BEDLOAD MOVEMENT AND ITS RELATION TO SCOUR

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ABSTRACT

Scour is associated with dilation of the grain bed through the scour depth. Individual particles move intermittently and at a speed much less than that of the water. Within the dilated blanket, particles are constantly jostling and can change vertical position. Many gravel-bed channels have a greater percentage of large particles at the surface than below the surface, as a result of larger rocks being pushed to the surface by the dispersive force in the dilated layer. The concentration of large rocks at the surface of a gravel streambed is not the armoring caused by winnowing away of finer grains. It is one aspect of the process of bedload movement that requires dilation of the grain bed. Scour and subsequent fill is another aspect of the same process. The areal pattern of bedload transport over the channel bed is determined by the distribution or pattern of boundary shear stress, a function of local curvature and bed topography. But where bedload transport does occur, the motion tends to be in bedload sheets and is associated with dilation of a near-surface layer.

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Introduction

Since the work of Fargue (5) and Leliavsky (6), much has been learned about channels in general and meanders in particular. These authors noted that the radius of curvature continually changes through the meander wavelength, an idea later refined in the concept of the sine-generated curve. Leliavsky, and his father before him, maintained that horizontal convergence and divergence of flow were directly related to the zones of more and less bedload transport. This general concept has recently been quantified by Dietrich and Smith (1983, in press) with respect to topographically induced accelerations in a meander bend. Earlier conceptions assumed that equilibrium bed topography in a bend is established when the force acting on bed particles toward the concave bank due to downslope component of the particle weight is balanced by the inward force toward the convex bank resulting from secondary circulation. Dietrich and Smith showed, instead, that shoaling over the point bar forces fluid outward toward the concave bank. In short, the forces due to spatial acceleration cannot be neglected, for they force the high velocity core of the flow toward the pool. This is caused by a velocity component toward the concave bank throughout the flow depth over the upstream shallowing part of the point bar.

Subtle details such as this continue to be illuminated by research while obviously important and apparently simple features continue to elude us because the variety of evidence scattered through many papers is not organized and brought to bear on a particular issue. One such feature, important in all aspects of channel morphology, is discussed here. The question is as follows:

At high discharge, material on the bed is entrained as bedload and scour occurs. Where does the entrained material go, how fast, how far, and how does such entrainment relate to bedload-transport rate?

Our approach here is to state in simple terms observed facts drawn from different sources and to construct from these a general picture. We do not claim that our summary is complete or that all relevant facts are known. We begin with a mere listing of features without source or quantitative detail. In later paragraphs some examples and sources are provided.

1. Bedload motion appears visually to engage only a thin layer of material on the streambed. Saltation, that is the rolling, hopping and sliding, involves a layer of only one or several grain diameters in thickness. Hopping heights are also equal to only a few diameters.

2. If the material in motion is larger than a few millimeters in diameter, dunes do not form. The motion is concentrated in what we call "bedload sheets." This term is used to describe a local area on the streambed over which many particles can be seen in motion at one instant; such an area may be less than a square meter (10 square feet), but may be larger. A bedload sheet will usually be adjacent to areas of equal size where no motion is occurring. A sheet may suddenly become inactive while an adjacent area becomes suddenly active. Bedload sheets, therefore, cover one area, then another. Activity can last for several seconds to some minutes, but is intermittent at any particular place.

3. Bedload sheets usually cause to form a long, low, dune-like bedform, with a steep front that moves slowly downstream. Because such a bedform has a length tens to hundreds of times longer than the front is high, it cannot be called a dune. We refer to it as a "sheet bedform."

4. Motion of granular material cannot occur if the grains are in close packing. Motion requires that the grains be dispersed, or dilated to some degree. If a bed is composed of material of uniform size and the applied tangential shear stress is sufficient to move the topmost layer, then it should also be able to move the next exposed layer and the next, unless the actual entrainment of the upper layers affects the ability of the shear stress from operating on layers at depth. Because under the circumstances assumed it is observed that entrainment involves only a few layers, it follows that the entrained material exerts a downward force that at some depth holds the stationary bed from moving. This dispersive stress has been measured (1).

5. In the dilated zone, particles are continually bumping into one another and any one particle can change position so that one formerly at the surface can, at a later time, be buried.

6. The dispersive stress acts differentially on particles of different sizes. Larger particles receive the greatest force with the result that large particles tend to migrate upward during motion, toward the position of zero upward stress at the top of the blanket of moving material.

7. In any flow event, it is observed that the distance a given particle moves downstream is amazingly short. When the mean downstream speed is computed, it is shown to be but a fraction of one percent of the mean water speed.

8. The distance a particle moves downstream in any flow event is but poorly correlated with its size. There is only a general tendency for small particles to move farther than large ones and the difference is surprisingly small.

9. When measurements of channel cross section using the same datum are available at high flow and low flow for the same flow event, scour or fill can be computed. The available data indicate the following:

When pools and riffles are sufficiently well developed to cause appreciable change of local water-surface slope with change of discharge, the riffles tend to build or fill at high flow and the pools scour. This behavior results principally from the slope changes.

Where the pool-riffle sequence is less pronounced and thus slope changes are minor as discharge varies, then nearly all sections scour at high flow whether in a straight or a curved reach.

10. The measurement of bed elevation is a measurement of the level of the firm or undilated bed material. The overlying blanket of dilated particles, though moving downstream intermittently, is apparently unable to support the weight of a probe or bedload sampler.

11. The mean distance of transport of particles in a year times the average depth of scour is approximately equal to the annual bedload.

The above simple statements seem necessary to explain a variety of observations by different investigators working in various environments.

Field Observations

The first example is the Rio Grande del Ranchos, a perennial stream on the west slope of the Sangre de Cristo Range near Talpa, New Mexico. Peak discharges occur in spring during snowmelt. Along a study reach 300 m (1000 ft) long including a straight segment and a curved reach, 32 cross sections were surveyed during a near bankfull flow of 4 m^3/s (130 ft^3/s) and again a month later during low flow of 0.7 m^3/s (25 ft^3/s). The channel averages 8 m (26 ft) in width and has a bed of gravel predominantly 21 to 33 mm in size. Fig. 1 shows a planimetric map and profiles of water surface and bed. Fig. 2 shows the cross sectional area of scour or fill plotted against distance along the channel. Fig. 3 shows the cross sections at high and at low flow for three typical cross sections, two representing places in the curved reach and one in the straight segment of channel. This figure shows that the bed was generally lower in elevation during high than during low flow, or there was net scour. In nearly all the sections in meander curves, the upper portion of a point bar filled at high flow while the deeper part of channel scoured, the latter exceeding the former or a net scour. Section 187 m (Fig. 3B) is an example.

During high flow, scour generally existed throughout the entire reach. No marked difference in magnitude of scour existed between straight and curved reaches nor between pool and riffle.

The volume of material scoured is not the volume of material carried out of the measuring reach, for the distance any particle moved is very small; thus the average speed of downstream travel is also small. This important concept is now supported by three separate studies. The first is the observation of painted rocks placed in Arroyo de los Frijoles near Santa Fe, New Mexico (9). Several thousands of marked rocks moved in 30 events and travelled average distances from 2 to 1227 m (6 to 4000 ft) with an overall average of 188 m (617 ft). The rock weights varied from 0.25 to 20 kg (0.5 to 45 lb) and "the small particles do not travel materially further than the large ones..." (p. 215).

Of great interest is a similar set of observations by Hassan and Schick (1983, unpublished) of marked rocks in a cobble ephemeral stream in Israel. The whole streambed consisted of limestone cobbles 64 to 90 mm in size with very little sand or fine gravel. The rocks were marked with magnetic inserts and the recovery made with a magnetometer. By this means, rocks could be found well below the surface and the percentage recovery was high. Data for a single flash flood were obtained. The greatest distance any cobble moved was about 100 m (300 ft) and some rocks were found buried to a depth of 0.3 m (1 ft). The distance moved was unrelated to rock size. The short distance of movement, uncorrelated to size, confirms the New Mexico findings mentioned above. The deep burial of some rocks suggests that the depth of the dilated blanket was at least 4 to 5 rock diameters in this channel.

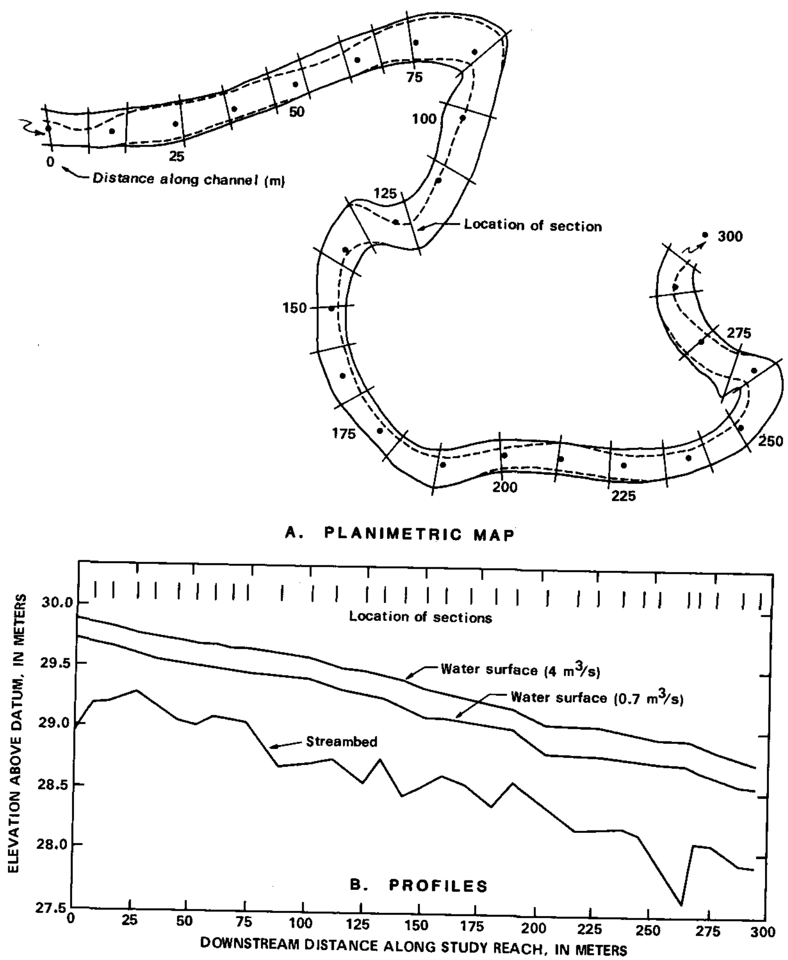

Fig. 1. Planimetric map and profiles of water surface and streambed, Rio Grande del Ranchos near Talpa, New Mexico.

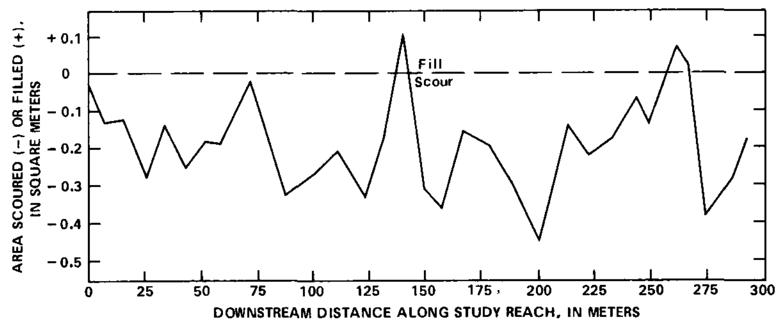

Fig. 2. Downstream pattern of streambed scour or fill, Rio Grande del Ranchos near Talpa, New Mexico.

A well-documented record (4) of scour, fill, and distance of downstream movement exists for the East Fork River, near Pinedale, Wyoming, described in detail in other papers (2, 3). The study area extends from a bedload trap (7, 8) to a point 3.3 km (2 mi) upstream. Composition of the streambed is predominantly sand but gravel bars are spaced at regular intervals. Underlying the sandy bed material is a stratum of coarse gravel and, sporadically, bedrock. Scour seldom extends to the depth of this stratum.

Fig. 4 shows a planimetric map of the study reach and the downstream variation of scour and fill. The scour-fill pattern is shown for a period of rising hydrograph, May 20-27, and of falling hydrograph, May 27-June 28. During the rise to high flow, more than three-fourths of the cross sections show scour or no change in bed elevation. Subsequently, during the recession to low flow, fill occurs. Between May 20-27, it is computed that 2544 m^3 (90,000 ft^3) of bed material were scoured and from May 27-June 28, 2784 m^3 (98,000 ft^3) were deposited as fill. Based on several years of operating the bedload trap, annual bedload is approximately one-third to one-half the volume of scoured material within the study reach of 3.3 km (2 mi) length, indicating that the annual travel distance of bedload is a little over 1000 m (0.6 mi).

The movement of fluorescent bed-material tracers, injected as a line source 10 m (33 ft) downstream of section 3047 m (Fig. 4A), was measured daily by bed-material sampling at all sections. Typical results, separated into five particle-size categories, are shown in Fig. 5. Fig. 5 is for data collected on June 3, 1979, the 16th day from the time of injection (May 18, 1979). As can be inferred from the figure, it appears that the smaller particles move slightly faster and further than the larger particles. Fig. 6 is a graph of the daily downstream displacement of the peak concentration (approximate centroid) for tracer particles of size between 0.5 to 1.0 mm. Because downstream displacement of the tracer was recorded only at measurement sections, the relation that describes the displacement shown in Fig. 6 is a curve which envelops the data rather than a best-fit to the data.

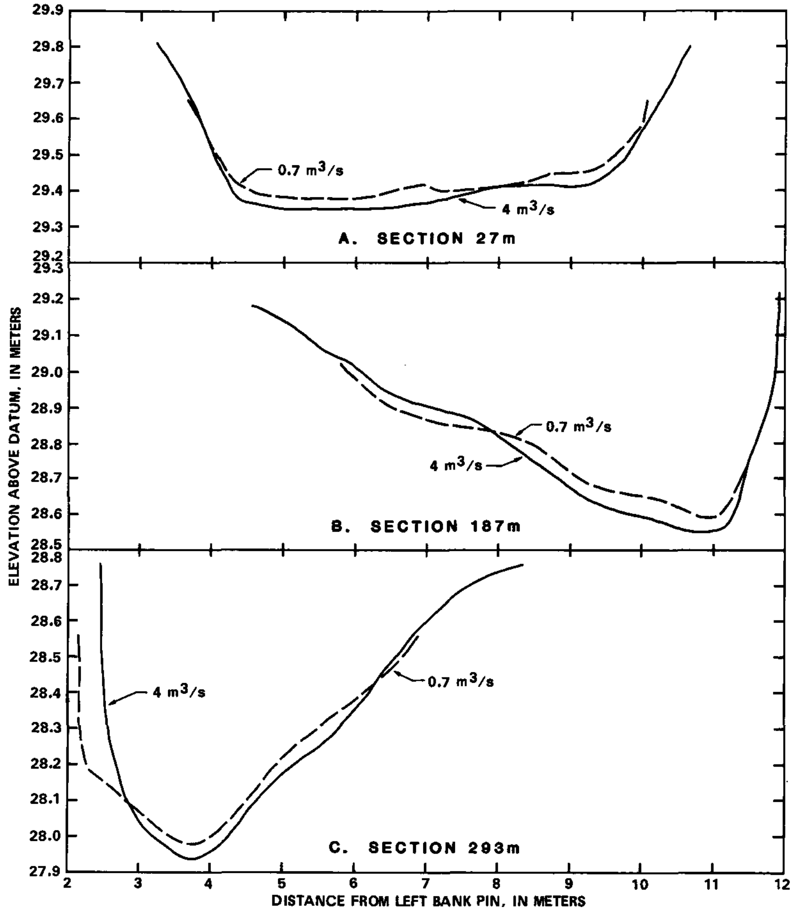

Fig. 3. Cross sections at high and low flow, Rio Grande del Ranchos near Talpa, New Mexico.

Graphs could be prepared for other particle-size classes or for other characteristics of the dispersed tracer. For example, the leading edge of the tracer defines first arrival time, or maximum particle speed, whereas the centroid of the distribution defines mean particle speed. For 0.5- to 1.0-mm particles, mean particle speed is about 30 m/d (meters per day) (100 ft/d); transport occurred during about 22 days, giving an annual downstream travel distance of about 650 m (2130 ft). A significant but minor part of the tracer travelled at 38 m/d (125 ft/d) to a total distance of 1200 m (4000 ft).

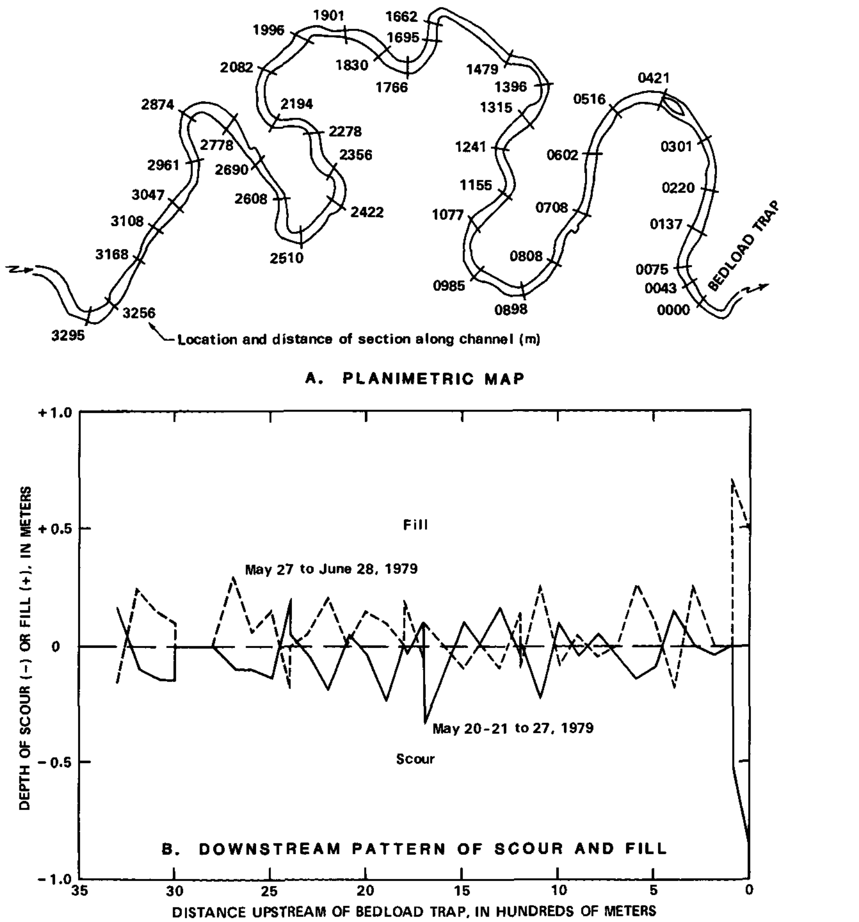

Fig. 4. Planimetric map and downstream pattern of streambed scour and fill, East Fork River near Pinedale, Wyoming.

The average travel distance shown by the fluorescent tracers conforms to that distance computed by considering the volume of scoured material and the measured annual bedload.

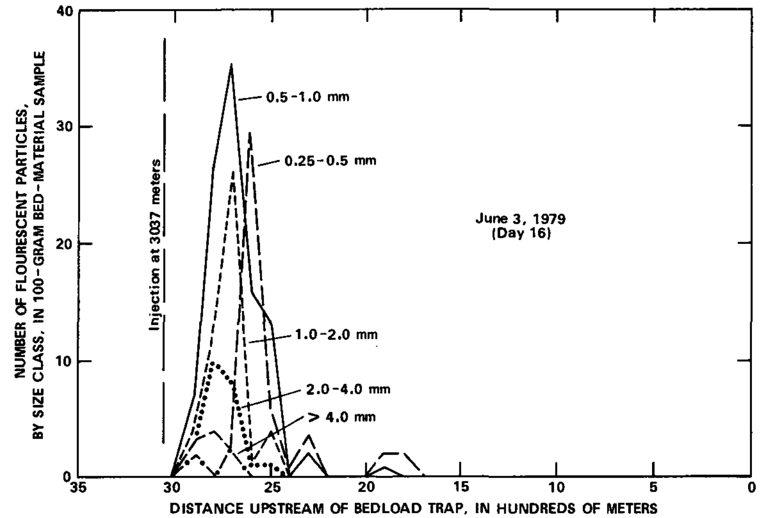

Fig. 5. Downstream distribution of bed-material tracers, June 3, 1979, the 16th day from the date of injection, East Fork River near Pinedale, Wyoming.

Discussion

Scour is associated with dilation of the grain bed through the scour depth. Individual particles move intermittently and at a speed much less than that of the water. Within the dilated blanket, particles are constantly jostling and can change vertical position. Many gravel-bed channels have a greater percentage of large particles at the surface than below the surface, as a result of larger rocks being pushed to the surface by the dispersive force in the dilated layer. The same phenomenon can be observed in many situations where grains of various sizes are jostled. For example if some coarse whole-wheat flour is added to finer white flour when making bread, and the mixture is shaken, the large whole-wheat grains become concentrated at the surface of the dry mix.

The concentration of large rocks at the surface of a gravel streambed is not the armoring caused by winnowing away of finer grains. It is one aspect of the process of bedload movement that requires dilation of the grain bed. Scour and subsequent fill is another aspect of the same process. The areal pattern of bedload transport over the channel bed is determined by the distribution or pattern of boundary shear stress, a function of local curvature and bed topography. But where bedload transport does occur, the motion tends to be in bedload sheets and is associated with dilation of a near-surface layer.

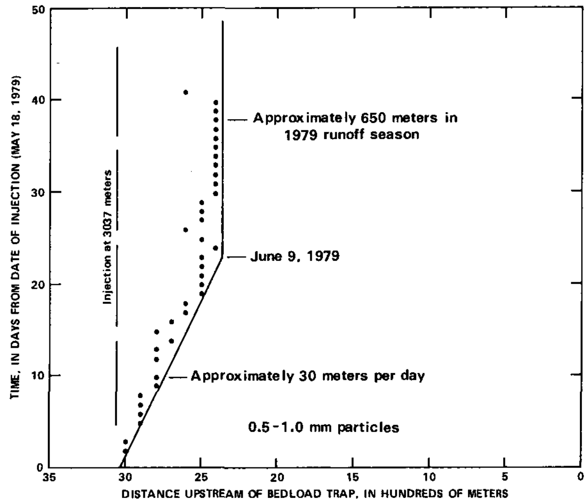

Fig. 6. Downstream daily displacement of the peak concentration of 0.5- to 1.0-mm bed-material tracers, 1979, East Fork River near Pinedale, Wyoming.

Appendix.--References

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