts and Megahan, 1974; Megahan, *et al.*, 1980), and widening (Grant, 1977; Platts, 1981; Lyons and Beschta, 1983; Beschta, 1984). In addition, increases in the percentage of fine (<0.85 mm) sediments in channel gravel beds have been attributed t increased fine sediment delivery to streams (Cedarholm an Salo, 1979).

METHODS

Two flume experiments were conducted at the Kalam Springs Field Laboratory of Weyerhaeuser Company, approx mately 80 km east of Longview, Washington. A sedimen deposition experiment was designed to test the influence o (1) the proportion of sand-sized sediment in transport, an (2) the rate of sediment transport on the particle-size compo sition of the resulting depositional (riffle) feature. A secon experiment tested riffle stability under increased concentra tions of sand transported.

Both experiments were conducted in an outdoor rectangu lar flume having two distinct reaches. The upstream reach wa 5.8 m long and 0.35 m wide. Slope and roughness were ad justed so that flows transported all bed sediments at the ra at which they were added at the upstream end of the flum Downstream from a 1.8 m transition reach was an addition 5.5 m of flume with a width of 0.41 m. The bottom slope o this section was decreased and hydraulic roughness increase resulting in the deposition of stable gravel riffles. Prete hydraulic conditions in both the upstream and downstrea flume reaches are summarized in Table 1.

Deposition Experiment

In the deposition experiment, specific volumes of sedimen mixtures (consisting of sand and gravel particles) were adde to the upstream reach of the flume; sediment which deposite in the downstream reach formed a riffle-like feature. Aft the sediment inputs were stopped, streamflow was continue until deposited sediments had armored and sediment transpor out of the test reach had ceased. Average hydraulic condition over the stabilized test riffles are shown in Table 1.

Four size gradations of bedload sediments were evaluate by pre-mixing selected proportions of gravel (median diamet = 9.0 mm) and sand (median diameter = 0.3 mm). The volum of gravel input during a given test run was held constant at 8 liters. Sand-to-gravel ratios of 1:1, 2:1, 3:1 and 5:1 wer evaluated, hence the total volume of sand in transport de pended upon the particular test being run. Two sediment in put rates of 20,000 and 6,600 kg $hr^{-1} m^{-1}$ were als evaluated (all transport rates are expressed in kilograms pe hour per meter width of channel); each test had two replica tions. After treatment, three subsamples of each riffle wer extracted by inserting small metal borders and manually r moving all material within the borders. One subsample wa taken from each of the upstream third, middle third an downstream third of the riffle. All samples were analyzed fo particle size distribution.

TABLE 1. Average Hydraulic Conditions in Regions of Uniform Flow (36 liters/sec) for Riffle Deposition Experiments.

	Flume Width (cm)	Depth (cm)	Flow Cross-Section Area (cm^2)	Hydraulic Radius (cm)	Average Flow Velocity (ms^{-1})	Slope ($m.m^{-1}$)	Froude No. ($v/\sqrt{gy}$)	Manning's n	Average Shear Stress ($N.m^{-2}$)
Flume, Upstream Section	35.6	10.8	384	6.7	0.94	0.025	0.92	0.009	26.5
Flume, Depositional Section (without riffles present)	40.6	12.7	516	7.8	0.70	0.0067	0.63	0.02	8.3
Flume, Depositional Section (with riffles present)	40.6	7.9	320	5.7	1.28	0.027	1.5	0.02	20.9

Stability Experiment

In the stability experiment, a riffle was created in the downstream reach with the 1:1 sand-to-gravel mixture used in the deposition experiment. One hundred and seventy six liters (280 kg) of that mixture were added at 6,600 kg $hr^{-1}m^{-1}$ and the resultant riffle was allowed to stabilize. Sand was then added to the flow and was transported over the stabilized riffle. Gravel-sized material which was removed from the test riffle after addition of the sand was caught in a 4-mm mesh basket placed at the outfall of the flume. All exported riffle materialw as dried and weighed.

The volume of sand added for each test varied (i.e., 35, 70, 105 or 140 kg). Furthermore, these volumes were added to the flow at two different rates (20,000 and 6,600 kg $hr^{-1}m^{-1}$) and each test condition was replicated twice. The riffle was reformed after each test.

RESULTS AND DISCUSSION

Deposition Experiment

Figure 1 illustrates the particle-size distribution of the four sediment mixtures compared to the average particle size distribution of the resultant test riffle features formed under conditions of both high and low rates of sediment input. The range of particle sizes in the test riffles was the same as the range of particle sizes of the sediment in transport. In all tests, however, the median particle size of the riffle sediments was considerably larger than that of the sediments in transport. Furthermore, as the particle size distribution of sediments in transport under the same rates became finer, the coarseness of the riffle relative to that of the sediment in transport became greater. The composition was also affected by the rate of sediment transport. Test riffles formed during the lower transport rate were more coarse, in all cases, than those formed during the higher rate of sediment transport (Figure 1).

Whereas the percentage of sand deposited within the various test riffles increases as a power function with an increase in the proportion of sand in transport (Figure 2), the increase is small over the range of sediment mixtures tested. Only subsamples from the downstream one-third of the riffles formed during the high input rate tests showed large increases in the sand-to-gravel ratio in the riffle. These results might indicate that downstream sections of riffles may be somewhat more sensitive indicators of the relative particle size distribution of sediment in transport than upstream sections. In general, however, the ratio of sand-to-gravel in transport did not greatly affect the percentage of sand in the riffle for the range of sand-gravel mixtures tested.

When the median particle diameter (d_{50}) of the riffle material is plotted against the sand-to-gravel ratio of sediment in transport, a weak but statistically significant ($\alpha = 0.05$) decrease in the median diameter of the riffle material occurs as the sand-to-gravel ratio increases (Figure 3). No consistent changes in the longitudinal profiles of the test riffles occurred as the ratio of sand-to-gravel in transport increased. The stabilized test riffles were higher in elevation at the upstream end and sloped to the downstream end at an average of 0.027 m/m. The water surface paralleled the riffle slope. The time required for the riffles to stabilize once the sediment inputs were stopped increased from approximately 1-1/2 minutes for those formed by 1:1 sand to gravel in transport, to about 8 minutes for those formed by 5:1 sand to gravel in transport. The test riffles which developed from the five parts sand to one part gravel were smaller in height and length than the other riffles.

The deposition efficiency of the sand and gravel (i.e., the total volume of sand and gravel in the riffle divided by the corresponding total volumes of sand and gravel input into the flow) expressed as a percent, was variable but tended to decrease as the proportion of sand in transport increased (Figure 4). The difference in depositional efficiency shown for sand and gravel is a relative indicator of the amount of particle size sorting that occurs during the depositional process. There was more sorting of gravel than of sand, and the amount of sorting decreased more rapidly for gravel than for sand as the proportion of sand in transport increased. Hence a predominant effect of increased rates of sand transport in natural channels may be to decrease the amount of particle size sorting

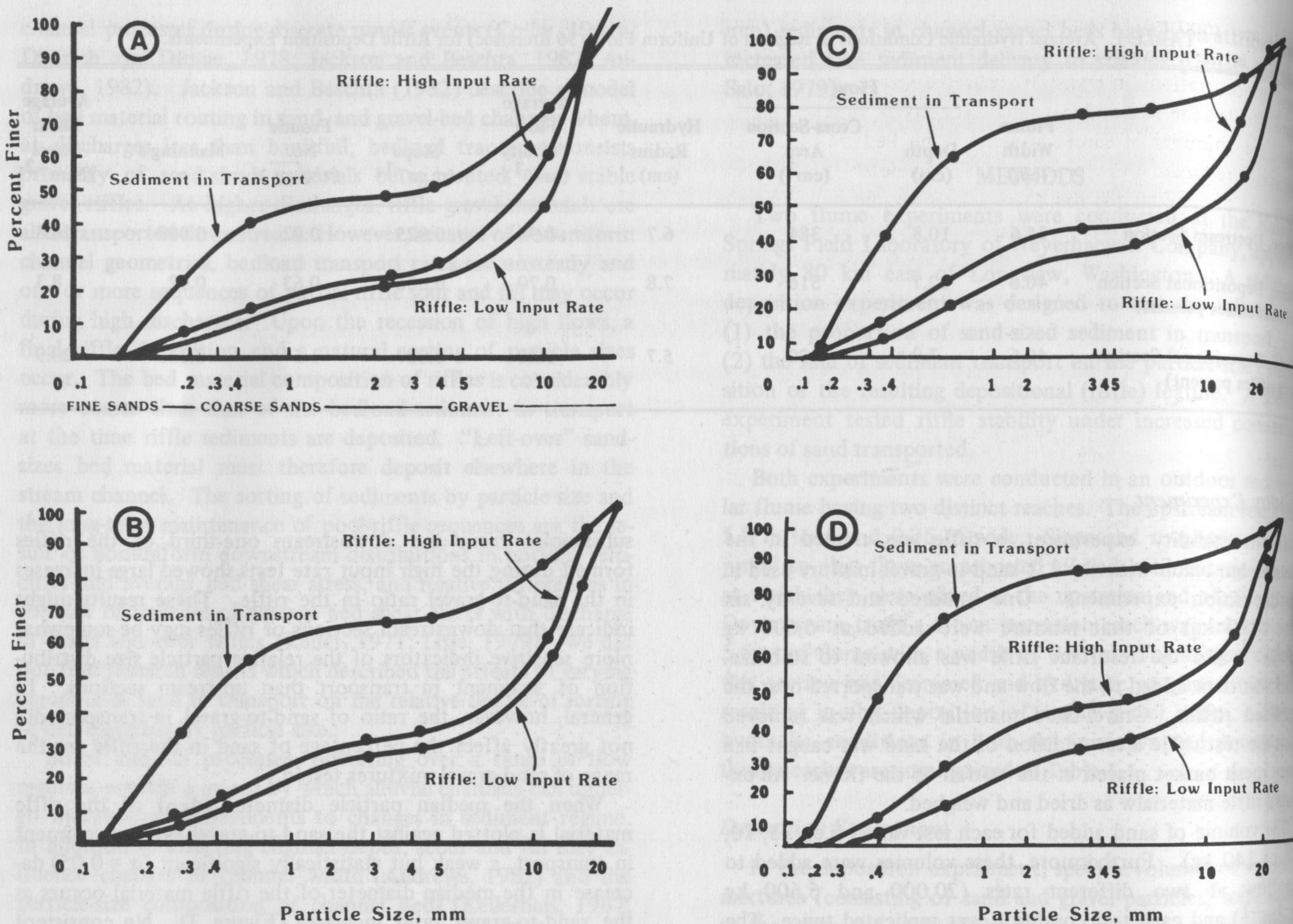

Figure 1. Particle-Size Distributions of Four Sediment Mixtures (A, 1:1 sand-to-gravel ratio; B, 2:1, C, 3:1; D, 5:1) and Average Distributions of the Resultant Test Riffles Formed Under High (20,000 kg $hr^{-1}m^{-1}$) and Low (6,600 kg $hr^{-1}m^{-1}$) Rates of Sediment Transport.

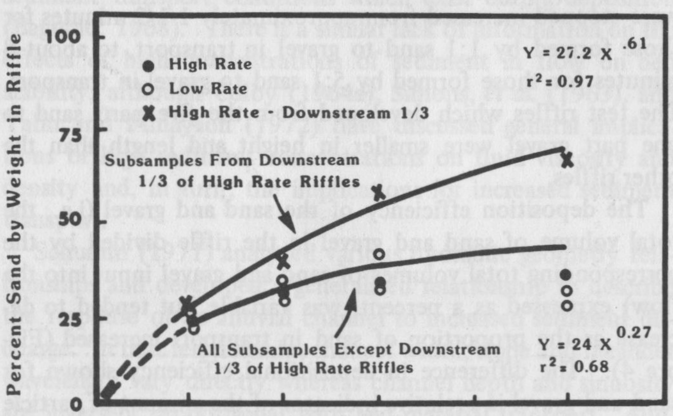

Figure 2. Relationship Between Percentage of Sand by Weight in Test Riffles, and Ratio of Sand-to-Gravel for High (20,000 kg $hr^{-1}m^{-1}$) and Low (6,600 kg $hr^{-1}m^{-1}$) Transport Rates.

which occurs as gravel riffles locally scour and redeposit downstream.

Stability Experiment

Relatively high rates of sand in transport resulted in initiating scour of riffles which were stable under conditions of no sand transport when shear stresses acting on the bed averaged 21 $N.m^{-2}$. The weight of material exported from each riffle increased with the increase in volume of sand transported over the riffle (Figure 5). No significant differences ($\alpha = 0.05$) between gravel export for different rates of sand transport (i.e., 20,000 vs. 6,600 kg $hr^{-1}m^{-1}$) were detected.

Measurement and analysis of fluid mechanics variables affecting the transport capacity of the flows at the riffle was beyond the scope of this study, hence the mechanisms by which gravel movement was initiated are not known. However, we hypothesize that the increased capacity of the sand-water mixture to transport bed gravels compared to that of pure water may be caused in part by the higher density of the nd-water mixture. Possible increases in fluid viscosity and hanges in the turbulent structure of the flow caused by high and concentrations in transport near the streambed may also ave affected the bedload transport capacity of flows. Finally, he large amounts of sand moving on the bed may have effectively reduced the mean particle diameter of the bed material, thus reducing the shear stress required to initiate motion (Andrews, 1983).

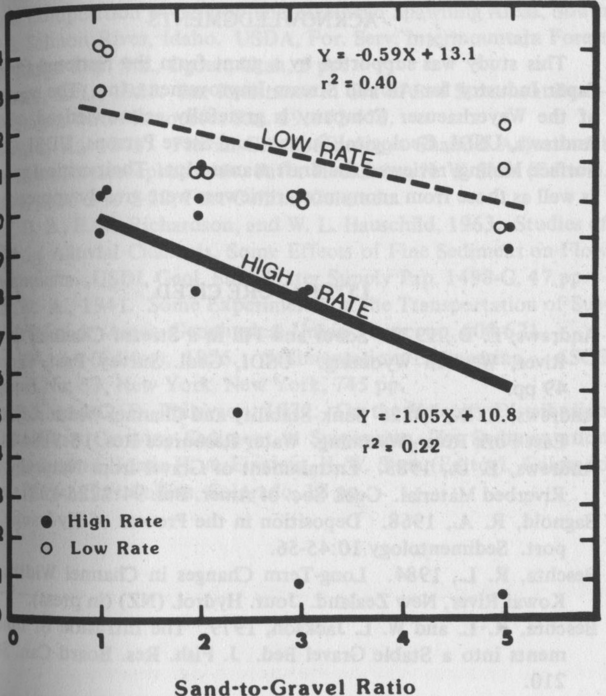

Figure 3. Relationship Between Median Particle Diameter (d_{50}) of Riffle Sediments and Ratio of Sand-to-Gravel in Transport for High (20,000 kg $hr^{-1}m^{-1}$) and Low (6,600 kg $hr^{-1}m^{-1}$) Transport Rates.

CONCLUSIONS

The results indicate that the particle size gradation of the ffles was not sensitive to increased proportions of fine bed aterial in transport at the time of deposition for the range f bed material mixtures tested. However, extrapolation of ese results to lower sand-to-gravel ratios (i.e., ratios < 1, igure 2) indicates changes in bed composition would be inuenced by the size distribution of sediment in transport. ithin the scope of this study, however, the rate of bedload ansport and the range of bed material sizes (as determined y the largest particles in transport) appear to be more imortant variables affecting the particle size composition of ffle features than the proportion of fine bed material in ansport at the time of deposition.

Possibly the most important effect of increasing the ratio f sand-to-gravel in transport, while holding total bedload ansport rates and total gravel volumes in transport constant, was to decrease the volume of gravel which ultimately deposited in the riffle. This, combined with the fact that there was only a small increase in the percentage of sand in the test riffles, means that most of the increased volume of sand in transport and a larger percentage of the gravel in transport did not deposit in the test riffles, but was transported through the flume. In addition, high rates of sand in transport caused the stable gravel riffles to undergo scour and caused the transport of gravel-sized materials.

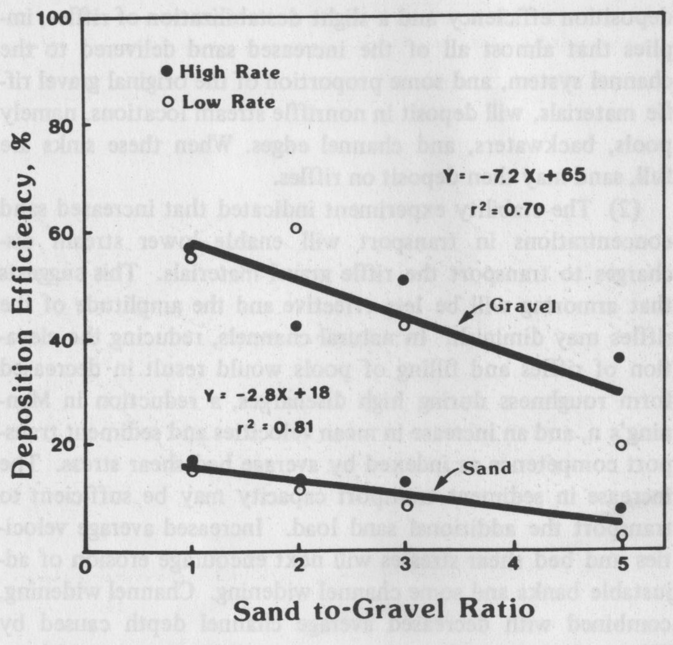

Figure 4. Average Deposition Efficiency of Sands and Gravels (each relationship significant at $\alpha = 0.05$).

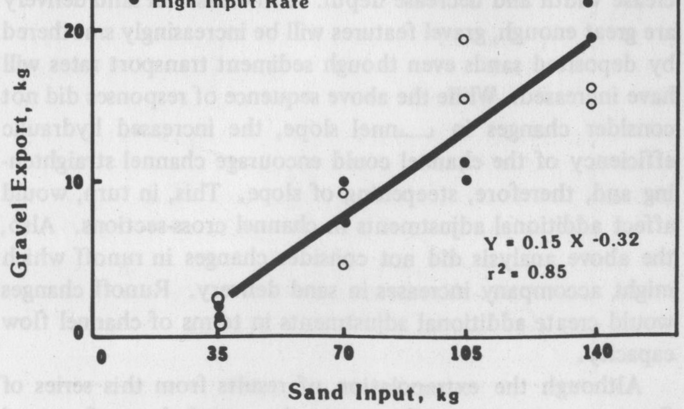

Figure 5. Gravel Export from Established Riffles in Relation to Total Sand Inputs (significant at $\alpha = 0.05$). High and low rates of transport correspond to 20,000 and 6,500 kg $hr^{-1}m^{-1}$, respectively.

When the results of these experiments are combined with descriptive process of nonuniform bedload transport in sand and gravel-bedded stream channels with sequences of pools and riffles (Jackson and Beschta, 1982), it is possible to suggest a series of events which occur as part of the morphologic response of such channels to increased sand delivery:

(1) The deposition experiments indicated that increased sand concentrations in transport (for sand-to-gravel ratios of greater than 1:1) will not greatly increase the percent sand composition in riffles. This, combined with reductions in gravel deposition efficiency and a slight destabilization of riffles, implies that almost all of the increased sand delivered to the channel system, and some proportion of the original gravel riffle materials, will deposit in nonriffle stream locations, namely pools, backwaters, and channel edges. When these sinks are full, sand may then deposit on riffles.

(2) The stability experiment indicated that increased sand concentrations in transport will enable lower stream discharges to transport the riffle gravel materials. This suggests that armoring will be less effective and the amplitude of the riffles may diminish. In natural channels, reducing the elevation of riffles and filling of pools would result in decreased form roughness during high discharges, a reduction in Manning's n, and an increase in mean velocities and sediment transport competence as indexed by average bed shear stress. The increase in sediment transport capacity may be sufficient to transport the additional sand load. Increased average velocities and bed shear stresses will next encourage erosion of adjustable banks and some channel widening. Channel widening, combined with decreased average channel depth caused by filling of pools, will result in an overall increase in width-to-depth ratio. Some additional aggradation of the bed will occur until velocities and shear stresses are sufficient to transport the stream's increased sediment load. Overall channel stability will be reduced.

Given the above sequence of events, the net response of a channel to increased sand delivery will be to fill pools, increase width and decrease depth. If increases in sand delivery are great enough, gravel features will be increasingly smothered by deposited sands even though sediment transport rates will have increased. While the above sequence of responses did not consider changes in channel slope, the increased hydraulic efficiency of the channel could encourage channel straightening and, therefore, steepening of slope. This, in turn, would affect additional adjustments in channel cross-sections. Also, the above analysis did not consider changes in runoff which might accompany increases in sand delivery. Runoff changes would create additional adjustments in terms of channel flow capacity.

Although the extrapolation of results from this series of flume experiments to changes in the morphology of natural channels will need further study, these changes are in general agreement with the channel adjustment concepts of Schumm (1971, 1977). Evidence from other studies is generally supportive of these concepts. This is particularly true with regard to channel width changes (Grant, 1977; Lyons and Beschta, 1983; Beschta, 1984) and the tendency for channel form roughness to decrease during high flows by the partial filling of pools and scouring of riffles (Andrews, 1979). Measurements of changes in channel depths have been less common than changes in channel widths for channels where accelerated sediment inputs have occurred, although Megahan, *et al.* (1980) documented increases in channel depths following reductions in sediment delivery.

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