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Observations of Bedload Behavior in Rivers and Their Implications for Indirect Methods of Bedload Measurement

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Abstract

Direct measurements of bedload processes gathered during a four-decade career with the U.S. Geological Survey provide some insight into bedload processes that is of use in the design of indirect measurement technologies. Simultaneous operation of a continuously excavated bedload trap and a Helley-Smith bedload sampler provide much of the information and led to a calibrated portable sampler which, from widespread use, provides confirming information from other locations. Pressure-differential design of bedload-sampler nozzles is a requirement; the pressure difference compensates for the increased resistance of a mesh collection bag in order to maintain a satisfactory sampling efficiency. There is likely little difference in the field performance of several popular pressure-differential samplers with varying exit/entrance flair ratios. Most often, bedload-transport rates increase rapidly with discharge. The exponent of the power relation relating transport rate to discharge is partly dependent on the size of bed material; coarser sizes tend to armor the streambed, delay initial motion, and this results in larger values of the exponent. Bedload transport is characterized by spatial and temporal variability. Thus, for any instant in time, the bedload-transport rate at one location in the river is not directly comparable to the transport rate at another location. These variabilities are important in the design of a bedload measurement program. For example, seldom are the highest transport rates and particle sizes found in the deepest and fastest water toward the outside of a bend, but rather, in the shallower water mid-way up the sloping surface of a point bar or adjacent to a lateral bar. Sampling locations need to span the full width of the stream. The total time to complete the measurement needs to be sufficiently long such that periods of both low and high transport rates are measured, yet sufficiently short that variation in water discharge is minimized.

General Statement

Luna Leopold became Chief Hydrologist of the U.S. Geological Survey (USGS) some 50 years ago. Immediately, he began a transformation of USGS from a water-data agency to the Nation's premier water-science agency. He implemented a hiring policy that attracted highly educated a

capable scientists and set forth research goals that resulted in a new wealth of earth-science knowledge. With these endeavors, there began the golden era for fluvial geomorphology.

A priority research item focused on sediment transport in streams, with a particular emphasis on bedload transport to match the knowledge and skill that USGS had in suspended-load transport. During the 50 years subsequent to the famous flume experiments by G.K. Gilbert (1914) on the transportation of debris by running water, few investigators attempted to obtain somewhat similar data from a natural river. As stated by Leopold and Emmett (1997), “However useful the Gilbert data, they apply to a flume, and a flume is, after all, not a river.” In natural rivers, neither the sediment nor the water discharge are controllable variables. The ability of a river to adjust its cross-sectional shape to the full range of channel-forming discharges is a characteristic not shared by any fixed-wall flume. USGS turned its attention to natural rivers.

A highly successful bedload sampler was developed by USGS employees Edward Helley and Winchell Smith (Helley and Smith, 1971). Modeled after the Dutch-built Arnhem sampler, but with a rigid nozzle and flexible sample-collection bag, the Helley-Smith bedload sampler (see Figure 1a) became a world-wide standard for data collection. One measure of success: 40 years ago, no bedload data existed in the files of USGS; today, thousands of data exist with the majority having been collected by use of the Helley-Smith bedload sampler.

Figure 1. Initial bedload activities of the U. S. Geological Survey. (a) Development of the Helley-Smith bedload sampler; (b) Open slot of the bedload trap, at low flow, on the East Fork River near Pinedale, Wyoming.

Beginning during the 1960s, but culminating with a successful 8-year operation in the 1970s, a bedload trap was conceived by Leopold and his associates and built on the East Fork River, near Pinedale, Wyoming. This device caught all bedload that dropped into a slot on the streambed (see Figure 1b); it was then transported by moving belt to the streambank, lifted to the surface for weighing and sampling, and returned to the river downstream of the trap (Leopold and Emmett, 1997). Simultaneous operation of the bedload trap and the manual deployment of Helley-Smith bedload sampler (see Figure 2a) allowed a field calibration of the sediment-trapping efficiency (Emmett, 1980) of the Helley-Smith bedload sampler. Detailed characteristics of the East Fork River, the bedload trap, and the transported sediment are provided in Emmett (1980) and in Leopold and Emmett (1997)

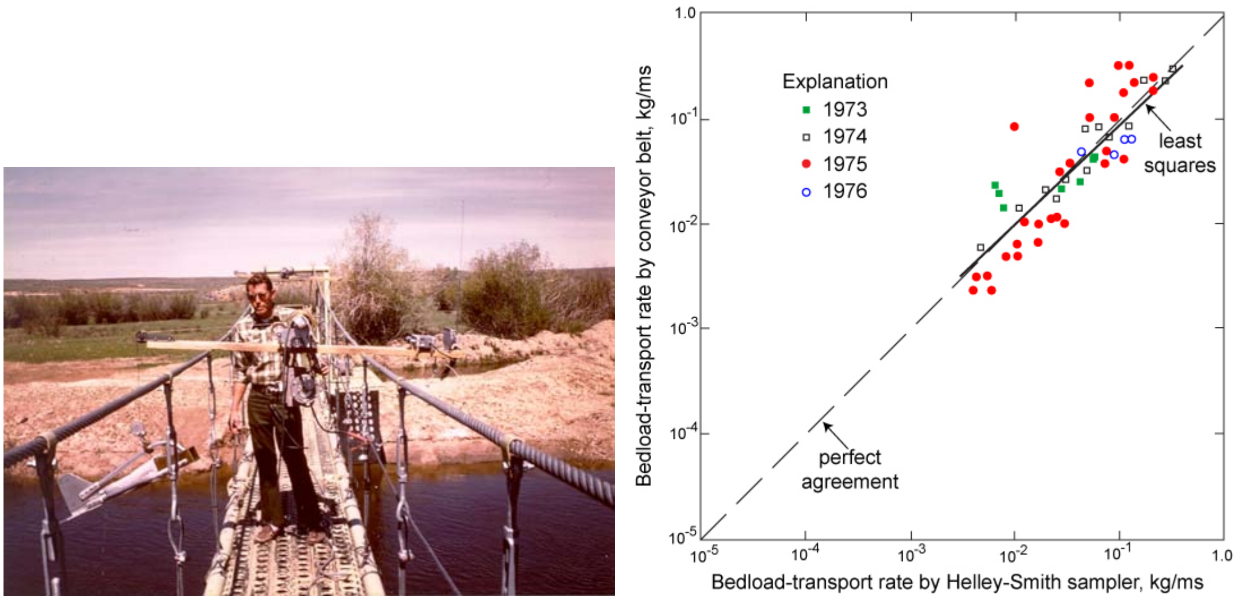

Figure 2. Calibration of the Helley-Smith bedload sampler at the bedload trap on the East Fork River near Pinedale Wyoming. (a) Helley-Smith bedload sampler being deployed from the suspension bridge atop the bedload trap. (b) The near-identical agreement in sampling efficiency between the Helley-Smith bedload sampler and the bedload trap, shown here for total bedload (adapted from Emmett, 1980).

During the same era, investigators outside the USGS were conducting valuable studies of bedload transport, notably the work by Ian Reid and associates in Great Britain (see, for example, Reid and others, 1984) and by Peter Klingeman and associates at Oak Creek, Oregon (see, for example, Klingeman and Emmett, 1982). Discussions herein rely only on observations by the author during studies conducted by USGS.

Introduction

Helley-Smith Bedload Sampler (And Some Variations Thereof)

A decade of using the Helley-Smith bedload sampler, primarily in gravel-bed rivers in the United States, resulted in valuable insight in sampling procedures and in estimates of bedload transport in rivers. But sampling characteristics of the Helley-Smith bedload sampler were unknown. Hydraulic characteristics were assessed in the mid-1970s (Druffell and others, 1976) and calibration of the sediment-trapping characteristics was enabled by operation of the bedload trap in Wyoming (Emmett, 1980). In this field calibration, streamwide values of bedload-transport rates and particle sizes, collected simultaneously and at the same section by the two methods, were related in a direct x versus y comparison to establish a near-identical efficiency of the two methods (see Figure 2b). Complete details are provided in Emmett (1980); suffice it here, the calibration was considered most applicable for particle sizes in the range of 0.5 to 16 millimeters.

The hydraulic studies indicated that because of flow separation, the difference in hydraulic efficiency of samplers with exit/entrance flair ratios greater than about 2 does not greatly change. Commonly used Helley-Smith type samplers with flair ratios varying from 1.4 to 3.2 (BL-84 and Elwa

to original Helley-Smith) have hydraulic efficiencies greater than one and are in the range of 1.35 to 1.55. Variations in the sample-collection bag, including bag size, mesh opening, and filament size, can have greater influence on this range in hydraulic efficiency than flair angle alone. Combined with operational ‘clogging’ factors, including quantity and particle size of bedload collected and the amount and nature of organic debris, there is little definable difference in the real-world performance of most Helley-Smith type bedload samplers. It all becomes apparent with initially converging flow lines of water and sediment into the nozzle and the slow but gradually increasing rejection of both water and sediment as samplers begin to fill from the time they are first placed in the water. This is a reason that samplers with an acceptable sediment-trapping efficiency must have an element of super hydraulic efficiency.

This was verified by field testing several interchangeable nozzles using the frame of a Helley-Smith bedload sampler (unpublished data by the author) during the calibration of the Helley-Smith bedload sampler. One nozzle was the prototype for what later became the nozzle for the BL-84 bedload sampler. These studies indicated samplers with a hydraulic efficiency of 1.0 tended to have a sampling efficiency of about 2/3 and samplers with a hydraulic efficiency of about 3/2 tended to have a sampling efficiency of about 1.0. Because the Helley-Smith bedload sampler was the only sampler design in widespread use at that time, it was the only sampler for which a true x versus y sediment-trapping calibration was completed.

Subsequently, unpublished field comparisons conducted in several rivers by the author and Robert Burrows, USGS, indicated little difference between the BL-84 and Helley-Smith bedload samplers in the measured values of transport rate and particle size. Similarity in performance extended to commonly used construction details, whether the sampler is of ‘thick wall’ or ‘thin wall’ construction.

Using the Helley-Smith bedload sampler, bedload was sampled both immediately upstream and immediately downstream of the open slot of the bedload trap to verify a 100 percent sediment-trapping efficiency for the bedload trap. Accordingly, the sediment-trapping efficiency of commonly used Helley-Smith type bedload samplers was shown to be about 100 percent.

Bedload-Sampling Procedures

Sampling procedures for Helley-Smith type bedload samplers evolved during routine use, during the calibration studies at the bedload trap, and during special studies to verify sampling procedures. Because bedload-transport rates were observed to vary from bank to bank, early sampling was designed to sample the full width of the channel, generally at about 20 equally spaced cross-channel locations. For the early sites, temporal variations were such that if two such traverses were conducted, each starting from the same bank, the total time required to complete the measurement accommodated the range of temporal variations observed at the measuring section. Thus evolved what became known as the single equal width increment (SEWI) sampling procedure (Edwards and Glysson, 1999) though in reality, two sampling traverses are required.

During calibration tests, because of the 8-gate design of the bedload trap (Leopold and Emmett, 1997), 24 cross-channel sampling locations were established and sampled on two traverses; each traverse began from the same bank so that time differences in sampling each vertical were about equal among all verticals; thus, this procedure did not favor any potential differences in temporal variations across the channel. During measurements with reasonably constant river stage, more than two traverses were conducted; frequently, differences in mean transport rate were observed between two traverses, but the addition or more then two traverses did not greatly alter a computed mean-transport rate. Thus, about 40 individual bedload samples were considered about minimum to establish a mean transport rate.

Alternatively to the SEWI sampling procedure, a multiple equal width increment (MEWI) sampling procedure was established for those instances where temporal variations were perceived to be of greater importance than spatial variations. This sampling procedure maintained the necessary 40 individual measurements, but the measurements were collected at fewer cross-channel locations, but on more traverses of the stream. A principal disadvantage of the MEWI procedure is that the cross-channel distribution of bedload-transport rate is most often not reliably predictable and, as previously mentioned, knowledge of cross-channel variations during previous measurements is no guarantee of knowledge during a later measurement. Thus selection of fewer cross-channel verticals has risks.

A decade after routine operation, the bedload trap was revisited to further explore sampling procedures. During a day of constant river stage, measurements of bedload were made at the original 24 cross-sectional locations using a Helley-Smith bedload sampler. The procedure was repeated all day, so that numerous traverses were completed for each day. Several days, each with a different river stage, comprised the total sampling. For each day, the 'true' transport rate and particle-size distribution was determined as the average from all traverses. Data for each day of measurement were analyzed for various combinations of equally spaced samplings with a total of about 40 individual samples, whether it be from 2 traverses of 24 locations, 3 traverses of 12 locations, 5 traverses of 8 locations, 7 traverses of 6 locations, 10 traverses of 4 locations, 20 traverses of 2 locations, and sampling only at one location. Results of the analytical combinations confirmed the sampling scheme that two traverses of 20 verticals closely matched the 'true' transport rate and particle-size distribution. But, as the number of cross-channel locations was reduced, the calculated average values began to differ more and more from the 'true' value. Though the data of this study are unpublished, all data remain in the USGS archives; the results suggest that reductions in accounting for spatial variability should be cautiously considered. Insight to bedload sampling in rivers has been reported by the author (Emmett, 1981a, 1981b, 1984).

Some Observed Bedload Behavior in Rivers

Bedload-Rating Curve

Bedload-rating curves are steep, whether transport rate is related to stream power or water discharge, and whether or nor considerations for incipient motion are included. Typically, the relation of bedload-transport rate as a function of water discharge or stream power has an exponent of about 2.5 to 3. Emmett and Wolman (2001) have shown that the exponent of the relation is partly dependent on size of bed material; coarser sizes tend to armor the streambed, delay initial motion, and this results in larger values of the exponent. Typical bedload ratings for some rivers discussed herein are shown in Figure 3. Figure 3a is partial data from the first several years of operation of the bedload trap on the East Fork River. Background relations shown in Figure 3 are constructed after discussions with Ralph Bagnold and are adapted from Leopold and Emmett (1976).

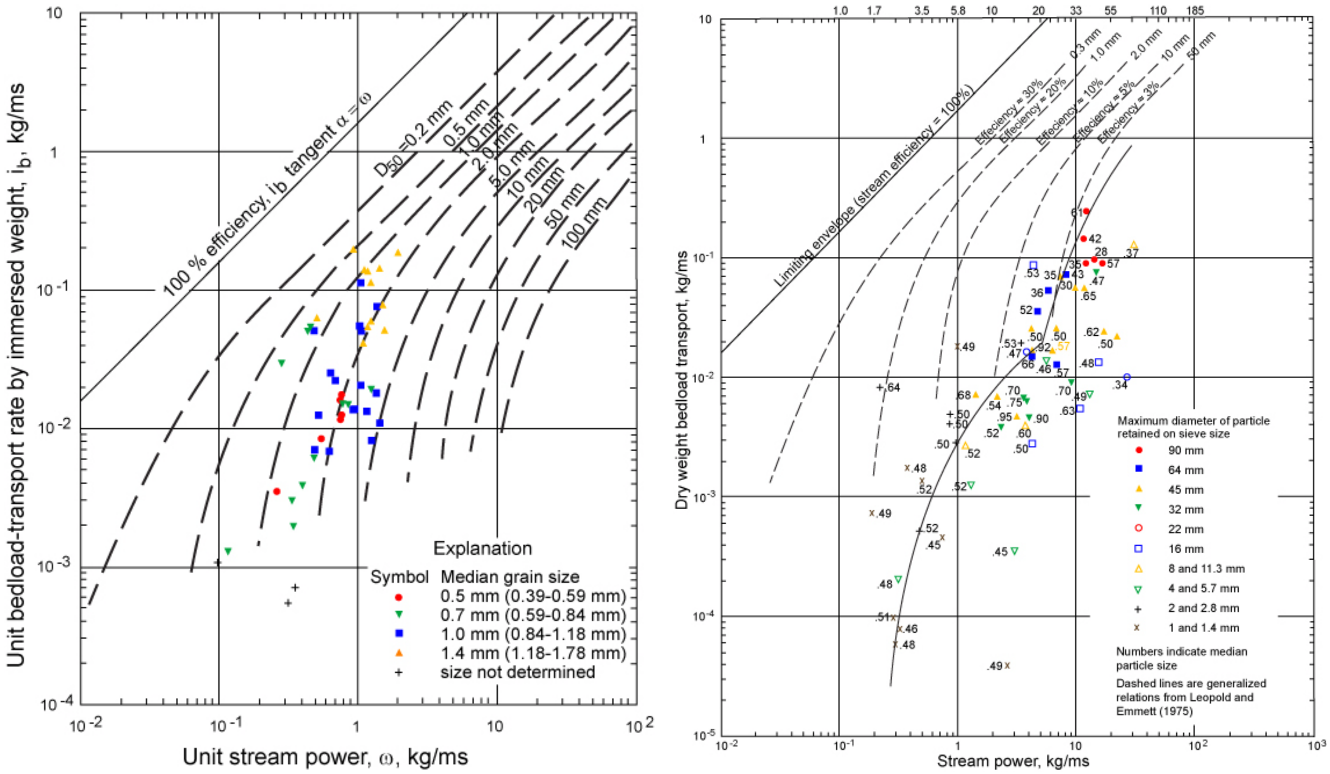

Figure 3. Examples of bedload-rating curves: unit bedload-transport rate as a function of unit stream power. (a) East Fork River at the bedload trap near Pinedale, Wyoming (adapted from Leopold and Emmett, 1976). (b) Snake River at USGS gage near Lewiston, Idaho; bedload particle-size change from sand to gravel marks the beginning of Phase II transport (adapted from Emmett, 1976).

Measured values of bedload-transport rate commonly range over more than 5 orders of magnitude, from a few, usually small, moving grains to almost all bed material of all sizes in motion. Although the usual logarithmic bedload ratings appear to be linear (data not fitted with straight lines in Figure 3), arithmetic bedload ratings (see, for example, Emmett and Wolman, 2001) often show smaller particles at low transport rate moving atop a stationary bed at lower flows, and a rapid increase in transport rate and particle sizes at higher flows. This ‘explosion’ in transport rate is usually complete by bankfull stage, but may begin at stages about half bankfull (Emmett, 1999; Ryan and Emmett, 2002). This increase in transport rate and particle size is apparent in Figure 3b for data collected in a large gravel-bed river, the Snake River, near Lewiston, Idaho. As the streambed is disrupted at high flows and there are no constraints on the availability and mobility of bed material, the median particle size of bedload abruptly changes from sand to coarse-gravel, the sizes comprising the median size of the bed material (Emmett, 1976). The rapid increase in bedload-transport rate and particle size constitutes the beginning of what is commonly called Phase II bedload transport.

The rating curves and an ‘explosion’ in the rating at about bankfull are such that the largest increment of bedload transport occurs near bankfull discharge (often called effective discharge), and that the next largest increments occur on either side of bankfull discharge. The upshot is that the most meaningful measurements of bedload are those collected at high flow. As is often the case, as much as 70 to 80 percent of the bedload is transported by that 10 to 20 percent of the annual water budget occurring at highest flows during only several percent of total time (Emmett, 1999).

Temporal Variability

Temporal variability in bedload-transport rate is easily visualized for sand-bed channels as sand dunes, either orthogonal or diagonal to the direction of flow, migrate downstream. In this case, bedload-transport rates vary from near zero at the dune trough to maximum values at the dune crest. Typically, instantaneous bedload-transport rates vary from near zero to about four times the mean; about 60 percent of sampled rates are smaller than the mean as any one sample may be large but no sample can be smaller than zero. Because dunes may be diagonal to the flow direction, the magnitude of bedload-transport rate near one bank is most often not synchronous with the magnitude at the other bank. And, in the downstream direction because of dune spacing, the magnitude of bedload-transport rate at one section is most often not synchronous with the magnitude at another section. This creates the challenge that for any instant in time, the bedload-transport rate at one location in the river is not directly comparable to the transport rate at another location. This is also a basis for the design of the calibration study for the Helley-Smith bedload sampler: the streamwide average bedload-transport rate measured by the sampler was compared to the streamwide average bedload-transport measured by the bedload trap during the same increment of time (same discharge).

Frequently, when particle sizes in motion are larger than several millimeters, dunes do not form, but bedload sheets, a long, low, dune-like bedform slowly migrates downstream. Thus, although many gravel-bed rivers have no apparent dunes migrating downstream, most still exhibit temporal variability in bedload-transport rate that can only be determined by measurement. That is, for a constant discharge, bedload-transport rate varies with time. This is shown in Figure 4 for Slate Creek, a tributary to the Salmon River near Clayton, Idaho. Bed material in Slate Creek has a median size of 43 millimeters; median size of sampled bedload was coarse gravel and there were occasional cobbles in transport larger than the 76-millimeter square nozzle of the Helley-Smith bedload sampler. Figure 4 indicates that concerns about temporal variability are as applicable for gravel-bed rivers as they are for sand-bed rivers. In essence, this temporal variability manifests itself as a longitudinal spatial variability.

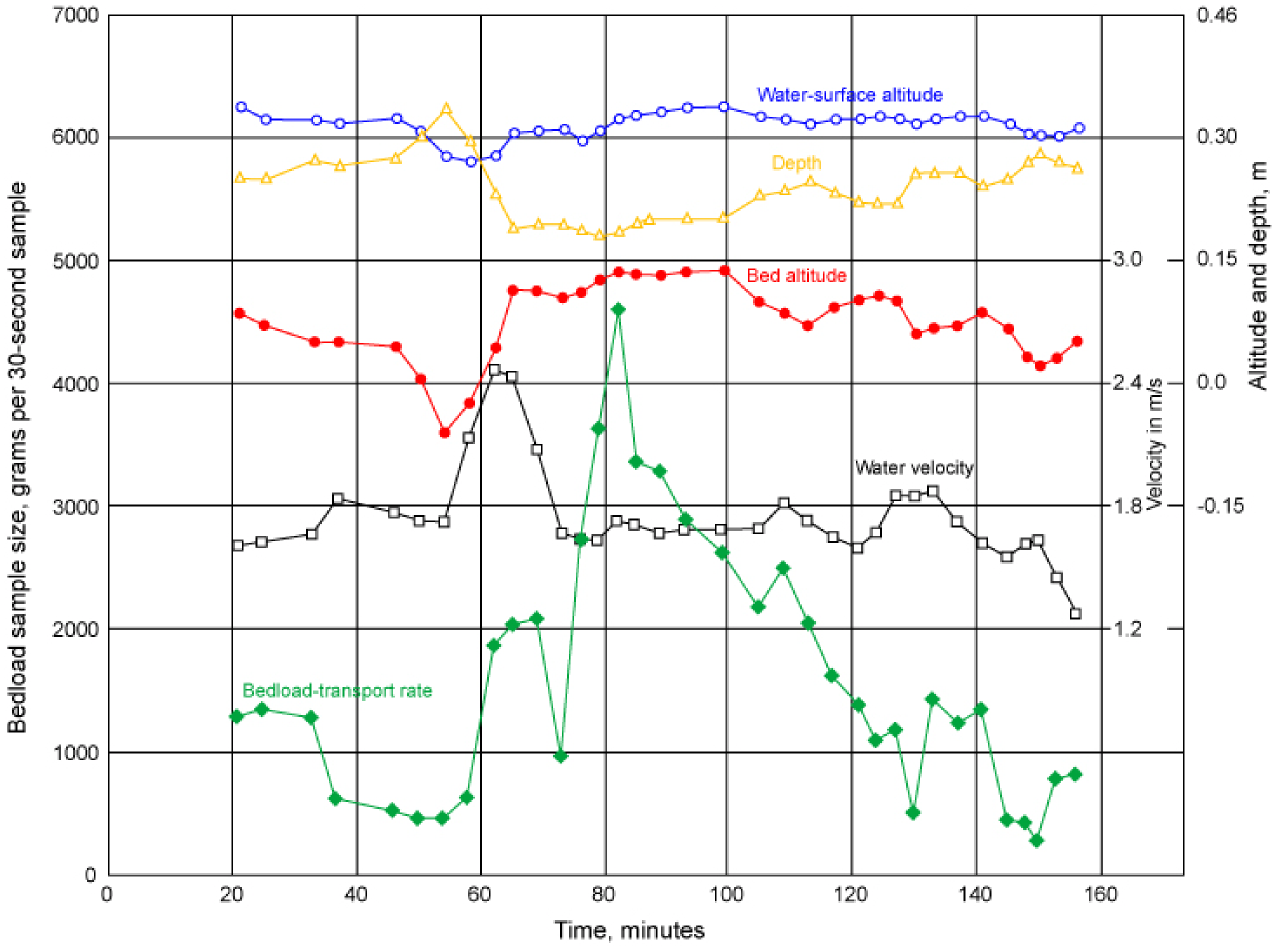

Figure 4. Temporal variability as measured on Slate Creek, a coarse gravel-bedded tributary to the Salmon River near Clayton, Idaho (adapted from Emmett, 1975).

Cross-Channel Spatial Variability

Bank-to-bank sampling of bedload provided information on the cross-channel distribution, or lateral spatial variability, of bedload. Not all results were completely expected, for example, seldom are maximum bedload-transport rates observed in the deepest and fastest water. Indeed, in curving reaches of channel, little to no bedload is observed in the deep, fast water toward the outside of the bend. Figure 5 illustrates this for the large, coarse gravel-bedded, Snake River and the smaller, fine gravel-bedded, East Fork River at the bedload trap. For both rivers, the channel cross-section is shown as well as the season-averaged cross-channel distribution of velocity, and bedload-transport rate and particle size. At the Snake River, no bedload is observed in the outer (right) channel though that is where maximum velocity occurs. Maximum transport rate is partway up the sloping surface of the inner (left) channel, and particle size is smaller toward the inner channel. This cross-channel pattern of bedload is related to the distribution of bed shear and to secondary circulations sweeping the sediment inward. As water discharge changes, there are subtle variations in the cross-channel distributions of bedload-transport rate and particle size such that knowledge of the distribution at one stage is no guarantee of knowledge of the distribution at another stage. Since the time of measurements during the early 1970s on the Snake

River, a number of studies of flow in bends have been conducted; these verify the results of the Snake River data and add important detail to knowledge of flow in bends.

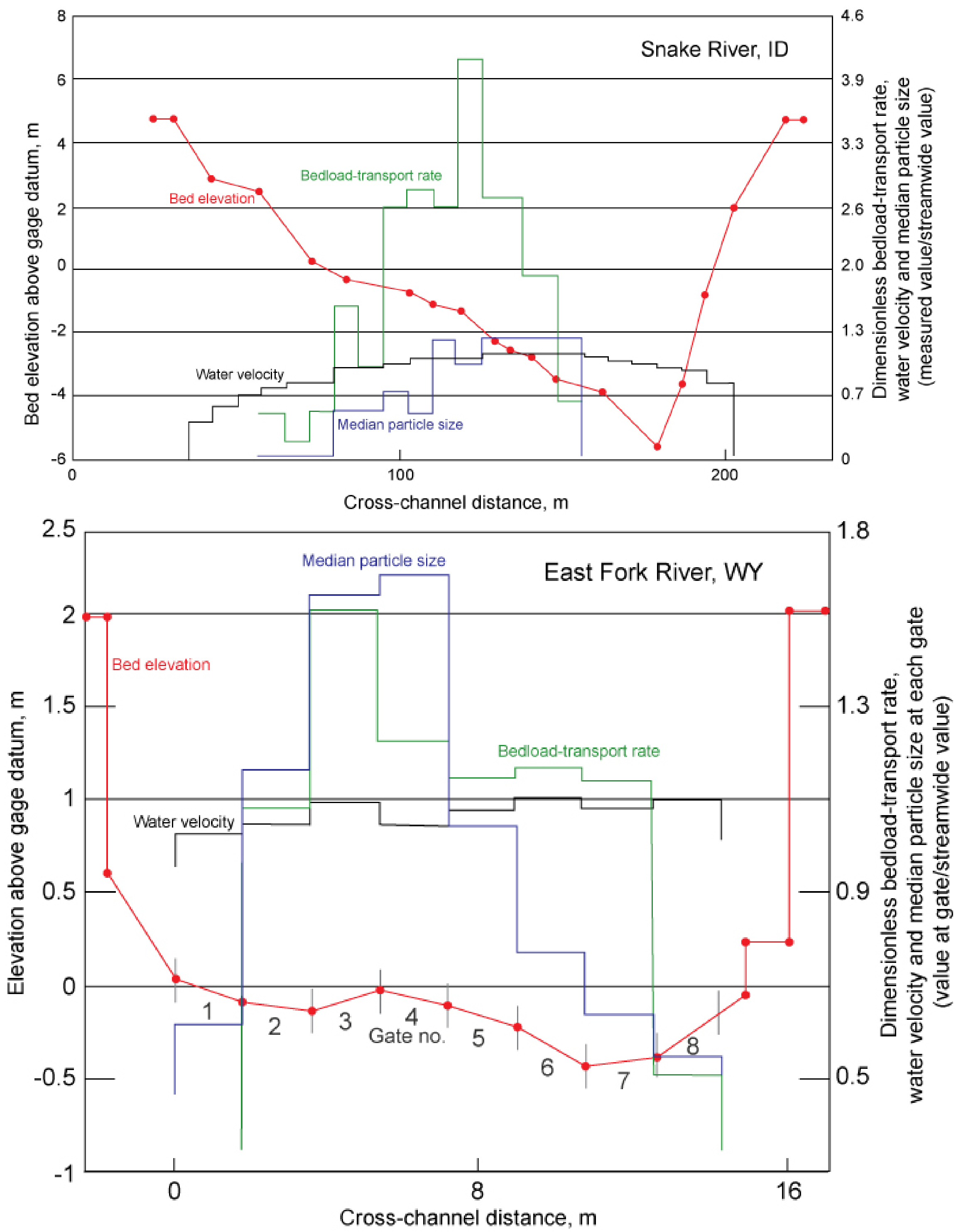

Figure 5. Spatial (cross-channel) variability in bedload characteristics. (a) Snake River at USGS gage near Lewiston, Idaho. (b) East Fork River at the bedload trap near Pinedale, Wyoming.

The East Fork River shows similar characteristics of lateral spatial variability; the bedload-trap section at the East Fork River is in a lesser bend, but has more of a central bar. For the same reasons of bed-shear distribution and secondary circulations, maximum transport rate and particle sizes occur atop the central bar; both maxima are skewed toward the inner (left) channel while faster velocities are skewed toward the outer (right) channel. As with the Snake River, as water discharge changes, there are subtle changes in the cross-channel distribution of bedload characteristics. Again, knowledge of the bedload distribution at one stage is no guarantee of knowledge of the distribution at another stage.

Reconnaissance of river channels, aided by aerial viewing from light aircraft, enhances our knowledge of spatial variability. Figure 6 is aerial views of the East Fork River near the bedload trap in Wyoming; light-colored depositional areas (point bars) appear on the inside of meanders bends as are alternating lateral bars associated with riffles in straight reaches of channel. The fact that the point bars have a spacing on the order of 5 to 7 channel widths, and the riffles (lateral bars) have a spacing of 5 to 7 channel widths suggests that the same processes operating in bends are operating in straight reaches. The bedload that forms these depositional bars alternates between channel sides every 5 to 7 channel widths and indicates a bedload direction corresponding to about the tangent of 1/6, or 0.167. This corresponds to an angle of about 9 to 10 degrees and suggests that even in straight channels, bedload motion is a zigzag course downstream. This general tendency was verified by bedload sampling at a number of sections on the East Fork River, Wyoming during 1979-1980 (for a list of references for the East Fork River studies, see Emmett, Leopold, and Myrick, 1983).

Figure 6. Spatial variations in bedload as indicated by locations of lateral bars and point bars. (a) Looking down valley at East Fork River near Pinedale, Wyoming; bedload trap is about 50 meters downstream of the road crossing. (b) Close-up of the meander loop in the foreground of part (a).

Dispersive Stress

Largely known from the research of Ralph Bagnold (see, for example, Bagnold, 1954), but observed in many painted-rock experiments (see for example, Leopold, Emmett, and Myrick, 1966) a dispersive stress normal to the direction of flow acts differentially on particles of different sizes; larger particles receive the greatest force such that large particles tend to migrate upward during motion. This is not only apparent when the largest particles in a debris flow appear at the surface, but in river flows, can occasionally give the appearance of coarse particles appearing to 'float' with only infrequent contact with the streambed. Subsequent to floods which barely submerge bridge crossings, cobbles and boulders frequently can be found littering the bridge surface, having been supported upward in the flow

by dispersive stress. In painted-rock experiments, it is dispersive stress that enables coarse particles to be observed at the streambed surface even though the underlying smaller particles had earlier scoured to some depth.

Concluding Statement

Some observed behavioral characteristics of bedload suggest the relative greater importance of bedload at higher flows, that the bedload-transport process is characterized by spatial and temporal variability, neither of which can be ignored, and that adequate direct-sampling techniques exist to quantify characteristics of bedload in natural rivers. At present, measurement of bedload is a time-consuming and expensive undertaking. Technology surrogate to direct sampling of bedload is both developing and encouraging; these indirect methods of measurement must provide information relevant to real-world needs. The ability of indirect methods to conform to observations from direct measurement should be useful in the continued development of surrogate technology.

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