A sorting mechanism for a riffle-pool sequence

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INTRODUCTION

Transport of coarse, heterogeneous debris in a natural stream under a wide range of flows usually results in a remarkably stable, undulatory bed profile, which manifests an in transit sorting process of the bed material. In general, finer material representative of the bulk of the normal bed load resides in the deep sections, or pools, below flood stages. At high flows, pools may scour to immovable boulders or bedrock. Coarser material transported at more infrequent flows forms the shallow sections, or riffles. Above a flow threshold, the pool fill material is often scoured and deposited in part over the riffles (Lane and Borland, 1954; Andrews, 1977). Interactions among coarse particles in motion in turbulent flow tend to concentrate them in groups with the coarsest particles at the surface (Langbein and Leopold, 1968). Incipient accumulations of coarse particles may be perpetuated by altering the flow conditions which influence bed load transport.

As flow increases, submergence of the riffle-pool bed topography modifies its effect on the local hydraulic conditions. At low flow, mean volocity and water surface slope are greater, and mean depth is less at a riffle than at a pool. Competence is greater at the riffle. As the stage increases, the water-surface profile tends to even out as the hydraulic gradient over a riffle decreases and that over a pool increases (Leopold and others, 1964). Corresponding values of velocity and depth tend to converge, although depth often less so (Richards, 1976; Lisle, 1976; Andrews, 1977). The convergence of respective values of water-surface slope over a riffle and pool and the greater depth of the pool cause mean shear stress, $\tau = \gamma RS_E$ (where γ is the specific gravity of water, R is the hydraulic radius or approximately the mean depth, and S_E is the energy gradient), to increase more rapidly at the pool (Leopold and others, 1964). As a result, competence as measured by velocity or bottom shear stress should become more evenly distributed over a riffle and pool (Richards, 1976) or even reversed in hierarchy at high flow (Gilbert, 1914; Keller, 1971).

Keller (1971) proposed the hypothesis of "velocity reversal" to explain the areal sorting of bed materials in a riffle-pool sequence by the reversal in hierarchy of bottom velocity values. His data from Dry Creek, California, for four stages show the convergence of mean values at the highest stage, above which bottom velocities at the pool presumably exceed those at a riffle. Andrews (1977) shows convergence of values of *mean* velocity with increasing discharge at sections comparable to pools and riffles until at bankfull flow the velocity at some scouring (pool) sections exceeds that at some filling (riffle) sections. Under Keller's hypothesis, coarse clasts entrained above the reversal flow are more likely to be deposited at a riffle than at a pool. Finer material transported below the reversal flow tends to collect in the pool.

Measurements of velocity near the bed may show relative differences in competence between local bed areas. It is difficult, however, to translate point velocity directly into a measure of competence, for which shear stress is the most widely accepted parameter (Vanoni, 1975). Several researchers have used velocity profiles to calculate local shear stresses, but the technique is difficult under some field conditions (Church, 1972; Smith and McLean, 1977). Measurement of mean shear stress from the flow geometry is a practical method for quantitatively relating the sorting of grains to the distribution of competence over reaches as long as riffles or pools.

This paper describes a sorting mechanism based on the reversal in hierarchy of mean shear stress at a pool and riffle. Measurements of shear stress and grain size distribution at a pool and riffle help substantiate this mechanism and quantitatively demonstrate the operation of the sorting process in one stream. Comparison with data from other streams reveals some influences of sediment supply and the interactions of heterogeneous bed-load particles.

RESEARCH DESIGN

Data for this study were gathered in the context of a larger study (Lisle, 1976) of frictional resistance of a riffle-pool-bend section of the East Fork River, an upper tributary of the Green River in western Wyoming. The site was chosen by Luna B. Leopold for direct measurement of total bed-load transport by a bed-load trap. Data on that phase have been published (Leopold and Emmett, 1976, 1977), and the present paper is one of several associated studies of river hydraulics and sediment transport (Bagnold, 1977; Andrews, 1977; Bennett and Nordin, 1977).

In this study reach, the channel is formed in glacial outwash providing the material for a basal gravel bed over which coarse sand mostly derived from the early Tertiary Wasatch Formation is transported as bed load. At low flow, the sand tends to smooth the riffle-pool bed profile. At bankfull flow, about 23 m^3/s, the channel is about 18 m wide and 1.2 m deep; the velocity is about 1.1 m/s. The average water surface slope over 1.5 km of channel length in this vicinity is 0.0007.

A 50-m-long riffle and a 90-m-long pool were chosen for study with the criteria that they typify these channel forms, are straight, and are near each other. The intervening reach, 1.0 km long, is not joined by any tributary. At low flow, the bed slope of the riffle is 0.0014 and of the pool is 0.0004.

The data include daily measurements of water-surface slopes, hydraulic radius at each reach, and percentage of sand-covered area of the pool bed. The water surface slope, S, is the measure of the energy gradient, assuming that the progressive variation of velocity with distance at each reach is insignificant in determining S_E. The riffle channel is uniform relative to other reaches; the pool channel constricts at about mid-section. Maximum error in the use of S for S_E because of backwater effects at the riffle is estimated to be about 10%. Values of S and R were measured from cross sections, and arrays of surveyed bank pins were used to gauge local water-surface elevations. The bed-surface composition of the pool was monitored by longitudinal sounding transects run in a boat equipped with a Model 1054 Ultrasonic Distance Meter and chart recorder. The bottom profiles display the presence or absence of sand in bed forms and indicate changes in bed elevation. Data were collected once daily at each reach every day except one during the period from June 2 to June 26, 1975. During this period three hydrograph peaks exceeded bankfull stage. The first peak marked the beginning of major spring runoff.

SCOUR AND FILL OF THE FOOL AND RIFFLE

The surface of the riffle bed is gravel (d_{90} = 46 mm, b-axis diameter coarser than 90% of the bed, from a pebble count; after Wolman, 1954) except at high flow when sand may overlie one-third of the channel. Coarse sand representative of the bed load (d_{50} = 0.5 to 1.5 mm) covers most of the basal gravel bed of the pool at low flow to a thickness under 1 m, but scours at high flow, progressively exposing the gravel. From periodic soundings of cross sections within the study reach, Andrews (1977) showed that most scouring sections begin to scour at about bankfull stage, below which they fill.

The percentage of the pool bed covered with sand began to decrease at discharges between 11 and 21 m^3/s (Fig. 1). Initial scour, assumed to be marked by the increased exposure of the gravel bed, essentially began no later than bankfull flow (Q_{bf} = 23 m^3/s) and at progressively lower flows during the rise to subsequent hydrograph peaks. A marked clockwise

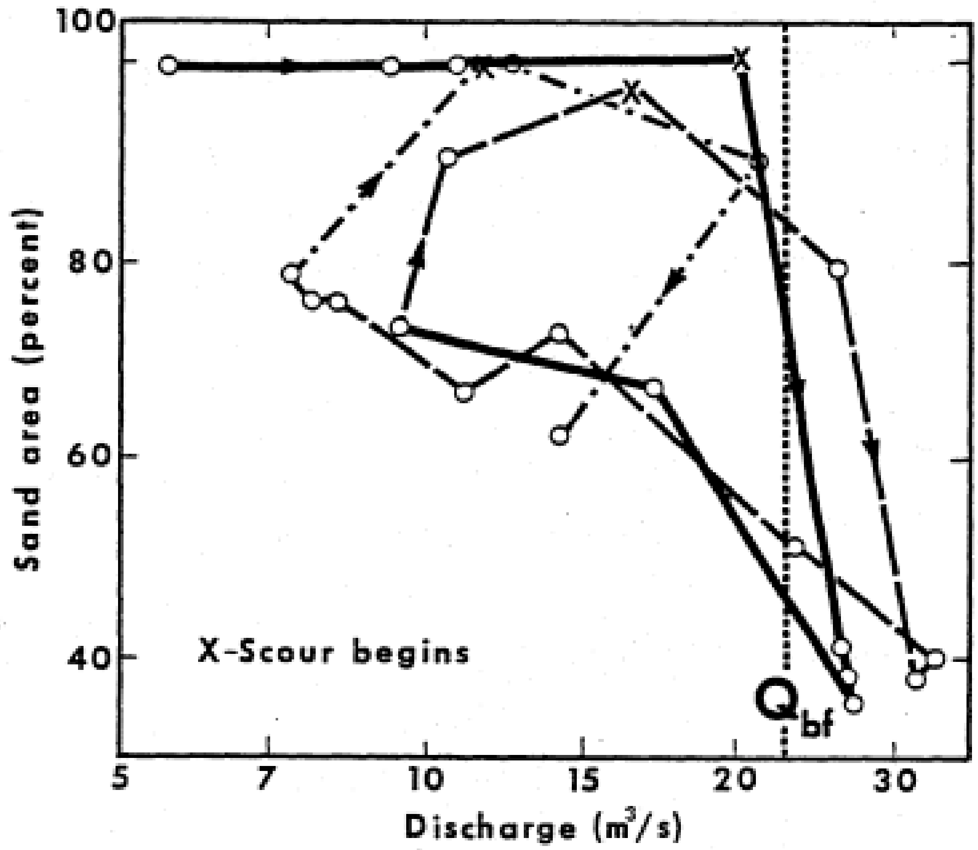

Figure 1. Percent of the area of the pool bed covered with sand versus discharge. Q_{bf} is bankfull discharge. Lines connect consecutive flows. Three line patterns correspond to the rise and fall of three hydrograph peaks.

hysteresis expresses the lag in redeposition of sand following each peak.

SHEAR STRESS REVERSAL

Figure 2 shows the variation of hydraulic radius, water-surface slope, and mean shear stress with discharge at the pool and riffle. The anomaly of the data points for the first four days (points marked "x" and "o" in Fig. 2), particularly for slope values, resulted from the rapid adjustment of the channel during the rise of the first hydrograph peak, when bed-load discharge was highest.

The pool's values for hydraulic radius are consistently greater than the riffle's but increase at a slightly lower rate with discharge.

For each reach, water surface slope varies nonlinearly with discharge. The sets of values converge at. Less-than-bankfull discharge at a value roughly equal to or greater than the slope of the over-all reach, $\overline{S} = 0.0007$. In addition to measurement error, the scatter of points results from variations caused by scour and fill of the sand. At high flow, for example, the remaining sand tends to be concentrated in the downstream portion of the pool, relatively elevating the bed there and maintaining a slightly greater roughness (Lisle, 1976). This relative elevation tends to reduce water-surface slope, but this result is subordinate to the over-all increase of slope with discharge at the pool. Different bed configurations at equal discharges (Fig. 1) thus complicate the slope-discharge relation.

Values of mean shear stress converge over a range of discharges between 12 and 16 m^3/s at τ values between 5 and 7 N/m^2 (Fig. 2). This interval of shear stress values is designated τ_r and the corresponding interval of discharge values is designated Q_r .

Significantly, Q_r falls within the range of the onset of scour at the pool. Keller's (1971) bottom velocities converged at a flow of a 1.2-yr recurrence interval. Because Q_r represents less-than-bankfull discharge, which often has a recurrence interval of about 1.5 yr (Leopold and others, 1964), the flow

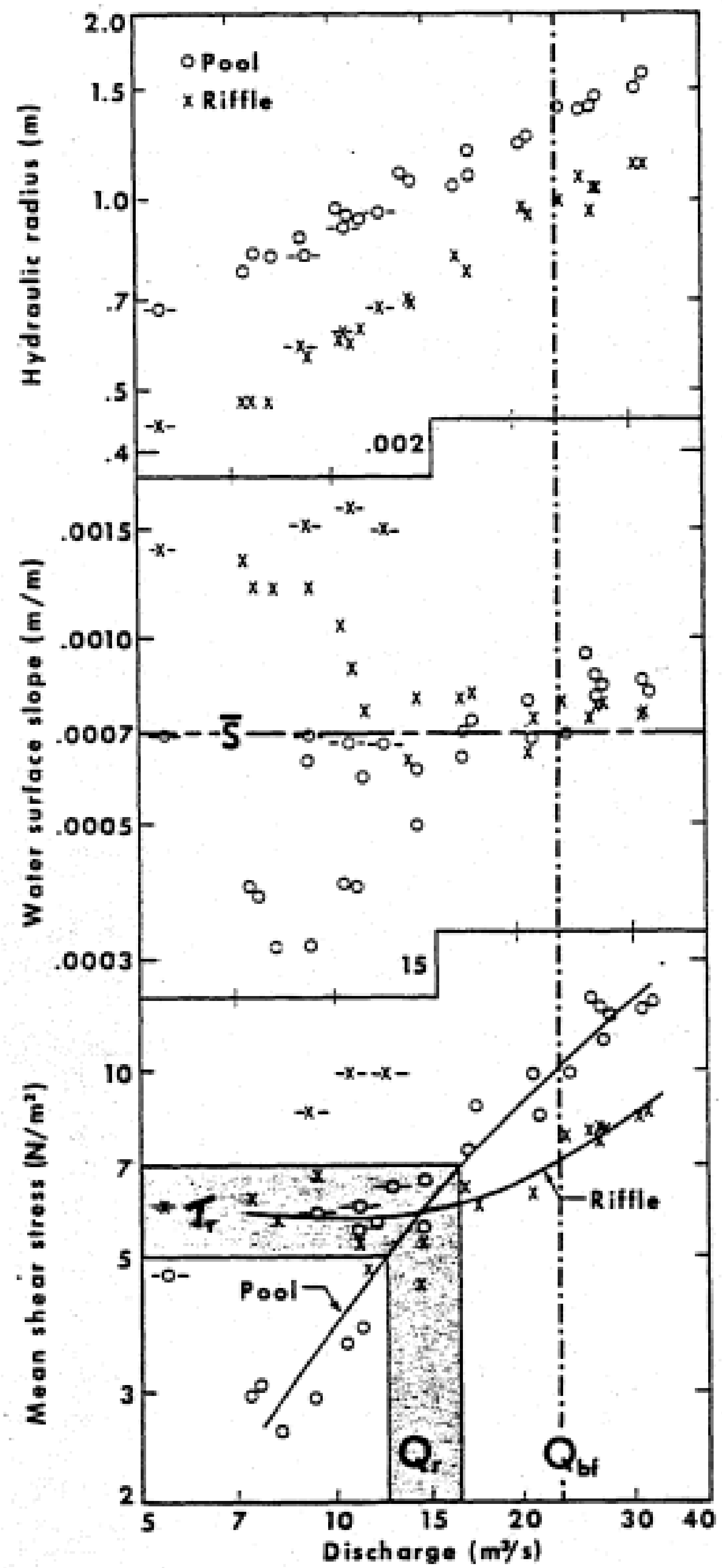

Figure 2. Values of hydraulic radius, water surface slope, and mean shear stress versus discharge for the pool and riffle. The anomalous first four data points are designated "x" and "o". $\bar{S}$ is the average slope over 1.5 km; Q_{bf} is bankfull discharge; τ_r and Q_r are, respectively, mean shear stress and discharge at reversal.

frequencies at reversal for the two studies seem similar.

Above Q_r, values of τ in the pool exceed those over the riffle. We can expect that the difference will become no greater at still higher stages if values of S do not depart systematically from $\overline{S}$ and the R versus Q relations remain linear.

AREAL SORTING

Grain size distribution of the bed load changed little with flow. The percentage of the coarsest size fraction of bed load sampled at a flow slightly above bankfull (Q = 23.8 m^3/s) exceeded that for a moderate flow (Q = 10.6 m^3/s) by only a few percent at most (Fig. 3). Up to the highest sampled flow (Q = 45.0 m^3/s), the size distribution was essentially unchanged.

Using threshold criteria, the maximum grain size theoretically entrained at $\tau_r = 7\ N/m^2$ is 8 mm (Vanoni, 1975, p. 96, after Shields, 1936). This size, designated d_r, is plotted (Fig. 3). How closely the average entrainment conditions approximate the conditions on the beds of the riffle and pool is conjectural. Local shear stress may be appreciably higher than the mean over irregular cross-sections. Because of a more uniform distribution of velocity and depth, variation of time-averaged shear stress over the riffle should be less than over the pool. Shallower depths in the riffle, on the other hand, should produce greater vertical velocity gradients and greater instantaneous shear stresses than those in the pool. Church (1972) showed that imbrication and close packing of particles in a stream bed inhibits entrainment, so that the Shield's (1936) criterion for incipient motion defines a lower limit. Possible differences in the bed structures of the two reaches may thus cause differences in entrainment conditions. With only qualitative assessment of these factors, it seems valid to use the values of τ_r without adjustment for local hydraulic conditions, to infer the sorting mechanism.

The value of d_r is finer than 99% of the riffle gravel and coarser than 89% of the bed load or the fill material covering the major part of the pool bed up to the

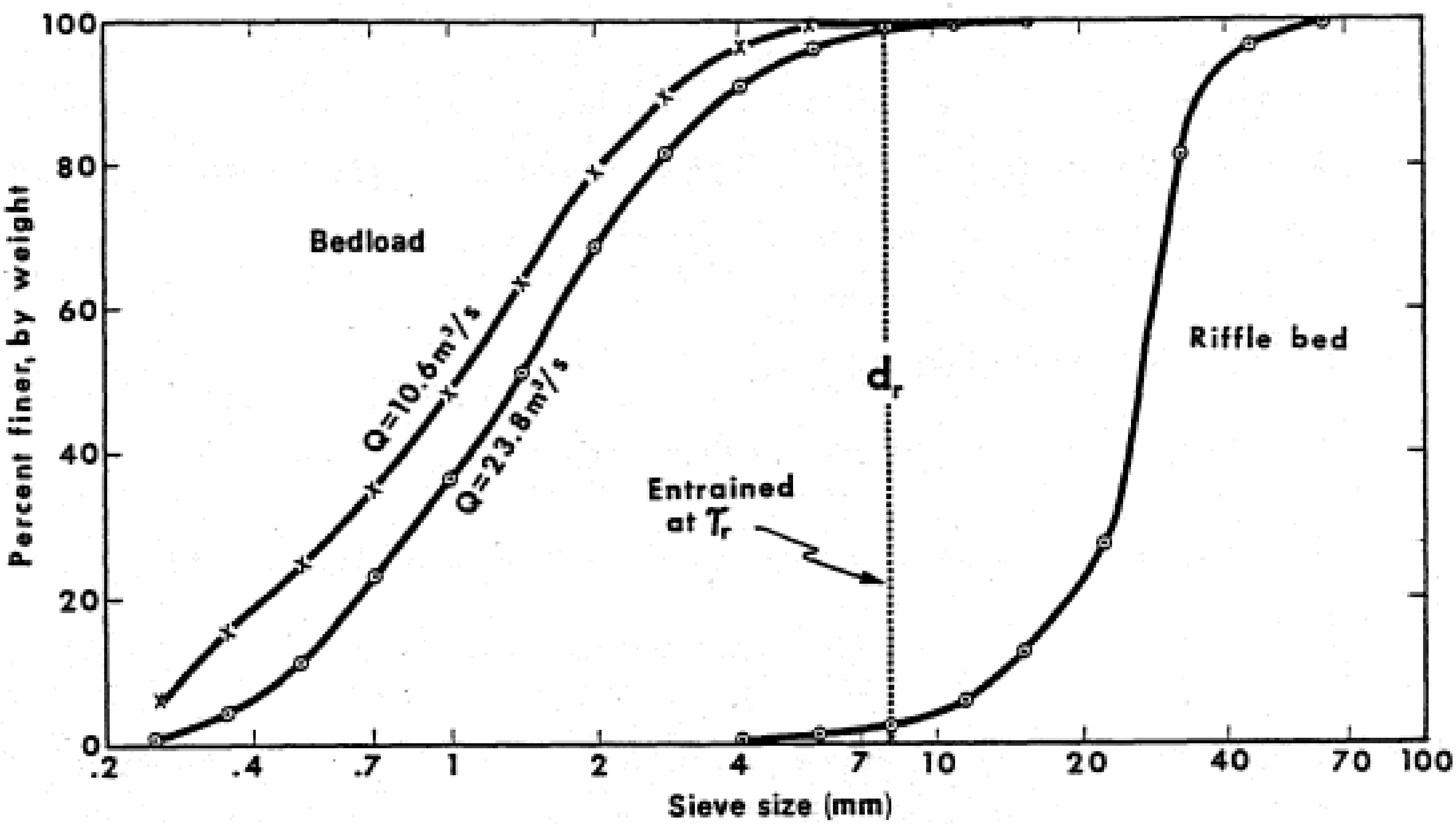

Figure 3. Grain size frequency for two bed-load samples at low flow ($Q=10.6\,m^3/s$) and high. flow ($Q = 23.8\ m^3/s$) (Leopold and Emmett, 1976) and for the surface of the riffle bed from a pebble count (after Wolman, 1954). The bed-load sizes represent the pool fill material. Grain size, d_r, theoretically is entrained at the upper value of τ_r, the mean shear stress at reversal.

reversal stage. Keller (1971) stated, "The size of the largest bed material beneath the fines in pools is dependent on the reversal velocity." More precisely, this grain size is the largest that may be eroded from the riffle and deposited in the pool just below the reversal stage. The coarser riffle gravel would be entrained at higher stages, and an excessive tractive force would then exist in the pool to convey the gravel to the next riffle or bar. As Keller (1971) argued, the riffle-pool form is maintained by the transient deposition of coarse clasts at the riffles during flows above the reversal stage.

Small pebble gravel (4 to 8 mm), approximating d_r, is the deficient size fraction of the surface deposits of the riffle and pool, presumably because it is a rare fraction of the introduced bed load (Andrews, 1977), and because dispersive stress and winnowing concentrate coarser gravel fractions at the surface of the riffle. As a surficial deposit over the study reach, this size occurs locally over point bars. A wider range of tractive forces exists over a meander bed at a given flow than in most straight reaches (Hooke, 1975) and thus provides the hydraulic environment for the deposition of a gradation of sizes.

INFLUENCE OF ARMORING AND SEDIMENT SUPPLY

In the East Fork, gravel transport, as described by this inferred sorting mechanism, was inhibited by armoring of the riffle bed, the distribution of transport capacity, and the supply of sediment. Consequently, gravel was not observed in quantity in the bed-load up to more than twice bankfull flow. Small pebble gravel comprised the uppermost size limit of the bed load, in part because the coarser riffle gravel was protected from transport by armoring and imbrication, which were ineffective for the finer pool fill. Concentration of coarse clasts tends to inhibit their transport (Langbein and Leopold, 1968).

Emmett (1976) demonstrated the effect of armoring on gravel transport in the Snake and Clearwater Rivers. Until much of the cobble pavement of the bed was entrained, these rivers transported coarse sand, which was finer than the material which the streams are competent to carry. Only when particles greater than 32 mm (the average median size of the bed material within 0.6 m of the surface) were entrained, did the intermediate sizes appear in quantity in the bed load. This occurred at a recurrence interval of from 1 to 2 yr, or approximately at bankfull flow. Below this, armoring limited the supply of finer grains to the bed load and significantly reduced the transport efficiency.

Milhous (1975) found that the armor layer in Oak Creek on the east edge of the Oregon Coast Range broke up when the d_{30} size was entrained. This occurred at discharges exceeding 3.5% to 1.4% of the time over 2 yr. These flows are more frequent than bankfull flows in English rivers, which are exceeded on the average 0.6% of the time (Nixon, 1959).

Data from other gravel streams also show general entrainment of the bed sizes near bankfull flow. At Seneca Creek, Maryland, painted pebbles of the median size on a riffle were eroded at a stage corresponding to about 0.75 bankfull depth (Leopold and others, 1964). Similarly, painted particles representative of the bed sizes of Dry Creek were eroded during a flood with an instantaneous discharge of a 1.5-yr recurrence interval (Keller, 1970).

Twenty-four millimetre gravel, the median size of the gravel surface over the riffle, is theoretically entrained at a shear stress of about 19 N/m^2 (after Shields, 1936). This requires a discharge which is over twice bankfull, our upper limit of observation, and much less frequent than at the gravel stream cited above. Thus the gravel bed appears to be essentially static for flows up to those of low frequency and high magnitude.

During high flow, the partial blanket of sand over the riffle further protects the gravel from tractive forces. The scour and fill of sand in the pool and riffle result from variation in distribution of transport capacity (Andrews, 1977).

The lack of supply of gravel from sources outside the stream was perhaps the predominant inhibiting factor on gravel transport.

Sand is the dominant size supplied to the East Fork (Andrews, 1977). If gravel were introduced in abundance, the channel would adjust to generate the necessary transport competence, and the riffle pool configuration with the attendant reversal mechanism would probably respond to more actively sort the coarser sizes.

SUMMARY AND CONCLUSION

Shear stress "reversal," equivalent to Keller's (1971) hypothesis of velocity reversal, offers a plausible mechanism for the sorting of bed material in the riffle-pool sequence of gravel streams at less than extreme flows. By either mechanism (shear stress or velocity reversal), the competence of flows in pools. exceeds that over riffles above a certain range of flows and thus tends to concentrate coarse material in riffles. Data from the East Fork demonstrated the reversal in hierarchy of shear stress values at a riffle and pool. Deposition of gravel on riffles was not observed, but some influences of sediment supply on this sorting mechanism have been inferred.

Although a stream's competence steadily increases with stage, the size of bed load material is limited by supply. The protective assemblage of gravel deposits in stream beds inhibits entrainment of all of the material held within. Finer material, the largest size of which is related to threshold conditions at the reversal flow, is available for transport in pools at low to moderate flows. At some stage above reversal, bed load grain size may increase abruptly when the coarser areas of the bed, such as riffles, are entrained.

On the East Fork, there was a large difference between the discharge at the reversal in competence and that required to entrain the gravel in the bed. Presumably the gravel framework of the bed has become static without the infusion of new gravel from sources other than the bed. In more active gravel channels, this difference is smaller, as most of the gravel is set in motion near bankfull stage. In either case, the switch in hierarchy of competence in a riffle-pool sequence near bankfull flow occurs in time to favor deposition of the coarsest bed load material on riffles and bars. The reversal mechanism operates on the size of the supplied bed load. The bed topography determines the local hydraulic conditions for bed load transport and areal sorting of grain sizes, however, and may be formed of coarser material of a distinctly different transport regime.

Of the elements of the form-process relation which govern the dynamic equilibrium of riffle-pool morphology, the most critical independent factor seems to be the quantity and grain size of the sediment supply. In this respect, the East Fork represents a case of distinct transport regimes for sand and gravel dependent on flows of different magnitude and frequency. The sediment regimes of other streams may also complicate or perturb the simple sorting mechanism presented here. For instance, channel erosion and deposition of poorly sorted debris associated with the flood of December, 1964, in northern California obliterated or diminished the riffle-pool sequence of some streams (Stewart and LaMarche, 1967; Kelsey, 1977, p. 283). In contrast, large flood flows of equal frequency in central Texas locally scoured pools and deposited coarse particles over bars, thus enhancing the form amplitude (Baker, 1977). Most likely the causative difference between these two examples is the greater relative volume of sediment contributed to the California streams from their highly erodible basins. The diminution of the riffle-pool sequence in these streams possibly manifests a decrease in channel roughness in response to the higher sediment load. A threshold magnitude of sediment input effectively perturbing the dynamic equilibrium of gravel streams, as suggested by these two examples, warrants investigation.

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