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Bedload and River Hydraulics—Inferences from the East Fork River, Wyoming

By LUNA B. LEOPOLD *and* WILLIAM W. EMMETT

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VERTICAL DATUM

Sea level: In this report, “sea level” refers to the National Geodetic Vertical Datum of 1929 (NGVD of 1929)—a geodetic datum derived from a general adjustment of the first-order level nets of the United States and Canada, formerly called *Sea Level Datum of 1929.*

SYMBOLS

A	Cross-sectional area, in square meters (m^2)
d	Mean depth of flow, in meters (m)
D	Grain diameter (particle size), in millimeters (mm)
D_{50}	Median grain diameter, in millimeters (mm)
D_{35}	Grain diameter at 35 percent finer, in millimeters (mm)
D_{84}	Grain diameter at 84 percent finer, in millimeters (mm)
f	Darcy-Weisbach friction factor (dimensionless)
g	Acceleration due to gravity, in meters per second per second (m/s^2)
i_b	Measured unit bedload-transport rate, in kilograms (mass immersed) per second per meter of width (kg/m·s)
i_b'	Theoretical unit bedload-transport rate, in kilograms (mass immersed) per second per meter of width (kg/m·s)
i_s	Measured unit suspended-sediment transport rate, in kilograms (mass immersed) per second per meter of width (kg/m·s)
N	Newton—a unit of force, in kilograms times acceleration due to gravity ($kg{\cdot}m/s^2$)
Q	Water discharge, either total or effective, in cubic meters per second (m^3/s)
S	Water-surface slope, in meters per meter (m/m)
S_s	Ratio of grain density to fluid density (dimensionless)
u	Mean velocity, in meters per second (m/s)
u_0	Mean velocity at initial value for grain motion, in meters per second (m/s)
u_*	Shear velocity, in meters per second (m/s)
u/u_*	Friction factor (dimensionless)
w	Width of flow [or width of bedload slot], in meters (m)
θ	Shields threshold criterion (dimensionless)
γ	Specific weight of water, 1,000 kilograms per cubic meter (1,000 kg/m^3)
ρ	Density of water, in kilograms per cubic meter (kg/m^3)
τ_0	Shear stress at initial motion, in kilograms per square meter (kg/m^2)
ω	Available unit stream power, in kilograms per second per meter of width (kg/m·s)
ω_0	Unit stream power needed for initial motion, in kilograms per second per meter of width (kg/m·s)
$\omega - \omega_0$	Excess unit stream power, in kilograms per second per meter of width (kg/m·s)

Bedload and River Hydraulics— Inferences from the East Fork River, Wyoming

By Luna B. Leopold *and* William W. Emmett

ABSTRACT

During 1973-79, bedload data were collected in a sophisticated trap on a river of moderate size, the East Fork. The transport rate was measured most days through a full snowmelt season, and the rate was determined separately for eight zones across the channel width. The quantitative data are unique and unlikely to be repeated. Nor need they be, because as a result of this effort a practical bedload sampler was adequately tested against full river measurement.

It was shown that bedload moves sporadically and randomly on the river bed. Therefore, transport rate is highly variable in short periods of time. There is also a wide variance from day to day. Yet, different rivers have transport rates, which are functions of discharge, depth, and sediment size, that are clearly distinct.

Comparison of computed and measured transport rates indicates that a major problem remains: What grain size is representative of the bedload when there is a wide or heterogeneous particle-size distribution? Size of the bedload in motion may be very different from the size of bed material obtained from samples of the streambed.

For general computation, the river channel slope may be averaged, and it may be assumed that water-surface slope does not change materially with changing discharge. Indeed, this generality is correct, in that, compared with depth, velocity, and width, slope is conservative at-a-station. However, in more detail, slope changes importantly with discharge in short reaches of channel, and those changes are very different in pool and riffle.

These local changes in slope are not merely an aspect of a detailed longitudinal profile but involve cross-channel as well as down-channel components. The pool and riffle sequence involves not only undulation of bed elevation and bar formation on alternate sides of the channel, but alternation of the zone of superovulation of the water surface, and changing relation of water-surface slope to discharge. These details can be seen only in the full topography of the water surface.

Riffles fill during high flow and scour at low flow. Changes in local water-surface slope illustrate this process. Pools are a storage zone for sediment in the low-flow season. Even though large volumes of sediment move, the distance moved is not large—in the East Fork River, sand of size 0.5-1 millimeter moved 650 meters during the 1979 snowmelt runoff season.

Bedload transport is greatest over or near bars and not in the deepest part of the channel. Direct observation of the locus of sediment transport indicates that this locus moves from one side of the channel to the other in concert with the occurrence of alternate bars. Separately, data indicate that at constant stream power, transport rate increases as depth decreases.

GENERAL STATEMENT

In the 80 years subsequent to the famous experiments of G.K. Gilbert (1914) on the transportation of debris by running water, only a few investigators have attempted to obtain somewhat similar data from a natural river. However useful the Gilbert data, they apply to a flume with fixed walls, and a flume is, after all, not a river. The ability to adjust the channel cross section to a variety of flows is one of the characteristics of a natural channel that is not shared by any fixed-walled flume. Clearly, the variety of conditions controlled in laboratory experimentation cannot be established in a natural river. The sediment in transport is determined by the geology and physiographic setting of the river; thus, the sediment is not a controllable variable. Furthermore, a principal characteristic of a natural river system is the variability of discharge, another parameter ordinarily held constant or controlled in flume experimentation.

Even with the limited ability to hold any variables constant, it would be highly desirable to have direct measurements of the bedload transport in a natural river and of the concomitant hydraulic characteristics of the flow. The problem has been particularly intractable, because no sampling device has been available that would provide reliable and repeatable measurements of the debris load moving along the bed of the river. If, on the other hand, sampling were not the procedure used, an apparatus would be needed that would trap the total sediment and provide measurements of the moving load through time and space across the river. Because of the variability through time, repeated measurements during successive seasonal flows would be required.

This project involved the construction of such an apparatus and operation of the apparatus for 7 years. The data from the sediment trap also allowed field calibration of a highly successful bedload sampler designed by Edward Helley and Winchell Smith of the U.S. Geological Survey (Helley and Smith, 1971). The development of this field sampler happened to coincide with the construction of a successful bedload trap. Thus, two methods of measuring the sediment moving along the streambed became available for simultaneous operation. The coincidence of these two developments allowed the bedload trap to be a field test of the sampler as described in detail by Emmett (1980a).

In the same decade, another bedload measuring device of sophisticated design was operated in Britain by Ian Reid and his associates (Reid and others, 1984). The results reported here might well be examined in conjunction with that report. The East Fork device caught all bedload that dropped into a slot on the streambed; it was then transported by moving belt to the streambank, lifted to the surface for weighing and sampling, and returned to the river. The Reid device weighed the sediment as it passed over sensitive underwater pressure sensors. Each of the installations produced interesting and useful information and each added to the value of the other.

This report describes the bedload and hydraulics of the East Fork River in western Wyoming. We begin with a description of the geologic and geomorphic setting of the river basin. The characteristics of the East Fork River in the general area and at the project site are then described with the aim of demonstrating that the East Fork is like many other rivers in the region and that it is normal rather than unique.

The bedload trap, including the history of its development, is then described. The operational procedure is detailed, as is the process of analyzing the data. Finally, the data are introduced. They consist of 140 sets of measurements, most taking 1 day to complete. These sets of measurements, listed at the end of this report, were made on 114 different days over 6 separate years during 1973-76, 1978, and 1979. Because of drought conditions, no data were collected during 1977, but on several days during 1976 and 1978, multiple sets of measurements were collected. Published data sources for bedload transport rates and size distributions are listed below:

Dates	Data source
1973-76	Emmett (1980a); Leopold and Emmett (1976; 1977)
1978	Emmett and others (1985)
1979	Emmett and others (1980)

In 1979, a much more elaborate set of measurements was recorded at 40 cross sections spaced about equally along a 3.3-km reach of the river (Emmett and others, 1980). In 1980, a more detailed set of data was collected at 42 cross sections along a 1.8-km reach (Emmett and others, 1982). The results of these studies help explain some of the features observed at the bedload trap.

Research Area

Most rivers, having peak discharge resulting from rainstorms, pose a difficult problem for the fluvial geomorphologist and hydraulician, owing to the rapid rise and fall of discharge and the inability to forecast when the observer needs to be at the measuring site. The authors spent considerable effort measuring hydraulic variables on a perennial river in Maryland, but the flashiness made it nearly impossible to complete the desired measurements during the time that discharge was relatively constant. Measurement of water-surface slope was particularly intractable. Therefore, we began serious work on snowmelt rivers in the Rocky Mountains. A decade of such work on a variety of streams led us to choose those in Sublette County, Wyoming, as being satisfactory for a long-term study of bedload.

The river that seemed to fit the eventual objective best was the East Fork River, a tributary flowing westerly out of the Wind River Range, joining the New Fork River near the town of Boulder, Wyoming (fig. 1). The New Fork then flows southwest to join the master stream, the Green River, a tributary to the Colorado River. The East Fork has several characteristics that made it highly desirable for the project. It is a snowmelt stream with a flood season that lasts from mid-May to late June. At all other times of the year, the flow is low, and little bedload is in motion. Rainstorms contribute practically nothing to the flood discharge.

The East Fork River heads in high mountains consisting of igneous and metamorphic rocks relatively free of fine-grained material. The river does not flow through any soft sediments until it is several kilometers from the mountain front, so the material carried is mostly sand and gravel with practically no silt or clay. Thus, it offered an opportunity to measure primarily bedload with unusually small amounts in suspension.

The other characteristic of the East Fork River that makes it different from all other streams in the upper part of the Green River system is that there is no lake on the East Fork to trap the sediment coming from the source or to attenuate the flows resulting from snowmelt in the high country. Without exception, all other streams of its size have a lake somewhere along the length, formed by a terminal moraine as in the case of New Fork Lakes, Willow Lake, Fremont Lake, Half Moon Lake, and Boulder Lake (fig. 1; New Fork Lakes are northwest of the area shown in fig. 1).

Another practical consideration was that the project site should be near a bridge crossing the river in order to obtain access to the far bank. Such a location was found in the SE$\frac{1}{4}$NE$\frac{1}{4}$NW$\frac{1}{4}$ of sec. 11, T. 31 N., R. 107 W., where a wooden county road bridge crosses the East Fork near the place chosen for the experiment. The location of the bedload project site is shown in figure 1. A contract was negotiated with the land owner to rent a small plot of land where the installation was made and where we could keep our equipment and make the measurements.

Acknowledgments

During more than a decade of work on this river, especially at the bedload trap, many individuals observed or participated for short or long periods. The list is too long for individual attribution, but two were of special importance to the research project: Robert M. Myrick in construction and operation, and James F. Wilson, Jr. in manuscript preparation. We thank all contributors, but for these two individuals, we owe a debt of gratitude.

GEOLOGIC AND GEOMORPHIC SETTING

Pre-Pleistocene Geology

The East Fork River heads in the Wind River Range, a mountain range extending 190 km north-northwest and 58 km wide, as shown in the location map (fig. 1). The range rises above an extensive basin; the elevation of the basin is about 2,100 m above sea level. Mount Bonneville is the highest point in the East Fork basin, at 3,831 m.

To the southwest of the Wind River Range are nearly horizontal sedimentary rocks in the Green River Basin. These rocks of Cenozoic age are overthrust by the Precambrian rocks of the range along a thrust plane that dips 30° to 35° to the northeast. "The Precambrian core of the uplift consists of migmatites at deeper levels in the center of the range and granitic intrusions and super crustal rocks at higher crustal levels at the southeast end. These rocks constitute some of the oldest Precambrian crust in the United States and are dated at 2.7 b.y. B.P. [billion years before present]." (Smithson and others, 1978).

These investigators ran a deep seismic-reflection traverse from a position about 120 km south-southeast of Pinedale northeast to a point about 120 km east of Pinedale—a distance of about 150 km. The depth to which the reflection data were considered

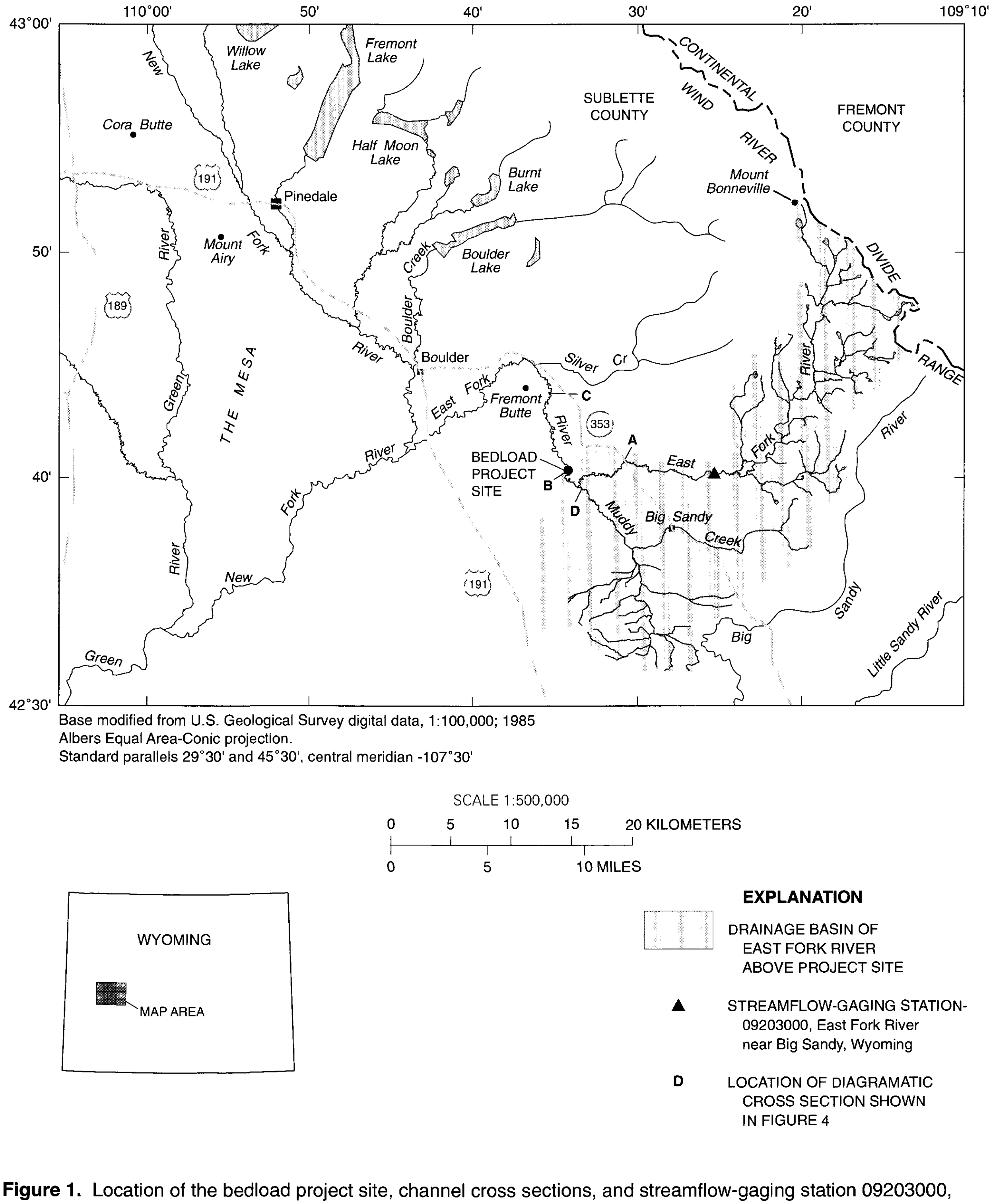


Figure 1. Location of the bedload project site, channel cross sections, and streamflow-gaging station 09203000, East Fork River near Big Sandy, Wyoming.

good was 60 km. The sedimentary rocks under the southwest end of the profile range in age from Cambrian through Tertiary. The sedimentary rocks directly under the thrust are deformed by folding and numerous faults. The fault can be traced to a depth of at least 24 km past the deepest possible sedimentary rocks, and the fault continues into the Precambrian crystalline rocks of the crust.

Glacial Sequence

More important to the present investigation are the results of massive glaciation during the Pleistocene Epoch (10,000 to 1.65 million years B.P.) studied first by Blackwelder (1915), the glaciation in the southwestern part of the range later reported by Holmes and Moss (1955), and the glaciation in the Pinedale area reported by Richmond (1973). At least four principal glacial periods are identified. The earliest well-preserved combination of fill and outwash terrace is called the Buffalo by Holmes and Moss (1955) and presumably is related to either the Cedar Ridge or the Sacagawea Ridge glaciations of Richmond (1973). This episode is considered by Holmes and Moss (1955) to be pre-Wisconsin. The two main glacial events, Bull Lake and Pinedale, both compound and involving successions of advance and retreat, are marked by massive moraines and widespread outwash plains that have subsequently been trenched, leaving extensive dissected terraces along the main river valleys. These are tentatively considered to be correlated with the last phases of Wisconsin glaciation. "The longest time interval between stages separates the Buffalo and Bull Lake. The interval between Bull Lake and Pinedale is substantial and greater than the interval between Bull Lake I and Bull Lake II or between any of the oscillations of the Pinedale." (Holmes and Moss, 1955, p. 651).

Subsequently, there was a minor advance, Temple Lake, indicated by moraines 16 to 30 km upstream from Pinedale moraines and a short distance below cirque headwalls. The outwash train forms a low terrace, Parker-Temple Lake, along some of the valleys. A still younger minor advance is considered contemporaneous with the Little Ice Age of late Holocene time (less than 10,000 years B.P.). Because the main source of sediment carried by the East Fork and other rivers is the suite of terraces within the valleys, the glacial sequence and the associated deposits are important in the present context.

A summary of Pleistocene and Holocene events prepared by Holmes and Moss (1955) is shown in table 1, and the heights of those terraces above the local streambeds are shown in table 2. The relation of terraces to glacial events was determined by tracing terraces upstream to the moraine at which each terminates, a method first used by Bryan and Ray (1940). For Boulder Creek, the longitudinal and elevation positions of terraces and moraines are shown in figure 2, which indicates that Pinedale ice destroyed remnants of Bull Lake and higher terraces, and that the main Pinedale terrace abuts and begins at the main Pinedale moraine; the Parker-Temple Lake terrace is traced through that moraine. Boulder Creek is immediately north of the East Fork River, and it may be presumed that the East Fork would have similar profiles.

Glacial Outwash Terraces Near The Bedload Project Site

The areal extent of different terrace remnants and moraines was mapped in detail by Holmes and Moss (1955) upstream along the East Fork River to a point 3.2 km (2 mi) south of Fremont Butte or about 3.7 km north (downstream) from the bedload project site. Using the nomenclature in table 2, we have outlined the terrace remnants in the vicinity of the project in figure 3. The terrace heights shown in figure 3 closely agree with those measured by Holmes and Moss (1955) farther downstream from the East Fork. However, a considerable length of stream near the project is bordered by a low terrace, 1.5 m above the river. This terrace seldom is flooded; it is higher than the flood plain subject to frequent inundation. Although not shown in table 2 for the downstream part of the East Fork, the terrace is believed to correlate with the Parker-Temple Lake terrace. Holmes and Moss (1955), in listing the flood-plain height at 0-1.5 m (0-5 ft), may have lumped the Parker terrace and flood plain together, because their mapping, encompassing 233 km^2 (90 mi^2), was primarily concerned with the older, more widespread units.

Our measurements and those of Andrews (1979a, 1979b) indicate that even at high flow little bedload is carried by the East Fork immediately upstream from its largest tributary, Muddy Creek, or where State Highway 353 crosses the river 10 river kilometers upstream from the project site (fig. 1). The explanation can be seen in the glacial geology.

Table 1. Summary of Pleistocene and Holocene events

[Modified from Holmes and Moss, 1955; --, no information given]

<table>
<tr><th>Moraine deposition</th><th>Terrace deposition</th><th>Frost action and mass movement</th><th>Eolian action</th><th>Vegetation</th><th>Early Man</th></tr>
<tr><td>Little Ice Age moraines</td><td>Flood plain</td><td>Younger talus; palsen</td><td>--</td><td rowspan="2">Chenopods and the composites. Grass maximum</td><td>--</td></tr>
<tr><td>Temple Lake moraines</td><td>Parker-Temple Lake terrace[1]</td><td>Older talus; felsenmeer and polygonboden</td><td>--</td><td>Occupation, Finley site</td></tr>
<tr><td>Recessional Pinedale moraines</td><td>Pinedale recessional terrace[2]</td><td rowspan="5">Periglacial frost action likely during glaciation</td><td rowspan="2">Widespread eolian action leeward of outwash</td><td rowspan="2">Fir</td><td rowspan="2">--</td></tr>
<tr><td>Main Pinedale moraine</td><td>Main Pinedale terrace[3]</td></tr>
<tr><td>Bull Lake II moraine</td><td>Bull Lake II terrace</td><td rowspan="2">Possibly some eolian action in Eden Valley</td><td rowspan="2">--</td><td rowspan="2">--</td></tr>
<tr><td>Bull Lake I moraine</td><td>Bull Lake I terrace</td></tr>
<tr><td>Buffalo till</td><td>Faler (?) terrace
Buffalo (?) terrace</td><td>--</td><td>--</td><td>--</td></tr>
<tr><td>--</td><td>Toboggan terrace</td><td>--</td><td>--</td><td>--</td><td>--</td></tr>
</table>

[1]Called Parker terrace by Holmes and Moss (1955).
[2]Called Lower Pinedale terrace by Holmes and Moss (1955).
[3]Called Upper Pinedale terrace by Holmes and Moss (1955).

Table 2. Heights of terraces above present streambed level

[Modified from Holmes and Moss, 1955; --, no data]

	Terrace height (meters; feet in parentheses[1])	
	Stream system	
Terrace	Boulder Creek-New Fork River	East Fork River[2]
Flood plain	0-1.5 (0-5)	0-1.5 (0-5)
Parker-Temple Lake[3]	10 (32)	--
Pinedale recessional[4]	14 (45)	6 (20)
Main Pinedale[5]	20 (65)	10 (33)
Bull Lake II	23 (75)	18 (60)
Bull Lake I	31 (103)	26 (85)
Faler	41 (135)	--
Buffalo	59 (195)	--
Toboggan	--	91 (300)

[1]Originally published in feet.
[2]Holmes and Moss (1955) did not map terraces as far upstream as the bedload project site; heights for East Fork River are presumed to be downstream from the project site.
[3]Called Parker terrace by Holmes and Moss (1955).
[4]Called Lower Pinedale terrace by Holmes and Moss (1955).
[5]Called Upper Pinedale terrace by Holmes and Moss (1955).

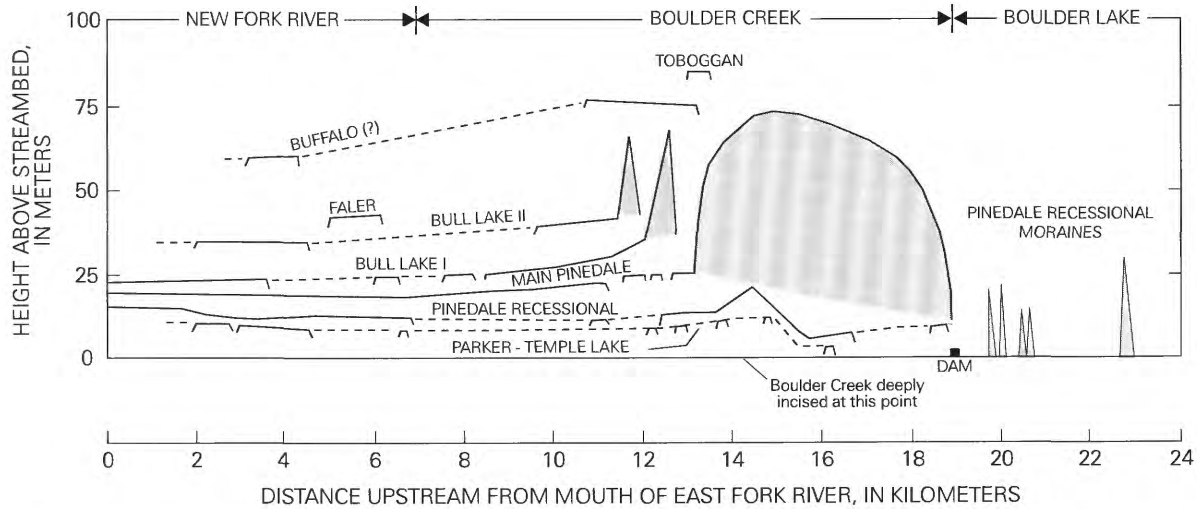


Figure 2. Long profile of terraces along New Fork River, Boulder Creek, and Boulder Lake (modified from Holmes and Moss, 1955).

The East Fork River heads in Precambrian rocks just south of Mount Bonneville (fig. 1) and flows southward for about 22 km on the high Fremont surface on which soils are thin, bedrock abounds, and rivers carry little sediment along the bouldery channels. About 10 km upstream from State Highway 353 the river changes to a westerly course, and flows in a canyon eroded in the main Pinedale moraine. The till is bouldery and well consolidated, so the rate of excavation of material must be very low. The river emerges from the moraine onto the unconsolidated and moderately well-sorted debris of the outwash terraces near the State Highway 353 bridge. The large rocks available in the moraine are seen in the channel bed for only a short distance downstream from the morainal margin. Thereafter, the streambed is much less steep and is composed of smaller and better sorted material.

Channel cross sections and terraces, associated berms and terraces, and observed bed and bank materials at three locations along the East Fork are shown in figure 4. Section *A* is near the State Highway 353 bridge just below the main Pinedale moraine. A prominent sage-covered terrace stands 2.8 m above the streambed, with lower levels of grass, shrubs, and willow at 1.5 m. Streambed gradient at this location is 0.0023; the bed material has a D_{50} (median particle size) of 90 mm. Section *B* of figure 4 is at the bedload project site, where the river slope is 0.0007, the D_{50} of bed material is 1.25 mm, and a nearby outwash terrace is at 7 m above the streambed. Section *C*, near Fremont Butte, 6.4 valley kilometers downstream from the project site, has berms at 1, 2.8, and 4 m above the streambed. These levels agree in part with those identified by Holmes and Moss (1955, table 2) and with levels determined from areal distribution of major mapped terraces, but the details obtained at specific river cross sections add some levels not mapped in the smaller scale areal studies.

A similar valley cross section of Muddy Creek near its mouth is shown in figure 4*D*. Some of the terrace levels are locally expressed as straths cut on the (Tertiary-age) Wasatch Formation bedrock, presumably by lateral migration of the river against the valley side.

The assignment of a given berm or level to its associated glacial outwash is not self-evident. With the present information, it appears safe to assign a terrace remnant standing about 7 m above the East Fork River to the Pinedale recessional terrace and the one at 10 to 12 m to the main Pinedale terrace. The flood plain that is forming presently and that is inundated during high flow is the level at 1 to 1.5 m above the streambed. The most ubiquitous low terrace along the East Fork is the one at 1.5 to 2.8 m; it probably is related to the minor glaciation called Parker or Temple Lake. This terrace is usually vegetated by sage and is not inundated. Considering the fact that little bedload was measured at the base of the moraine near State

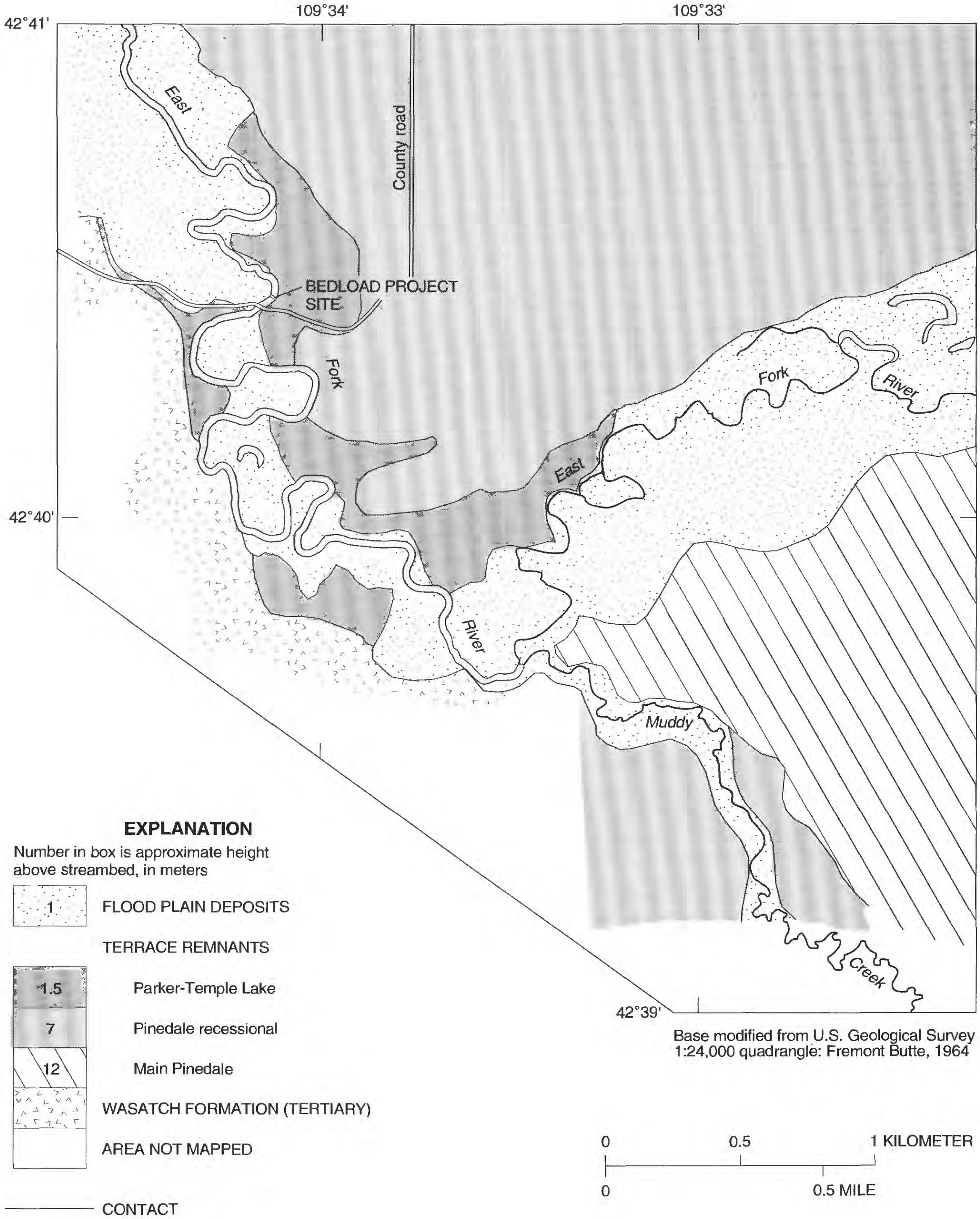


Figure 3. Terrace remnants in the vicinity of the bedload project site (modified from Leopold, 1982a, fig. 3).

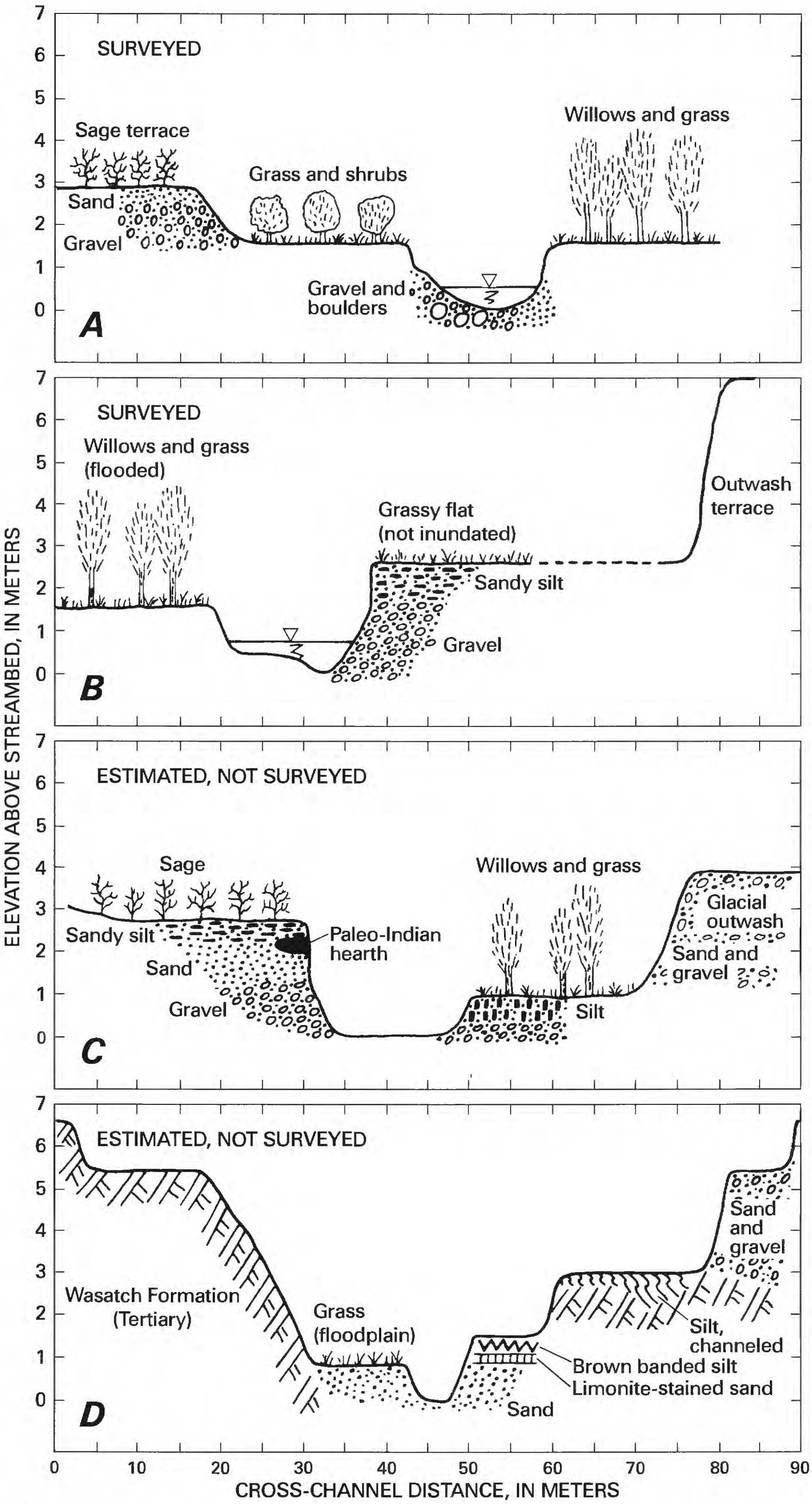
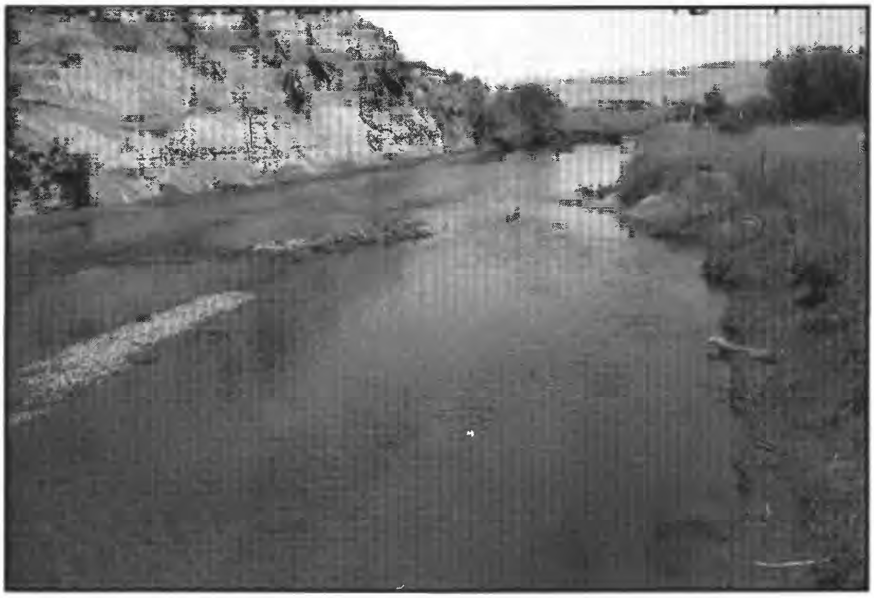


Figure 4. Cross sections of channels and terraces. ***A***, East Fork River 15 meters downstream from State Highway 353 bridge. ***B***, East Fork River at the bedload project site. ***C***, East Fork River at Fremont Butte. ***D***, Muddy Creek near mouth. Views are downstream. Locations are shown in figure 1.

Highway 353 or upstream from the mouth of Muddy Creek, most of the bedload carried by the river through the study reach is postulated to be derived from lateral erosion of the unconsolidated sand and gravel of the Parker-Temple Lake terrace, and from the places the river is impinging on the Pinedale recessional terrace shown in figure 5. These terraces can be eroded both by Muddy Creek and by the East Fork River downstream from the mouth of Muddy Creek. Some bedload also is contributed as small alluvial fans emanating from gullies eroded into the steep slopes and walls of the Wasatch bedrock as shown in figure 6. All of these sources would produce sediment in the sand and gravel size range observed in the trapped bedload.



A

B

Figure 5. East Fork River in the vicinity of the bedload project site. ***A,*** Looking downstream, Wasatch Formation cliff at left, flood plain on right. ***B,*** Looking upstream, Pinedale recessional terrace on left, flood plain on right, gravel-covered streambed with central gravel bar. ***C,*** View of valley from top of Wasatch cliff; flow is toward left; project site in background where white trailer is located near road.

C

Figure 5. (Continued)

Archaeology

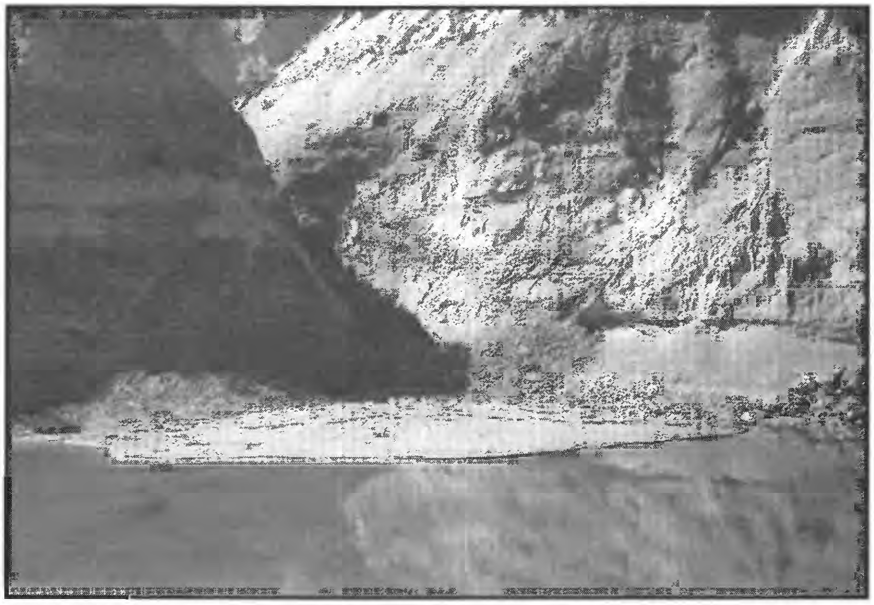
Archaeology is an important part of geomorphic history. This is especially true as it relates to the history of alluvial terraces and the sources of bedload.

Several Paleo-Indian hearths have been exposed by lateral erosion of the Parker-Temple Lake terrace. One is shown in the section near Fremont Butte (fig. 7A). Three were eroded from the streambank within a few meters of the bedload trap. Each consisted of a bowl-shaped pit 23 cm deep and 75 cm across the top. They are lined with rounded rocks very close to 60 mm in diameter, now completely blackened by carbonized fuel. Some of the blackened rocks show a caliche film over the carbon coating. These people apparently built fires in the rock-lined holes, heated the rocks, then placed tubers over the rocks for roasting. No bones of any kind were found in or near the hearths. The hearths found were all close to the river and were built in the surface 1 to 1.5 m above present streambed. Similar hearths found in eastern Wyoming have been dated at about 3,000 B.P. (Frison, 1988).

Surface finds of points and blades are not diagnostic as to stratigraphic level. One obsidian blade found near the bedload project site, apparently washed from deposits of the Parker-Temple Lake terrace, closely resembled those from the Finley site, but was of the Yuma rather than the Folsom type (Howard and Hack, 1943). The Finley site is in the Kilpecker dunes near Eden, about 100 km south of the project site.

All the hearths found along East Fork River have been covered subsequent to use by 10 to 20 cm of alluvium or colluvium. They are, therefore, younger than the end of the deposition of the Parker-Temple Lake outwash but are old enough to have received some depositional cover. This terrace, important as a source of East Fork River bedload, is thus of Holocene age but older than 3,000 years B.P.

More interesting anthropologically are the numerous flakes and cores found scattered on the ground surface of unglaciated Cora Butte, located about 12 km northwest of Pinedale (fig. 1). This hill is one of several in the vicinity, including Mount Airy (southwest of Pinedale, fig. 1), that is underlain by the Wasatch Formation, leveled on the top and capped with 2 to 3 m



A

B

Figure 6. Wasatch beds that supply source sediment when eroded. ***A***, Small alluvial fan at mouth of minor gully in cliff of Wasatch Formation. ***B,*** Sloughing of Wasatch cliff. ***C***, Rill and small alluvial fan on Wasatch cliff. ***D***, High-water mark about 1.5 meters above water surface, showing minor bank erosion at times of high flow.

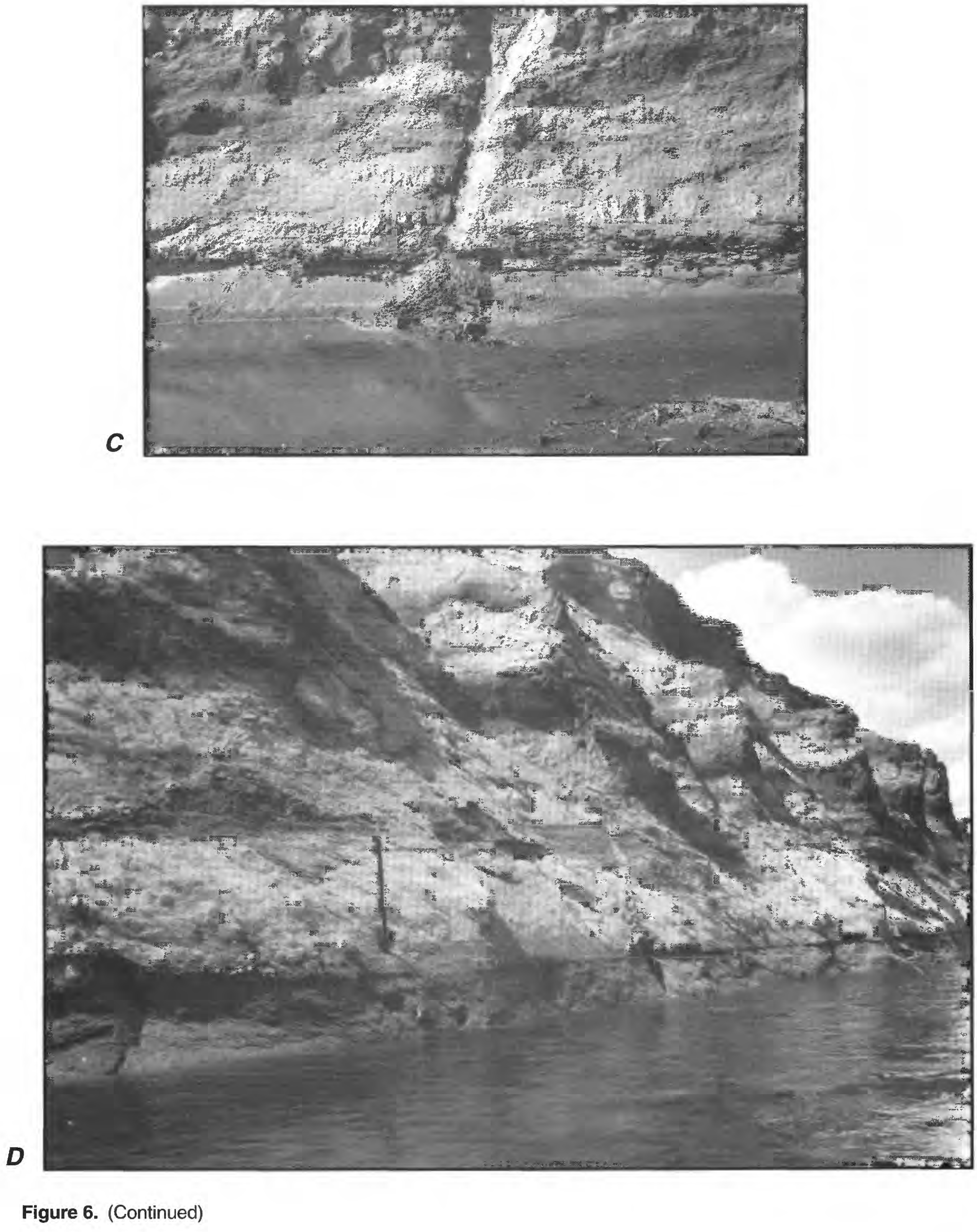


Figure 6. (Continued)

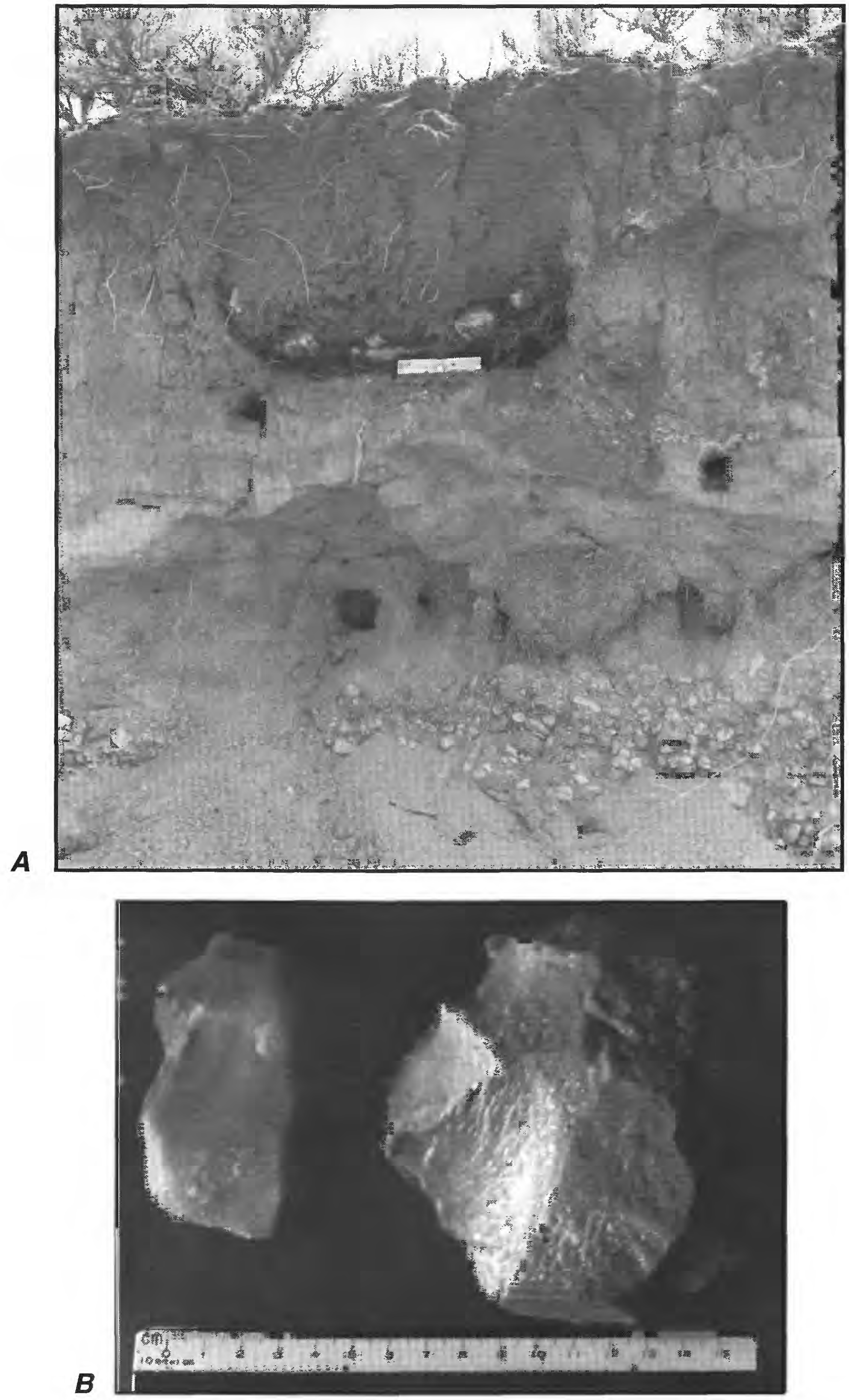


Figure 7. ***A,*** Paleo-Indian hearth in Parker-Temple Lake terrace. Hearth is covered with about 0.5 meter of colluvium or alluvium (ruler is 15 centimeters long). ***B,*** Crude artifacts made of yellowish-green quartzite found on surface hillslopes of Cora Butte.

of rounded river gravel. In late Tertiary or early Pleistocene time, a series of pediments were eroded by streams flowing south-southwest. Gravel from the cap, over time, was moved downslope, and is found scattered on the flanks of the hill. The cores and flakes are scattered among the rounded rocks derived from the hilltop. All the flakes are riven by percussion from cores of a distinctive yellowish or yellowish-gray, fine-grained, dense quartzite that is not indigenous to the Wind River Range. One such core and a tool of the same material are shown in figure 7B. The flakes have no desert varnish, but some have a yellowish-orange surface stain. Some have lichen colonies as large as 1 cm in diameter. Others have some caliche deposit on the underside and on the edges of the top side.

The common occurrence on unglaciated Cora Butte of these crudely worked rocks is in marked contrast to their absence on any glaciofluvial terrace in the vicinity. The possibility that they predate these terraces is intriguing.

CHARACTERISTICS OF THE RIVER

The point chosen for installation of the bedload trap on the East Fork River has a drainage area of 466 km^2 (180 mi^2). Approximately one-half of the area is drained by Muddy Creek, which joins the East Fork about 4 km upstream from the bedload trap. Muddy Creek contributes much of the sand fraction of the sediment load in the East Fork but little of the water during the spring snowmelt season.

The U.S. Geological Survey gaging station near Big Sandy (station 09203000, fig. 1), having 54 years of record (1939-92), was located about 15 km (9 mi) upstream from the project site. The drainage area at the station is 205 km^2 (79 mi^2), and the mean annual flow for the period of record is 2.9 m^3/s. Because most of the runoff is from elevations upstream from Big Sandy, that figure probably is about the same as the mean annual flow at the bedload project site. But because of irrigation diversions between the two sites, peak discharges during late May and June are about 6.5 m^3/s greater at the gaging station than at the project site. Peak flows of the East Fork River result from spring snowmelt; rainstorms do not cause appreciable hydrograph rises. During a typical spring runoff season, which begins in early May, the river peaks during the first week of June and returns to low flow during July, as shown in figure 8. The flood-frequency curve for East Fork River near Big Sandy is shown in figure 9. Recurrence interval at bankfull stage is about 1.2 years.

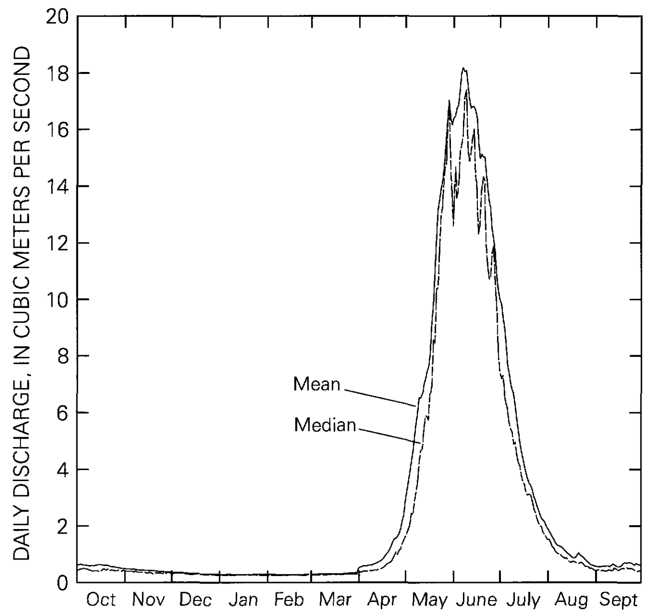


Figure 8. Mean and median daily discharge, East Fork River near Big Sandy, Wyoming, water years 1939-92.

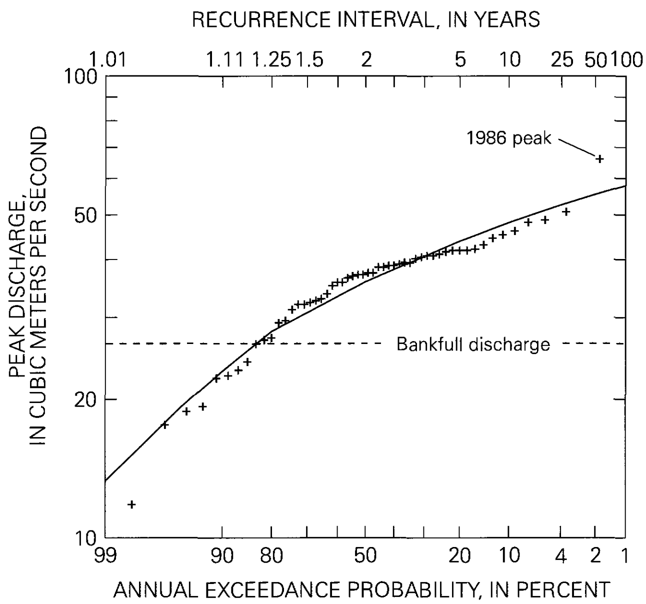


Figure 9. Flood-frequency curve (annual flood series), East Fork River near Big Sandy, Wyoming, water years 1939-92.

It was observed that bankfull stage or initial overflow onto the flood plain near the project site occurred at a discharge of about 20 m^3/s, which would have a recurrence interval in the annual flood series of about 1.2 years. The corresponding 1.2-year flood at the gaging station upstream indicates a bankfull discharge of about 26.5 m^3/s at that location (fig. 9). The diurnal fluctuation in discharge is exemplified in figure 10. Early in the season, when the flow at the project site was derived primarily from snowmelt at intermediate elevations in the mountains, the peak discharge occurred at about noon of the day following snowmelt and at 1400 hours later in the season. The length of river from the project site to the high peaks of the Wind River Range is about 50 km (32 mi), and the delay between snowmelt and arrival of peak runoff is about 20 hours. Thus, the speed of travel of the runoff wave averages about 2.5 km/hr (0.7 m/s, or 2.3 ft/s).

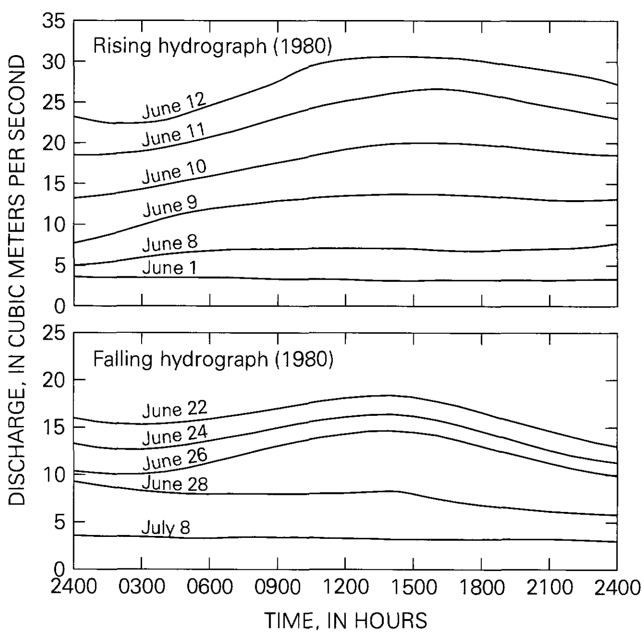


Figure 10. Diurnal fluctuation in discharge of East Fork River at the bedload project site.

The flow-duration curve for the Big Sandy gaging station is shown in figure 11. Daily mean discharge at bankfull stage at the station is equaled or exceeded about 1 percent of the time.

The year-to-year variation in annual peak discharge and mean annual flow are shown in figure 12A. Note that the mean of the peak discharges is 35.8 m^3/s,

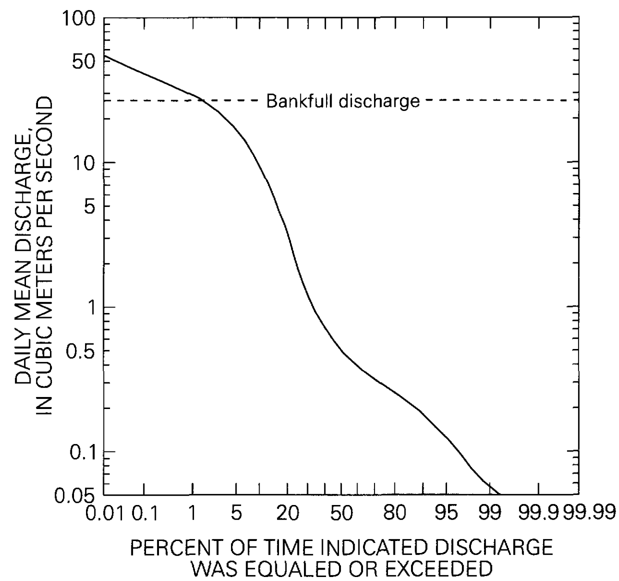


Figure 11. Flow-duration curve, East Fork River near Big Sandy, Wyoming, water years 1939-92.

and one standard deviation of this mean is 9.34 m^3/s. It also is interesting to note that the peak discharge of the year increases greatly as the mean flow for the year increases (fig. 12B). The larger the snow pack in the mountains, the larger the mean flow for the water year. The volume of the peak alters the annual peak discharge as well.

The Bedload Project Site

The East Fork River, between its exit from the Pinedale moraine and its junction with the New Fork River, flows in a meandering channel sporadically impinging on low and high terraces of unconsolidated sand and gravel. In a few places it has eroded steep banks of poorly consolidated bedrock of the Wasatch Formation. The river has moved rather freely, developing a flood plain vegetated with willow. Many meander scars and oxbows and much scroll topography can be seen. Only two important tributaries enter along this 30-km reach: Muddy Creek and Silver Creek. Muddy Creek heads in a broad irrigated terrace surface, and derives most of its flow in modern times from irrigation return flow. Silver Creek heads in the mountains and derives its flow from spring snowmelt. The character of the East Fork River valley and its relation to Muddy Creek can be seen on an aerial photograph (fig. 13).

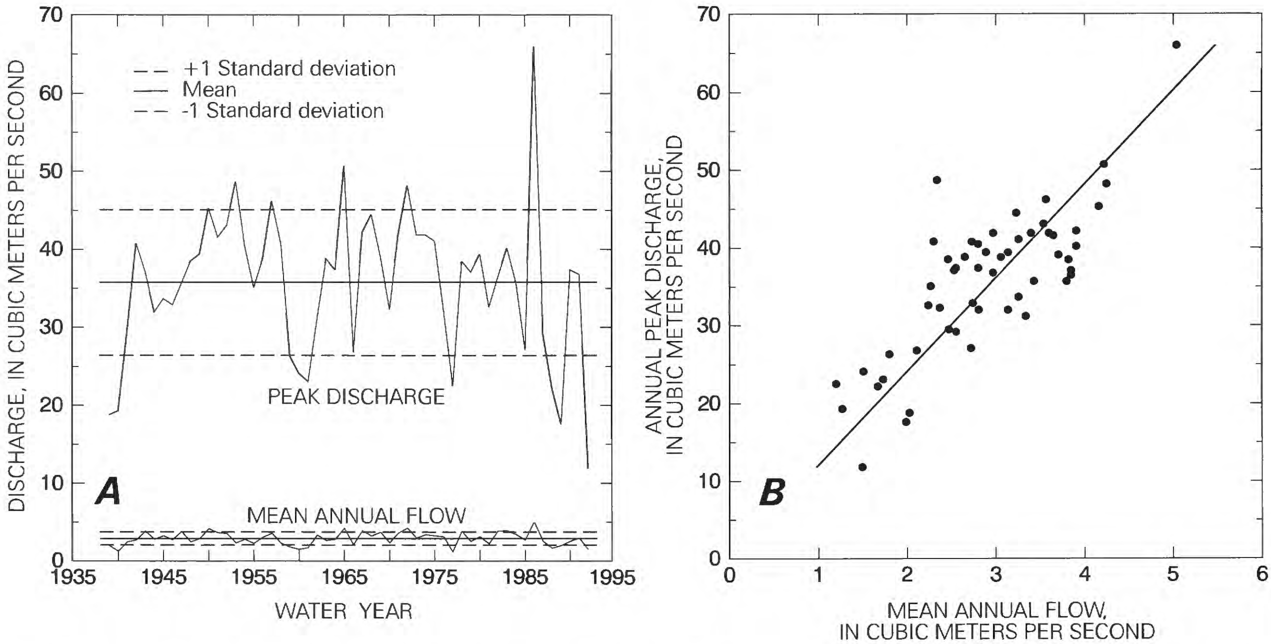


Figure 12. ***A***, Year-to-year variation of annual peak discharge and mean annual flow, and ***B***, Relation of annual peak discharge to mean annual flow, East Fork River near Big Sandy, Wyoming, water years 1939-92.

An important practical necessity in the choice of a location for the bedload trap was a road bridge allowing us to cross with equipment during construction. The site chosen was about 65 m downstream from a small wooden bridge (fig. 14). Near the left bank downstream from the bridge, there always was some accumulation of sand where a point bar would naturally tend to form on the convex bank. Although two log bents supporting the bridge were in the water, the bridge seemed to have no effect on our measurements. The occurrence of a bend downstream from the site also had little effect, except that it tended to increase slightly the water-surface slope below the trap.

The project site at low flow and high flow is shown in figure 15. The natural channel cross section at the site where the bedload trap was built is shown in figure 16, and the discharge rating curve at that site is shown in figure 17.

Water temperature in May and June typically is in the range of 5 to 10°C. For example, in 1975 the mean daytime temperature of the water at the bedload trap was 7.1°C during the last week of May, 4.2°C during the first 2 weeks of June, and 7.5°C during the third week of June.

Bed Material And Its Distribution

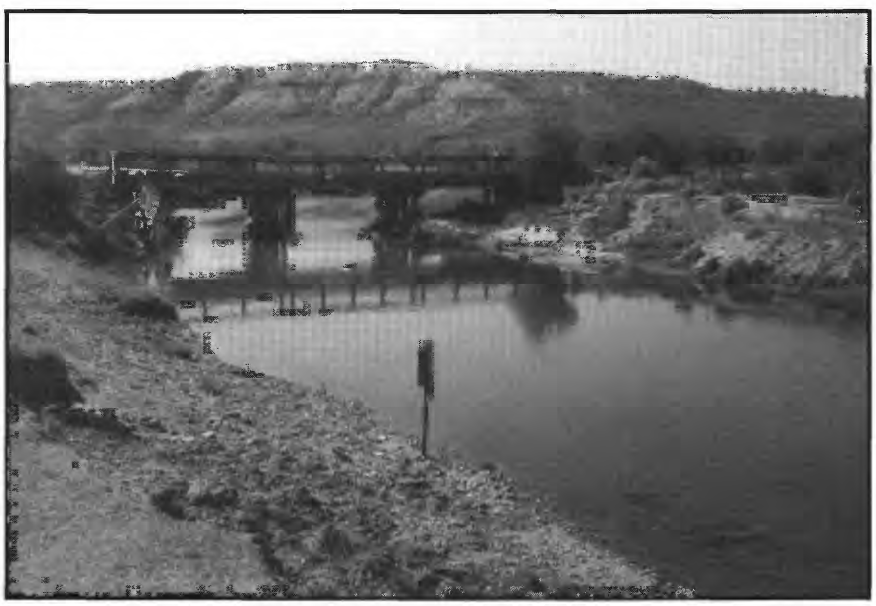
When the bedload project site was chosen, the senior author thought that the river carried primarily fine to medium gravel, for though sand can be seen, on casual inspection what meets the eye are numerous gravel bars protruding above the water surface at low flow. This impression was reinforced by the profusion of cobbles and boulders in the channel about 10 km upstream from the site at State Highway 353, as shown by curve 1 in figure 18. There, the median particle size (D_{50}) is 90 mm.

Sand is far more prominent in the bed material than had earlier been supposed; the median size at the bedload trap is 1.25 mm, as can be seen on curve 2, figure 18, with 23 percent by weight greater than 10 mm. The actual moving bedload caught in the trap (curve 3) has nearly the same D_{50}, 1.13 mm, but contains only about 3 percent bed material exceeding 10 mm.

The areal distribution of bed material in the reach near the project site is shown in figure 19. The actual site for the trap was specifically chosen to be immediately downstream from a central gravel bar (island) and at the head of a deep pool that characterizes the meander bend downstream.

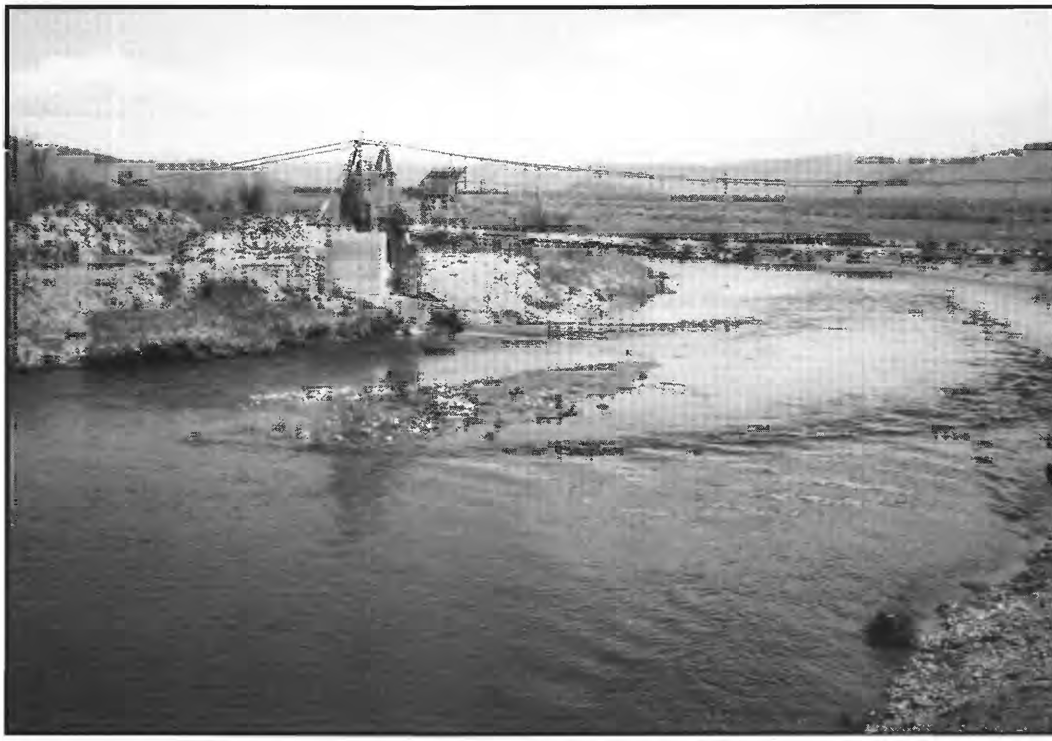
Figure 13. Aerial view of East Fork River valley upstream from the site of the bedload trap. Muddy Creek enters from the southeast in lower part of the photograph. Project site is approximately 600 meters north of area shown at top of photograph.

A



B

Figure 14. Research site before installation of the bedload trap. ***A,*** Looking south-west, showing location of site (at vehicles); flow is left to right. ***B,*** Looking upstream; wood bridge is 65 meters upstream from the trap site.



A

B

Figure 15. Site of the bedload trap at low flow and high flow. ***A,*** Looking downstream at low flow, showing the low gravel bar left of center of the channel and just upstream from the trap. At far left can be seen the levee built to prevent the water from flowing into the diversion channel, the spoil from which rises above the flat lower surface. ***B,*** Looking upstream at a stage at which high flow inundates the flood plain.

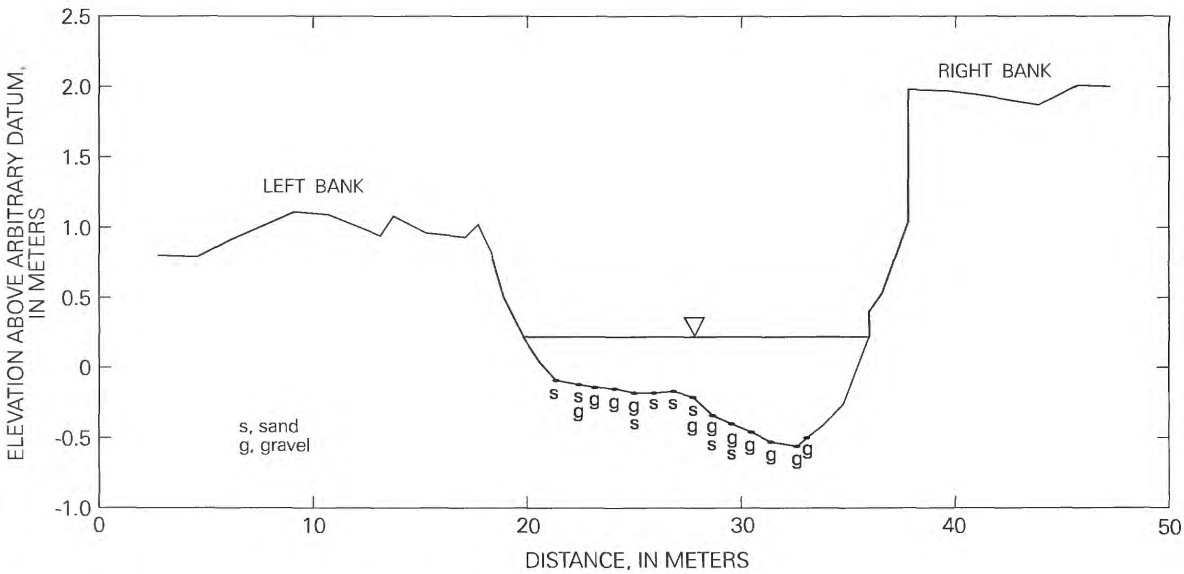


Figure 16. Cross section of East Fork River channel at the site of the bedload trap, prior to construction.

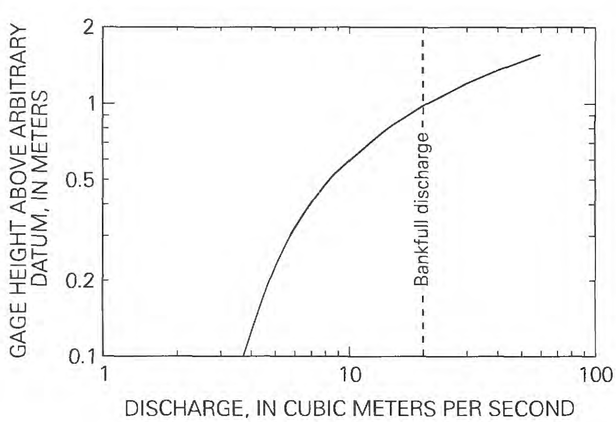


Figure 17. Discharge rating curve for East Fork River at the site of the bedload trap.

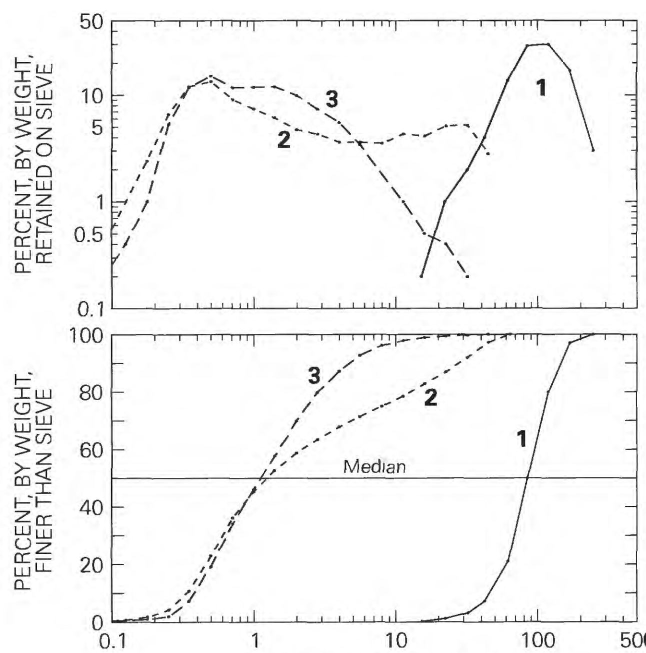


Figure 18. Size distributions of bed material in East Fork River at State Highway 353, and of bed material and bedload at the project site.

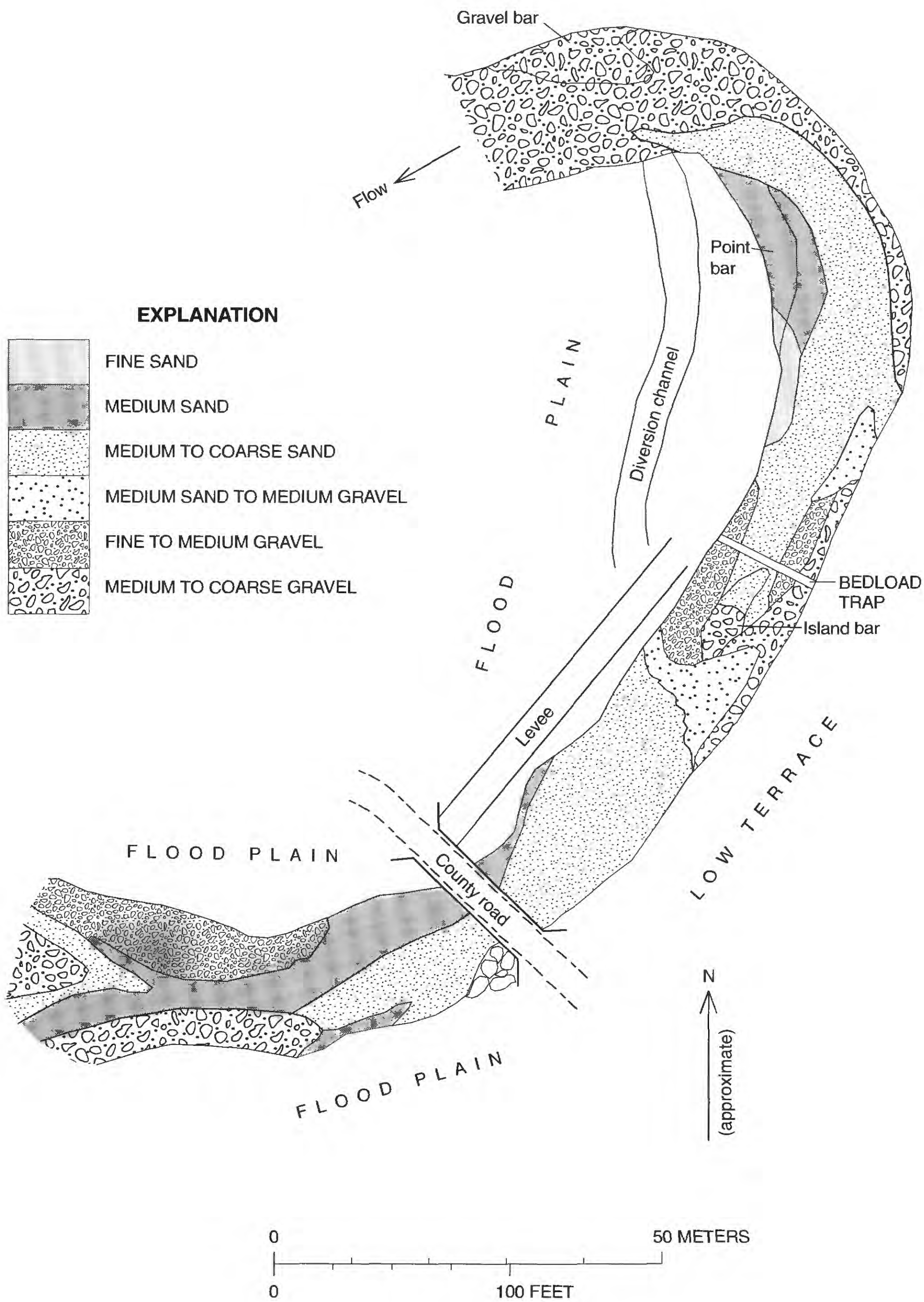


Figure 19. Distribution of bed material in the project reach, July 12, 1976.

The number of rocks larger than 22 mm that fell into the bedload trap was surprisingly small in most field seasons. There were a few days when some coarse particles were caught, but because of the paucity of data, relations of the degree of coarseness to stage or any other hydraulic parameter were not obvious. There was some indication of an increase in size as transport rate increased.

Hydraulic Geometry

In the natural channel cross section before the bedload trap was constructed, width increased slightly with increasing stage. The equations for the hydraulic geometry (width, w; mean depth, d; mean velocity, u; cross-sectional area, A) in metric units, for water discharge, Q, in m^3/s, were:

$$w = 14.6\ Q^{0.06} \quad \text{(m)}, \tag{1}$$

$$d = 0.19\ Q^{0.57} \quad \text{(m)}, \tag{2}$$

$$u = 0.35\ Q^{0.37} \quad \text{(m/s), and} \tag{3}$$

$$A = 2.8\ Q^{0.63} \quad (\text{m}^2). \tag{4}$$

When the bedload trap was built, the width of the gated slot was constant with stage, and the flow above the width of the bedload trap was designated "effective water discharge." The equations for the hydraulic geometry of the effective water discharge, Q, became:

$$w = 14.6, \tag{5}$$

$$d = 0.18\ Q^{0.65}, \tag{6}$$

$$u = 0.39\ Q^{0.35}, \text{ and} \tag{7}$$

$$A = 2.6\ Q^{0.65}. \tag{8}$$

The relation of slope to discharge is more complicated. The value of water-surface slope, S, is highly dependent on the length of the reach used for measurement, and it is not obvious over what river length slope should be measured for any particular computation, as will be demonstrated later. We began slope measurements in 1968 with a leveling survey of the water surface at near-bankfull stage, extending from a place upstream from Muddy Creek to a point downstream from the bedload project site. A slight downstream flattening of slope was measured, presumably associated with a decrease of bed-material size with little change in discharge. Downstream from Muddy Creek the mean slope was close to 0.0007, the value used for a variety of computations. Later in 1976, an effort was made to measure local slope of the water-surface in the vicinity of the bedload trap. These surveys confirmed the average value of 0.0007 in general, but indicated that slope increased somewhat with discharge. In 1978 the reach from the county road bridge to a place 274 m downstream was surveyed nearly every day. The shots made to the water surface on both banks were spaced at about 10 m in the critical subreach near the bedload trap. The 1978 survey extended downstream around the meander loop below the project site.

Values of water-surface slope in the vicinity of the bedload trap plotted against discharge showed scatter comparable to the natural variance of bedload data. Thus, slight changes of slope with discharge were insignificant. Therefore, the use of a mean value of 0.0007 throughout appeared justified. We discuss in a later section the variation of slope between pool and riffle, and differences in slope that arise from the choice of channel length over which slope is measured.

The friction factor, u/u_* (u_* is the shear velocity), at the bedload trap is dependent on the relation of velocity to depth, slope being constant. There is considerable scatter of values, but the relation for all the years of record shows no significant variation with discharge and can be expressed as a constant value of 12.2. Pools and riffles have somewhat different relations of u/u_* to discharge, as will be discussed later.

The upshot of these considerations may be stated fairly as follows. The increase of velocity with discharge in the East Fork is nearly the same as the average of many rivers (Leopold and others, 1964). Depth increases somewhat more with discharge than the average, and width increases less than the average, but all the exponents are within the range usually observed. Slope surveyed over river lengths of 20 widths or more can be considered constant at a value close to 0.0007, but in shorter reaches slope varies with discharge, depending on the particular combination of pool-and-riffle sections included in the surveyed reach. Hydraulic resistance, or values of the friction factor u/u_*, varied little with discharge at the project site.

DEVELOPMENT AND OPERATION OF THE BEDLOAD TRAP

A bedload trap that could be disassembled and moved, even though laboriously, from one river to another would be desirable. It was with this objective in mind that the initial development was directed. The general principle chosen was to have an open slot at streambed level into which the moving load would fall, the slot sufficiently wide that particles would not be able to jump across the opening. The trap would have to be emptied periodically. Doors or gates that would close the slot would be necessary so that when the emptying mechanism was not in operation the trough would not immediately fill with sediment.

Initial Design

The first design of the bedload trap consisted of a metal tube of rectangular cross section made of units that could be bolted together, with enough units available to completely cross the streambed. Each unit had an individual gate that slid parallel to the streambed, and, we hoped, could be closed when the machine was not in operation. The emptying device was an endless belt that would move toward one side of the river and dump its sediment while going over a pulley or cylindrical roller. The returning part of the endless belt was protected from the sediment load by the overlying loop of the belt. The sediment accumulating at one end of the endless belt was to be lifted to the level of the streambank by another endless belt on which were attached a series of perforated cups. The horizontally sliding gates for closure of the slot were operated by a lever that could be moved by hand, for the lever extended upward well above the water surface. Anticipating that much of the sediment moving in the East Fork would be sand, but some gravel to 20 mm would be moved, we chose a slot width of 4 in. (10.2 cm). This choice implied that nearly all particles to 1-cm diameter would be caught, and from the authors' data, the efficiency for catching 2-cm rocks would be not less than 80 percent.

With the advice of Ralph A. Bagnold, the senior author designed and built an apparatus incorporating the features mentioned above. Installation was attempted on the East Fork River during 1967 at the same location later used for construction of the successful bedload trap. Photos of this initial trap are shown in figure 20.

After three field seasons (1967-69) of arduous work, the results were disappointing. The apparatus was removed from the river. Despite the lack of success, this initial trial was fruitful, in that many lessons were learned that were incorporated in the final design. These lessons included the following.

It was impossible to get the rectangular metal tube deep enough to have its top surface flush with the original streambed. The tube was assembled in the river at low flow. It was to have been sunk into the channel bed by excavating a trough beneath it. However, after a trench was dug, the sand and gravel of the streambed continually filled in by sloughing of the trench banks, even though little water was flowing in the river. It became obvious that the flow had to be diverted by coffer dams, and a bypass channel had to be excavated to divert the flow around the site during construction.

Another problem was that the return loop of the endless belt inevitably collected some sediment that leaked around the overlying loop of the belt. Sediment falling on the part of the belt returning to the far side of the river consequently was dragged toward the far-side roller, where there was no mechanism to extract it. Thus, within a short time, sediment jammed that roller, and the friction caused the belt to stop. The only way to prevent this action was to have the return loop of the belt above the water, so that all the submerged part moved sediment toward the sump, from which accumulating debris could be removed. This meant that the return loop of the endless belt must be supported subaerially by a bridge.

Finally, gates to close the slot need to be designed so that during closure there are no frictional surfaces that can be jammed by sand. The original gates were operated manually. Sand caused so much friction that it was difficult to transmit the required mechanical energy to those gates between the middle and the far side of the river. This experience suggested tainter gates with curved surfaces rotating about a horizontal axis, and operated by hydraulic pressure, rather than a manual lever.

Successful Design

The successful bedload trap consisted of four principal parts:

1. A concrete trough constructed across the river, the top of which was flush with the streambed. The top surface of the trough had an open slot extending across the full width of the channel. The slot could be closed by eight tainter gates operated

A

B

Figure 20. The initial unsuccessful bedload trap installed at the same location where the successful machine was constructed later. ***A,*** The long metal tube containing the endless belt could not be lowered into the streambed because the excavation continually sloughed. ***B,*** The metal tube did not reach all the way across the channel to the left bank.

separately by hydraulic pressure carried through flexible rubber tubes. Each of the eight gates was 1.83 m (6.0 ft) in length. The slot opening was 0.203 m (8 in.) wide. The width of the slot was guided by laboratory experiments of Poreh and others (1970), who had anticipated that a successful bedload trap would someday be constructed as an open slot into which sediment could fall. They showed that the efficiency of such a slot depends on the ratio of slot opening (width, *w*) to size of sediment (*D*). The efficiency increases as this ratio, *w/D*, increases, approaches 100 percent when the width is 20 times the particle size, and equals 100 percent when the ratio is above 40, for all flow conditions tested.

2. An endless rubber belt 0.305 m (12 in.) wide, lying at the bottom of the concrete trough, threaded around large rollers or pulleys, installed in concrete wells on each bank of the river, and returning subaerially to the far bank on rollers supported by a suspension bridge.
3. An endless belt operating on a nearly vertical axis and carrying perforated buckets that scooped accumulating sediment from the bottom of the receiving well, lifted the sediment 3 m above the ground surface, and dumped it into a tapered hopper sitting on a large weighing scale. The hopper was periodically emptied by opening a bottom door.
4. A horizontal endless belt, with one end beneath the evacuating door of the sediment hopper, that moved the sediment from the hopper to a transverse endless belt 12 m downstream, which in turn dropped the sediment into the flowing water of the river to be carried downstream in a normal manner.

In the winter of 1971-72, the senior author drew the designs for the bedload trap, chose the principal dimensions, and made engineering drawings of the various parts. These drawings were then taken to an architectural engineering firm for the drafting of construction drawings and for the preparation of engineering specifications. From these final drawings the schematic plans of the machine, shown in figure 21, were prepared. The engineering drawings are in the Leopold file in the Bancroft Library of the University of California, Berkeley.

In the summer of 1972, after the main snowmelt runoff ceased, construction of the redesigned bedload trap was begun. The construction phase was supervised by Robert M. Myrick, appointed by the senior author as project construction engineer. His was not an easy job.

A bypass channel was cut across the neck of the river curve downstream from the trap location. A coffer dam was built across the river to divert the flow into the bypass. The ground-water table was close to streambed level, and though there was no flow through the construction site, when the wells were excavated preparatory to pouring concrete, water in the excavation could not be pumped out fast enough to keep up with inflow. The bottom slab of each well had to be poured under water. The site is far distant from any power source, so electrical power was generated onsite by a large propane-fueled motor-generator.

As can be seen on the river cross section before the trap was installed (fig. 16), the deepest part of the channel was near the right bank. Depth gradually decreased toward the left bank. When the concrete trough was constructed in the channel bed to hold the gates and the endless belt, the surface of the concrete tended to follow the original cross slope of the bed, and was set 0.4 m deeper near the right bank (gate 1) than near the left bank (gate 8). Photographs of various parts of the installation are shown in figure 22.

The concrete well on the right bank was deep enough that the top surface of the belt was considerably above the bottom of the well. Before the belt went around the first roller, the sediment was scraped from the belt and fell to the bottom of the well. The perforated cups on the near-vertical endless belt reached to the bottom of the well and scooped up accumulating sediment, lifting it above the ground and dumping it into the hopper. The weight of the sediment accumulating in the hopper was continually monitored. The sediment was allowed to accumulate to about 115 kg, then the bottom hatch was opened. The sediment dropped onto the downstream belt and, on its way, was sampled by scooping portions of the bulk in transport on the belt.

Operation

During the runoff seasons from 1973 to 1979, with the exception of 1977, a year of low runoff, the bedload trap was in operation nearly every day from late May to mid-June. A typical run for bedload measurement will be described.

The water-stage recorder at the left bank well was inspected. The motor-generator was inspected for oil and set in operation. In the control trailer containing the electrical control buttons and the levers for activating the

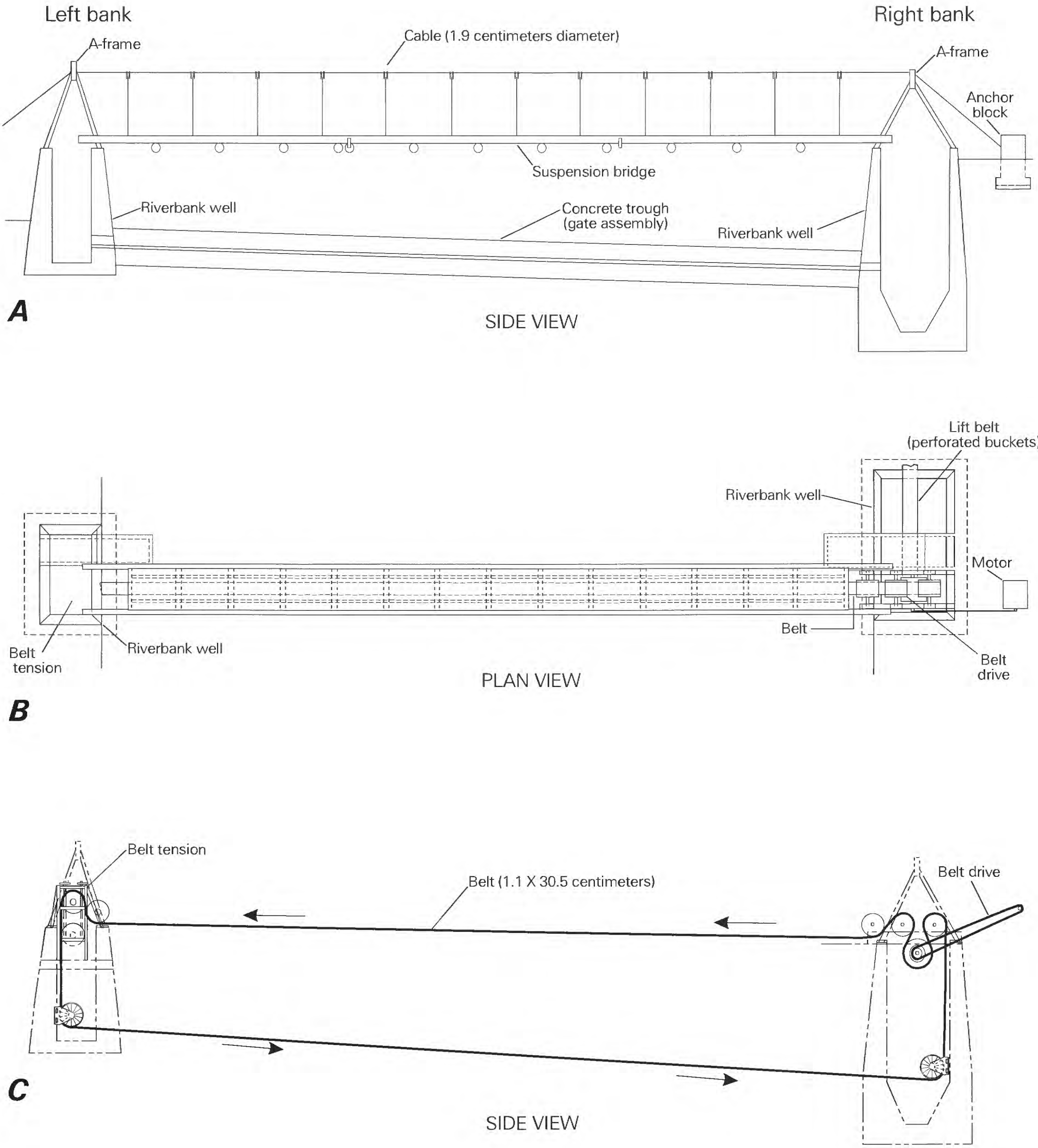
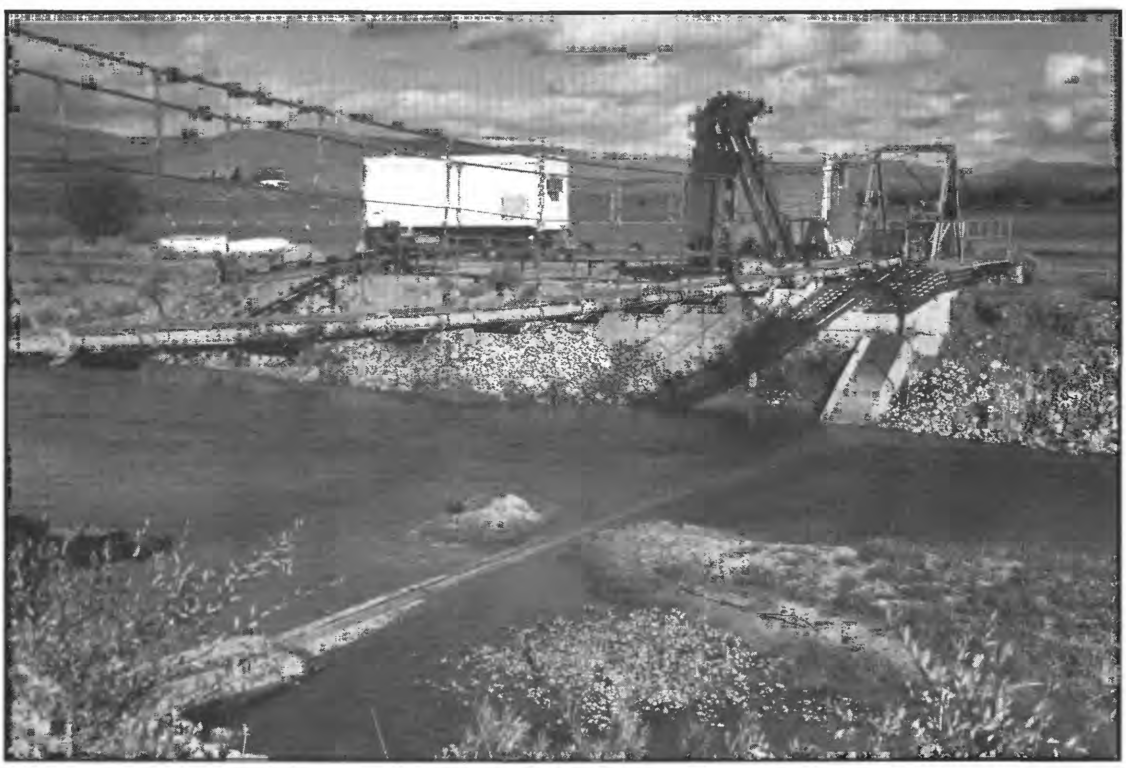


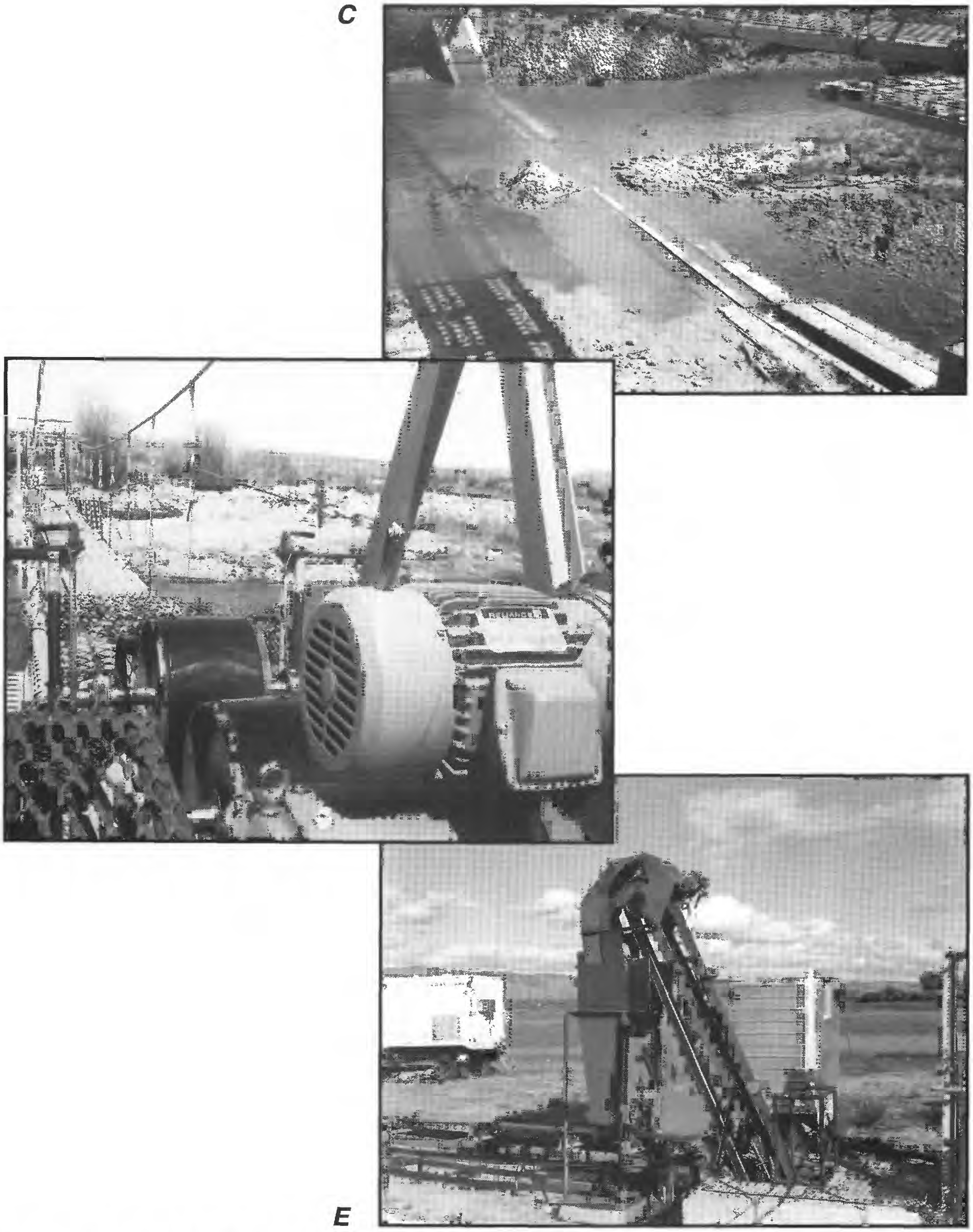
Figure 21. Simplified engineering drawings of mechanism for the bedload trap. ***A***, Downstream view of suspension bridge, deep concrete wells on each bank, and concrete trough in streambed. ***B***, Plan view showing location of belt-drive motor and lift-bucket endless belt on right bank. ***C***, Diagram of the endless belt under water in the concrete trough, and carried subaerially by the suspension bridge on its return to the left bank. Details of lift belt (perforated buckets) not shown.

A



B

Figure 22. The bedload trap on East Fork River. ***A,*** View downstream showing suspension bridge, concrete wells on each bank, and control trailer on right bank. ***B,*** View from left bank at low flow. The concrete trough in the streambed is partly emergent in the foreground; the slot into which sediment falls is closed by the metal gates. ***C, D, E, F,*** and ***G,*** on following pages.



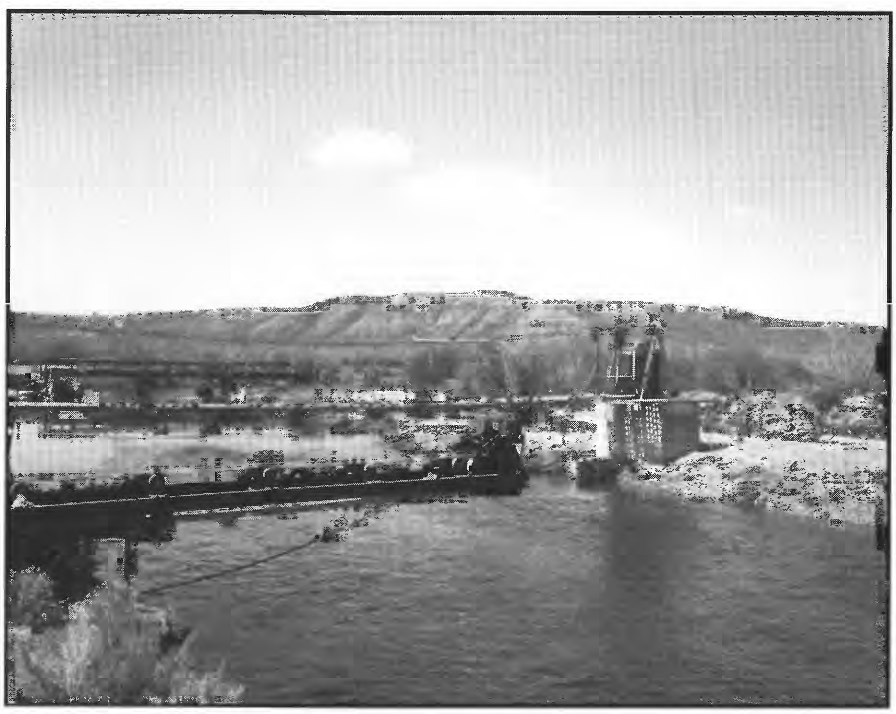
C

D

E

Figure 22. The bedload trap on East Fork River (continued). ***C,*** Trough in streambed seen from left bank at low flow; the nearest gate is open, but all other gates are closed. ***D,*** View from right bank along the length of the suspension bridge. In the foreground is the main motor and in the middle ground are two of the drums that drive the endless belt. The belt returns to the left bank on rollers under the walkway of the bridge. ***E,*** The near-vertical endless belt with lift buckets; these reach into the deep well on right bank, from which they lift sediment to the hopper for weighing; the hopper is the tapered vertical tube in center of photograph.

F



G

Figure 22. The bedload trap on East Fork River (continued). *F*, The endless belts leading first downstream from the weighing hopper, and the orthogonal belt extending over the river for returning bedload to the channel. ***G,*** View from right bank looking upstream; the endless belt in the foreground carries sediment back to the river after it is weighed and sampled.

hydraulically operated gates, the main belt in the trough of the trap was started at the lowest possible speed with all eight gates closed. The lift-bucket belt also was started. It was first necessary to assure that the main belt and the receiving right-bank concrete well were clean of sediment, so the belt was run with all gates closed for about half an hour.

During the run with all gates closed, the weight of the receiving hopper was recorded in pounds each minute. Some sediment may have remained in the receiving well or on the main belt, and this residual was monitored until the hopper recorded less than about 3 lb/min (1.4 kg/min), considered to represent a zero load. Then the first gate was opened, and the speed of the main belt was increased to its normal value of about 0.3 m/s. At this speed, sediment from the farthest gate reached the receiving well in about 0.8 minute. Thereafter, for not less than 30 consecutive minutes, the weight of the hopper and its accumulating load were recorded each minute. Gage height was recorded at the beginning and end of the measuring period by observing the staff gage. During many runs, the incremental weight was plotted as a function of time to obtain a visual picture of the transport rate. When the hopper had received about 250-300 lbs (113-136 kg), the downstream belt and the transverse belt were activated, the hopper door was opened, evacuating the load, and samples were scooped off the moving belt, bagged, tagged, and stored for later weighing while wet and for subsequent drying for size analysis.

The gate then was closed, and the main belt was operated for about half an hour until all sediment had been removed and the received weight had dropped again to about 3 lb/min (1.4 kg/min). Next, the second gate was opened, and the process repeated until all eight gates had been used. The entire operation lasted about 8 hours. At low flow, when sediment transport was small, the eight gates were all opened, and the total bedload of the river was measured at one time. At the end of the day all gates were closed, and operation of the main belt was continued to evacuate as much sediment as possible from the trap.

The variation in load for a typical run at low discharge is shown in figure 23A for a time when the bed was clearly visible over much of the slot length and no dunes were visible. Transport rate for the whole river, all gates open, averaged about 14 kg/min at low discharge. A similar plot at higher discharge (fig. 23B) shows large fluctuations in transport rate, indicating the passage of sand dunes, the peaks separated in time by 20 to 30 minutes.

Discharge was measured using a current meter each day for which the stage was not well represented on the discharge rating curve. During several seasons, a two-traverse measurement of bedload was made from the suspension bridge using a Helley-Smith sampler, each measurement consisting of 48 half-minute samples across the river, as described in detail by Emmett (1980a). These measurements were repeated daily, or more often, throughout the period of bedload-trap operation.

Bedload mass was measured on a large weighing scale that carried the weight of the hopper in which the moist sediment accumulated. Weight in pounds was recorded each minute, read visually from the scale. These successive accumulated weights were subtracted to determine the pounds of wet sediment per minute. A run lasted 30 minutes or more. The weights were averaged to obtain pounds (wet) per minute. It was determined experimentally that a dry sample in a plastic bag weighed 0.85 of the wet weight. Thus, immersed mass was calculated as follows:

$$(\textit{Immersed mass, in kg/s}) = (\textit{Wet weight, in lb/min}) \times \left[\frac{0.85}{2.205}\right]\left[\frac{2,640-1,000}{2,640}\right]\left[\frac{1}{60}\right], \qquad (9)$$

where the first term converts from wet weight in pounds to dry mass in kilograms, the second term converts from dry mass to immersed mass, and the third term converts from minutes to seconds.

To get the unit bedload-transport rate, divide by 14.6 m, the width of the trap, to yield immersed mass in kg/m·s. This is the unit bedload-transport rate, i_b, which is listed in table 3 at the back of this report.

BEDLOAD AND RIVER HYDRAULICS

The first relation, presented in figure 24, is the usual bedload rating defined by simultaneous values of measured unit bedload-transport rate (rate per meter of channel width) and the effective water discharge (that part of the total discharge that passed over the 14.6-m width of the bedload trap). Data are from table 3 at the back of this report. The unit suspended-sediment transport data for measurements at the bedload trap, typified by data from 1979 (Emmett and others, 1980),

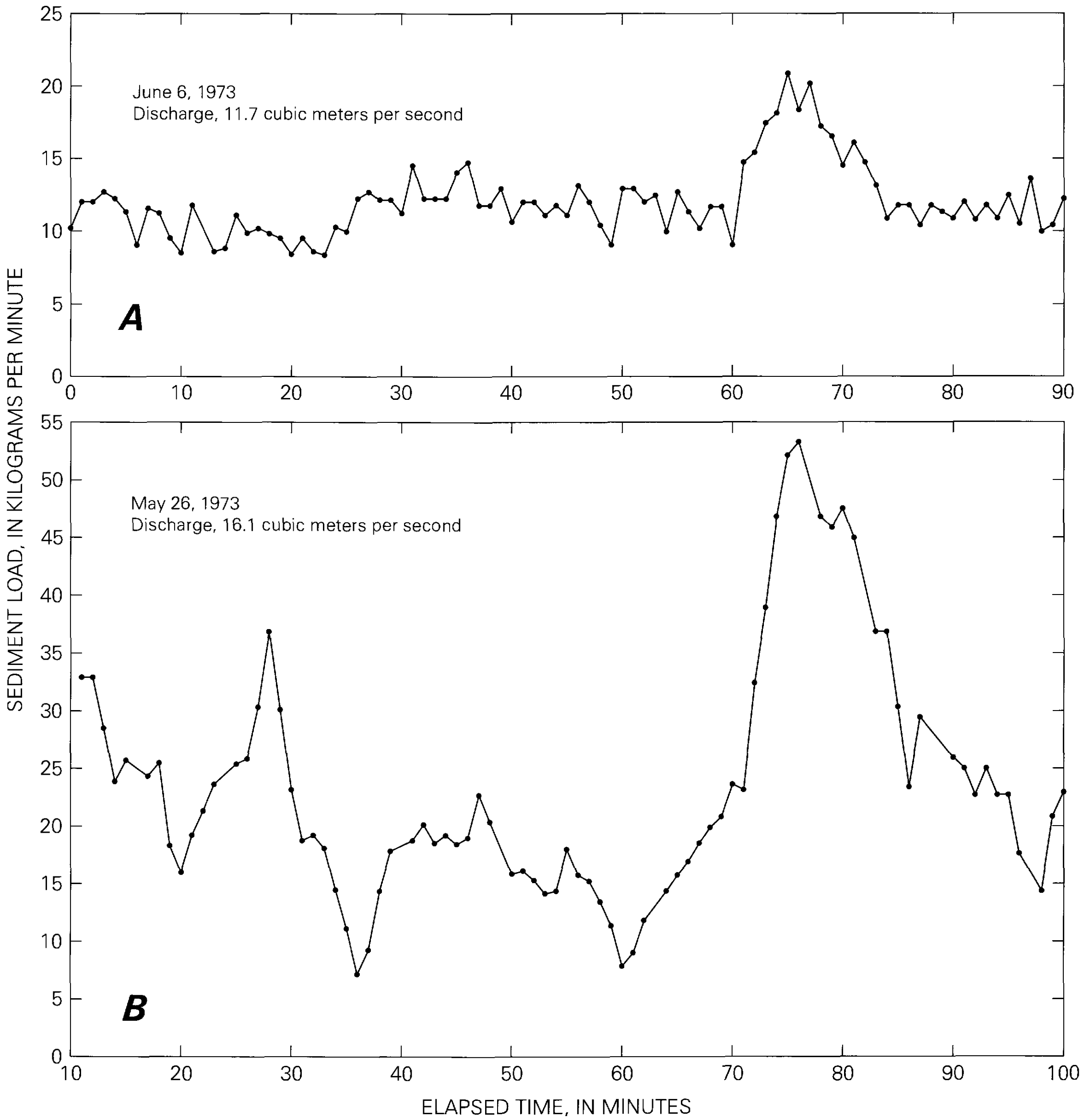


Figure 23. Typical measurements of weight of sediment accumulating in the hopper as a function of time. Weights are expressed as increments during each 1 minute of time. ***A***, River at a low discharge. All gates open; few or small dunes were moving. ***B***, River at a higher discharge. All gates open; incremental weights fluctuate as dunes pass into the trap.

are shown in figure 25. As is true with most sediment ratings, points scatter widely, although the transport rate is extremely sensitive to discharge.

The variance observed in bedload data has become more understandable in the light of recent measurements and observations of movement on the streambed. Some zones or areas of the bed become active, whereas adjacent areas, apparently identical, are without motion. These areas change in an apparently random manner, from active to inactive. A small area of motion, affecting one or only a few grain diameters in thickness, may result in a very low bedform front that might be described as a long flat dune having a very small amplitude, but differs from a dune in that avalanching down the front does not occur. A description of these "bedload sheets" is given in Drake and others (1988).

This sporadic and random motion explains part of the variance seen in plots of bedload data. To smooth this variance in data collection in a Helley-Smith sampler, a large number of individual measure-

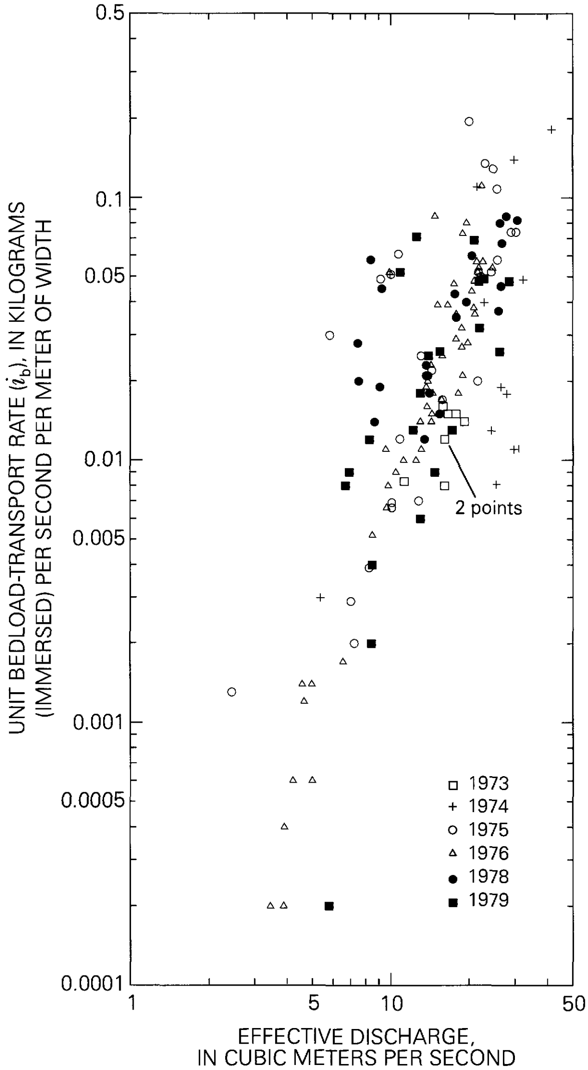


Figure 24. Measured unit bedload-transport rate as a function of effective water discharge, East Fork River at bedload trap.

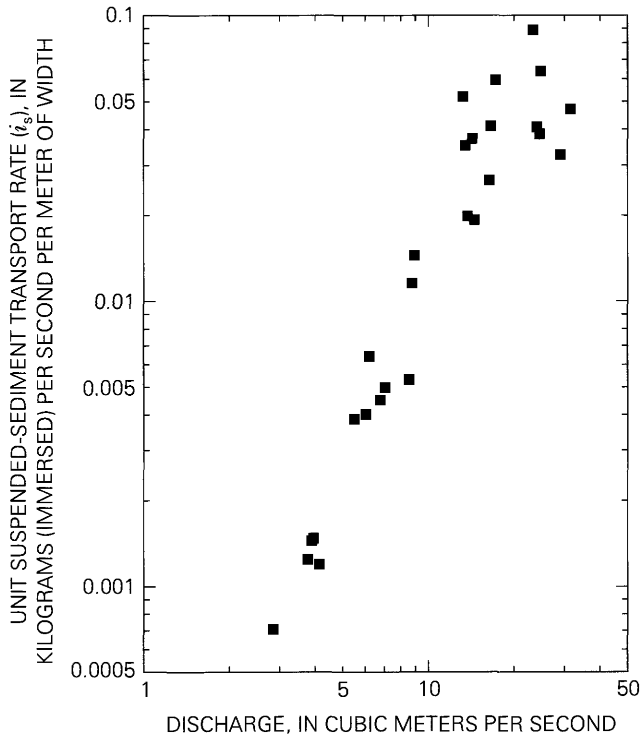


Figure 25. Measured unit suspended-sediment transport rate as a function of discharge, East Fork River at bedload trap (1979 data).

ments are needed. Having made thousands of such measurements, the junior author has recommended a reasonable compromise consisting of about 20 equally spaced samples across the channel. The time of collection for each sample usually is either 30 or 60 seconds. This process is repeated once, so that one measurement is the average of 40 bedload samples. The efficacy of this procedure was demonstrated by comparison of simultaneous measurements in the bedload trap and by the Helley-Smith sampler (Emmett, 1980a).

The next step in developing sediment rating curves for bedload is to compare different rivers using a common set of coordinates. This step may be exemplified by the relation described by Leopold and Emmett (1976, p. 1003), in which the data for several rivers were expressed in the form of a plot of unit bedload-transport rate as a function of unit stream power. The graph consists of a family of curves delineating the relation for different sizes of debris. The steep slope and great sensitivity of the transport rate at low values of stream power give rise to large variability in transport rate for small changes in available stream power.

Refining this type of empirical plot, Bagnold (1977) showed that the extreme sensitivity of the graph at low values of power could be reduced by plotting on the abscissa $\omega - \omega_0$, the available power per unit width minus the power needed for initial motion. The same strategy has previously been used in bedload equations in which load is a function of the difference between shear stress available and shear stress needed for initial motion.

The value of ω_0, power at initial motion, can be estimated by transposition of the Shield's equation. The available power per unit width is

$$\omega = \gamma \frac{QS}{w} = 1{,}000\,udS\,(in\ mass\ units), \qquad (10)$$

where γ is the specific weight of water.

The Shields threshold criterion, θ, is

$$= \frac{\tau_0}{\gamma(S_s - 1)D} \text{ for grain size (particle size),}$$

D, where τ_0 is shear stress at initial motion; in mass units, $\gamma = 1{,}000$ kg/m^3; S_s is the ratio of grain density to fluid density; $(S_s - 1) = 1.64$; depth, d, is in meters; and grain diameter, D, must be expressed in meters for consistency of units. θ has a dimensionless value of 0.04 for turbulent steady flow. Velocity at initial grain motion, u_0, is approximated by 5.75 u_* log 12 d/D, where in mass units, shear velocity is

$$u_* = \sqrt{\frac{g\tau_0}{\rho}} = \left[\frac{9.8\tau_0}{1{,}000}\right]^{1/2}; \qquad (11)$$

g is acceleration due to gravity, and ρ is the density of water.

In mass units, power at initial motion in kg/m·s is

$$\omega_0 = \tau_0 u_0 = (0.04 \times 1640 \times D)^{3/2} \times \left[\frac{9.8}{1{,}000}\right]^{1/2} \times 5.75 \log\frac{12d}{D}$$
$$= 65.6^{3/2} D^{3/2} (0.0098)^{1/2} \times 5.75 \log\frac{12d}{D}$$
$$= 302 D^{3/2} \log\frac{12d}{D}. \qquad (12)$$

The size, D, used is D_{50} (50 percent finer) of the transported load and must be expressed in meters. The measured values of unit bedload-transport rate, i_b, are plotted against excess stream power, $\omega - \omega_0$, for the East Fork River data in figure 26.

Another source of variance in bedload data is the variation of transport rate at constant stream power. The transport rate varies both with flow depth and with bed grain size. These effects have been determined quantitatively by R.A. Bagnold. Using the flume data of Williams (1970), in which runs were made at chosen depths of flow, Bagnold (1980) found that at constant power,

$$i_b \propto d^{-2/3}, \qquad (13)$$

where i_b is transport rate and d, mean flow depth. Analyzing the Gilbert (1914) data, in which a variety of grain sizes was used, Bagnold found that

$$i_b \propto D^{-1/2}, \qquad (14)$$

where D is expressed as the median (D_{50}) size of the transported load.

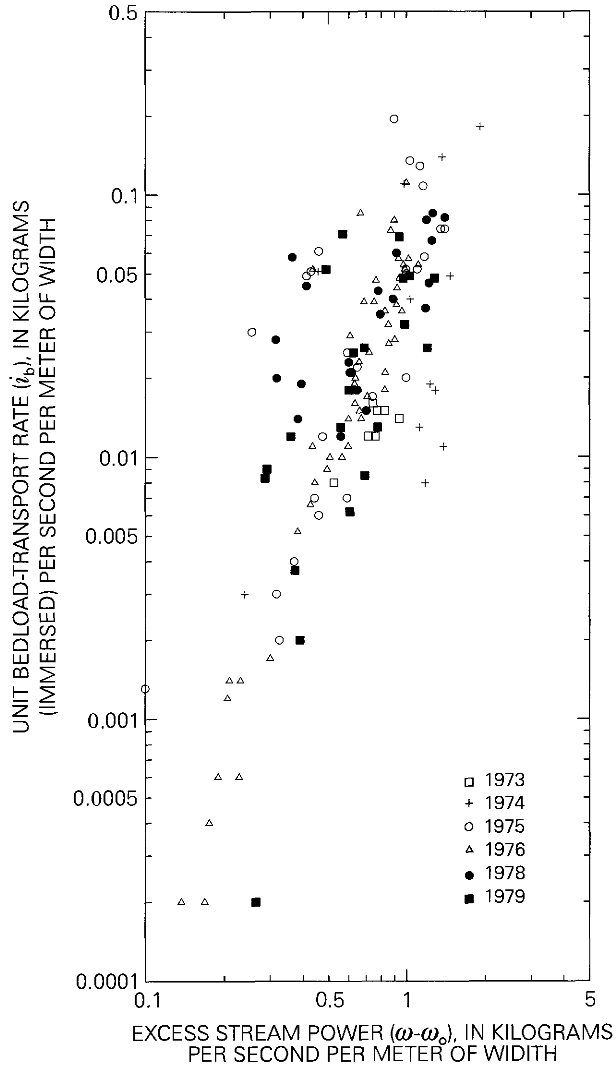


Figure 26. Measured unit bedload-transport rate as a function of excess stream power, East Fork River at bedload trap.

Because different rivers at various discharges differ widely in depth and grain size, transport rates vary accordingly. This has the interesting complication that for a constant available power, shallowing of the river increases its ability to transport sediments. Thus, in a braided river, decrease of depth increases transport rate per unit of width. That is, more of the available power is used for sediment transport and less for frictional loss.

It is desirable to find some empirical relationship that accounts for the effect of grain size and depth. Bagnold (1986) proposed that the data from each river be adjusted to account for the variance due to depth and grain size. Using arbitrarily chosen values for reference—a standard depth of 0.1 m and a standard particle size of 1.1 mm—a new theoretical transport rate, i_b', could be computed by adjusting observed transport rate as follows:

$$i_b' = i_b(observed) \times \left[\frac{d}{0.1}\right]^{2/3}\left[\frac{D_{50}}{0.0011}\right]^{1/2}. \qquad (15)$$

Following Bagnold's original expression, particle sizes in equation 15 are expressed in meters. When average values of observed transport rates in each of several rivers are adjusted by the above relation, the data plot in an unusually straight line through a range of at least five orders of magnitude. This general relation of the adjusted transport rate (from Bagnold, 1986, fig. 1) is given by

$$i_b' = 0.28\,(\omega - \omega_0)^{3/2}. \qquad (16)$$

The general variation of transport rate as the ⅔-power of depth and the square root of grain size explains the major differences among rivers, but clearly does not account for day-to-day variations among hydraulic parameters in a given river. In the East Fork, day-to-day variations are shown to differ from pool to riffle. Unusually high transport rates are measured downstream from a pool on the first hydrograph rise as the pool is scoured. Such conditions are not dependent on the grain-size and depth parameters, but on sediment availability.

Cross-Channel Variation Of Transport Rate

The location of the bedload trap was chosen upstream from a channel bend to the left, downstream from the wooden bridge of the county road, and immediately downstream from a gravel bar, just left of the centerline of the channel (fig. 19). When the trap was constructed, this gravel bar was centered on gate 6. Its character is well illustrated in figure 15A. The channel deepens toward the right bank, yet the data indicate consistently that the deepest section carried the least bedload. Both visually and quantitatively, the gravel bar was associated with more active transport than other parts of the channel. Small dunes were seen to extend laterally from this bar and arrive downstream as if the dunes were moving more rapidly at a distance of 1 m than at a distance of 0.5 m from the bar.

The cross-channel distribution of bedload transport as measured at the eight gates, averaged for discharges of 25 to 30 m^3/s, is shown in figure 27. The lower graph shows that the deepest water is near the right bank (gates 2 and 3), but the major transport is between gates 4 and 6. Gate 6 is at the centerline of the gravel bar upstream from the trap. Thus, the gravel bar is near a shallow zone, but it is the locus of the principal bedload transport at discharges near bankfull, when the transport rate is greatest. As an example, the highest transport rate recorded during the 1978 runoff season was at gate 6 on the day of largest discharge, approximately bankfull. Thus, the product of an overall channel slope and a local water depth gives only a poor indication of local bed shear stress.

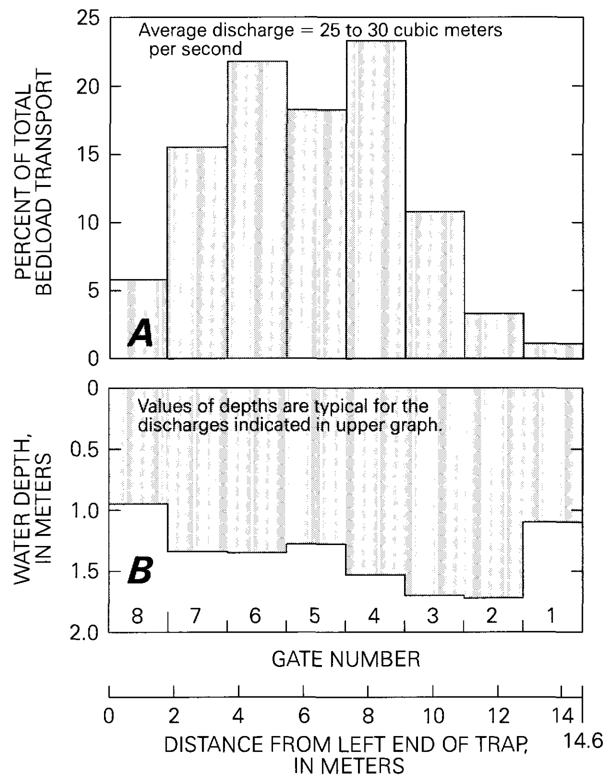


Figure 27. Cross-channel distribution of: ***A***, bedload transport, and ***B***, water depth, East Fork River at bedload trap. As plotted, the depths simulate the channel cross section (see fig. 16).

That bedload transport is far from uniform over the whole width of the channel bed was demonstrated by the daily bedload measurements at U.S. Forest Service sites in the Colorado Front Range in 1989 (U.S. Forest Service, Fort Collins, Colo., unpublished data). In these mountain streams, the beds of which were medium to coarse gravel, 85 percent of the total bedload occurred in 50 percent of the channel width, and 50 percent of the total bedload occurred in about 29 percent of the channel width. This cross-channel variation is not unlike that for the East Fork River (see Leopold and Emmett, 1977); this distribution becomes important when bedload transport rate per unit width is extrapolated to estimate the total bedload of the river.

HYDRAULIC RESISTANCE

Bedload transport rates at the trap on the East Fork were measured during six runoff seasons. Each measurement tabulated at the back of this report (table 3) is the result of recording accumulated weight each minute during several hours. These observations demonstrate that the bedload passing a particular location varies rapidly through a large range with time. We demonstrated time after time, that when a sampler is placed on the river bed at the same location at intervals of a minute or two, the bedload trapped in the sampler may vary from zero to several thousand grams.

This great variability results from two basic causes. First, if the grain size is in the sand range, the principal mode of transport usually, but not universally, is by dunes. Second, where the bed material is larger than coarse sand, sediment may move as "bedload sheets" mentioned earlier. In this mode of motion, a particular location on the bed changes from no motion to intense movement, instantaneously and randomly.

Inspection of figure 23 indicates that bedload movement in the East Fork is primarily by dunes. Dunes, then, must provide an important part of the total flow resistance.

Grain resistance is also a component of total flow resistance. Our measurements indicate a small but steady increase in median size, D_{50}, of the moving load with increased transport rate. The median size increased from 0.7 mm when the transport rate was 0.007 kg/m·s, to 1.4 mm when the transport rate was 0.09 kg/m·s.

The most useful measure of total flow resistance is the dimensionless u/u_* or the ratio of mean flow velocity to shear velocity. It was shown by Leopold and Wolman (1957) that for gravel bed rivers the hydraulic resistance can be defined by:

$$\frac{1}{\sqrt{f}} = 1 + 2\log\frac{d}{D_{84}}, \qquad (17)$$

which is identical to the relation

$$\frac{u}{u_*} = 2.8 + 5.7\log\frac{d}{D_{84}}, \qquad (18)$$

where f is the Darcy-Weisbach friction factor, and D_{84} is bed material size 84 percent finer. Equation 18 was later substantiated by Limerinos (1970), and for gravel rivers in England a nearly identical relation was published by the Hydraulic Research Station, Wallingford (1977).

Though this relation represents a satisfactory average, many gravel rivers deviate more or less from the equation for reasons that are not clear. For the East Fork, the values of u/u_* group closely within the range of 11 to 14, averaging 12.2. The values of u/u_* decrease slightly with increasing transport rate if computed on a day-to-day basis.

The bedload grain size expressed as D_{84} in the East Fork seldom is larger than about 4 mm. If ordinary depths were 1.2 m, the ratio d/D_{84} was about 300. For this condition, the value of 16.9 for u/u_* would seem rather smooth for gravel rivers. Even a reach-averaged bed material D_{84} of about 15 mm gives a value of 13.6 for u/u_*, the smoother end of the range of values of u/u_* for the East Fork River. But the amplitude of the dunes on the bed was estimated as 10 cm. If this were the roughness element, then the ratio of depth to roughness would be 1.2/0.1 = 12, for which a corresponding u/u_* would be about 9.0. This suggests that when dunes are the dominant bed form, their size may be used as an estimate of the dominant roughness height. Conversely, the dominant roughness element might be surmised from the relation of depth to u/u_*.

SEDIMENT RATING CURVE COMPUTED FROM HYDRAULIC GEOMETRY

The hydraulic geometry equations for at-a-station data give the average value of each hydraulic parameter for a range of discharges. Therefore, it should be possible to compute a sediment rating curve by substituting these values in an expression for sediment transport. When a sediment rating curve has been established by direct field measurement, the utility of any formula for computing transport rate may be determined by the comparison of computed and measured sediment rating curves. The possibility of computing a sediment rating curve from a formula is attractive, but needs to be used with caution.

As a first approximation, at-a-station curves for depth and velocity can be constructed from the empirical formulas given in the previous discussion of hydraulic geometry. From these constructed at-a-station curves, selected values may be chosen to represent a range in discharge. For each, sediment load can be computed using one of the usual formulas.

The most consistent results in our computations were obtained by using the Ackers and White (1973) formula for total load, and the sum of bedload and suspended load measured at the same discharge for measured load. The size of sediment that gave the best result in that formula was the D_{84} of the bedload caught in the Helley-Smith sampler. But in all computations that were tried using a single grain size in the formulas, such as D_{50}, the computed load was too large for small values of discharge and too small for large discharges. That is, the slope of the computed sediment rating curve was less than the slope of the curve representing measured sediment load. However, this general technique appears fruitful, and additional trials in a variety of rivers is highly recommended.

It is an open question: what grain size should be considered the effective or representative size when the load is heterogeneous in size? Not knowing better, we usually assume that D_{50} is the most representative. It may not be the effective size. In fact, the effective size may change with water discharge or total load. Given that more than one bedload formula appear to compute too large a load at small discharges, perhaps the effective size should change progressively with discharge (Emmett and Leopold, 1977).

Scour And Movement Of Bed Material

Movement of Marked Rocks in Relation to Bed Shear

In early May 1969, two groups of rocks, each group painted a different color for identification, were placed on a gravel bed 257 m upstream from the bedload project site. Each group consisted of 100 rocks 22 to 45 mm in size placed as a sheet of closely spaced rocks about 1 diameter thick. Recovery was made July 26, 1969, after the spring runoff, the peak of which was May 28, 1969, at a discharge of 29.8 m^3/s and a local maximum water depth of about 1.8 m. The local slope at that stage was about 0.0007, which provided a bed shear of 12 N/m^2, which according to the Shields diagram is sufficient to move a rock of about 15 mm. Thirty-three percent of the green rocks moved more than 3 m, and 90 percent of the yellow rocks moved more than 6 m from their original position.

On May 31, 1970, three groups of painted rocks were placed on the gravel bar 10 to 17 m upstream from the project site. All rocks were in the size range 16 to 22 mm. The peak discharge occurred June 5, 1970, at 22.6 m^3/s. After the spring runoff, a search was made on July 1, 1970. Of 60 red rocks, all but 6 moved more than 2 m, and of 100 green rocks, all but 14 moved more than 3 m. Thus, about 87 percent of the red and green rocks moved some distance. Maximum water depth over the rock groups was 1.19 m. With a local slope of 0.0007, that provided a bed shear of 8 N/m^2, which according to the Shields diagram should be capable of moving a rock 10 mm in size.

These results indicate that for rocks placed where the bed material is of size similar to the emplaced rocks, the Shields diagram gives a reasonable estimate of whether the rocks should move under the peak flow observed. But even when adequate shear occurs, not all those rocks will move. This is a detail about which little information is available. A new type of Shields diagram is needed that involves heterogeneous sediment and the percentage of any given size that will move under given circumstances.

Distance Moved by Marked Rocks

The following paragraphs emphasize distance that rocks moved, rather than bed shear. In the coarse-rock groups (1969 experiment), the recovery of marked rocks after a single snowmelt season ranged from 21 to 91 percent (fig. 28A). In each case, the available shear stress at peak flow at the site of placement was just able to move the size of rocks placed. In all cases, the total distance moved during a runoff season lasting several weeks was surprisingly short. Recovered rocks in the coarse-rock groups had moved 35 m or less. In the fine-rock groups (1970 experiment), 22 to 53 percent of the rocks placed were recovered, and most of these had moved less than 40 m (fig. 28B).

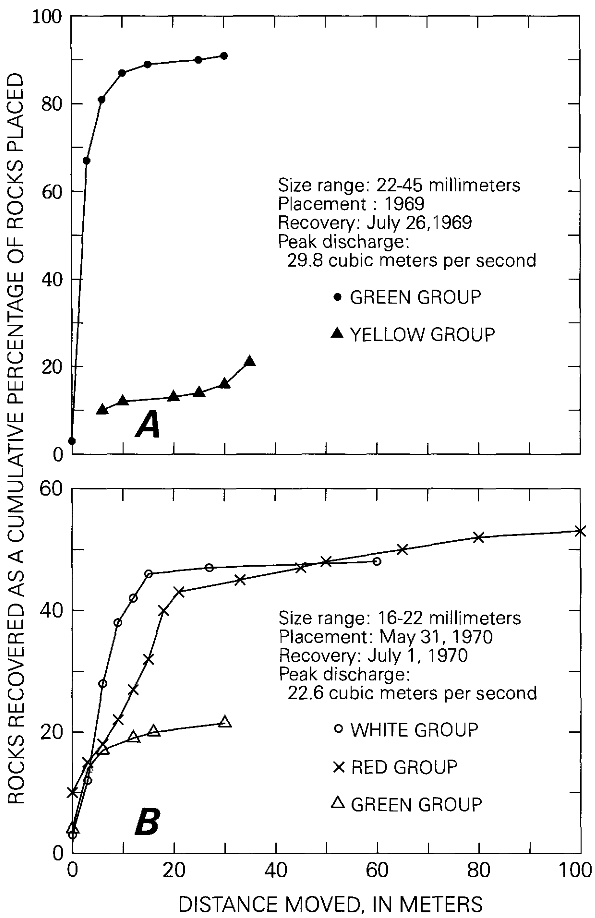


Figure 28. Percentage of painted rocks that moved different distances in East Fork River during a season of snowmelt runoff. ***A***, 1969 experiment. ***B***, 1970, experiment.

It was our experience that after a single flood season many painted rocks could be recovered a short distance downstream from the point where they were placed. After a second season, a few could be found, and after three seasons none could be found. Thus, we observed that even when shear stress was available to move rocks of a given size, by no means were all such rocks moved an appreciable distance. Given time, however, all would move eventually. It seems probable that where a rock of gravel or cobble size moves at all, it is likely not to move far in a single season. It is as if individual rocks were plucked out of a group and soon replaced. This action is different from the action in those reaches where the streambed was covered with sand that scoured and subsequently filled during the same season.

On one cross section, scour chains were set in the streambed as described by Leopold and others (1966, p. 215), and the painted rock group was placed near the chains to determine if scour to some depth was associated with movement of surface rocks. It was found that painted rocks were carried away, whereas the chains remained at the bed surface, indicating that removal of rocks was only to a depth of one rock diameter. This finding is in agreement with our observations of rock removal and replacement on the surface of a gravel bar on a perennial river in Maryland.

The total distance rocks moved over several seasons is indicated by the following. On May 26, 1971, three groups of painted rocks—16, 22, and 32 mm in size—were placed in the East Fork River downstream from the mouth of Muddy Creek. Three rocks of 22 mm size and three of 16 mm were found August 28, 1975, at a location 3,670 m downstream from where they had been placed. Thus, they moved about 3.7 km in 4 years.

These observations, combined with the relative dearth of medium gravel to cobble size caught in the bedload trap, imply that gravel movement is sporadic and for only short distances in a single season, although there are numerous gravel bars seen in the river. These bars must be rather stable, losing and gaining rocks a few at a time—a process that maintains the shape and position of the bar over long periods of time.

Each of the above conclusions was corroborated by a more extensive field measurement project in nine mountain streams in Colorado in the spring runoff season of 1989. Rocks chosen from the bed surface representing size D_{35}, D_{50}, and D_{84} were collected, painted, and placed in straight lines across the channel. A total of 30 such lines comprising 769 rocks varying in size from 39 to 250 mm were observed each day during the snowmelt runoff season (Leopold and Rosgen, 1991).

From this detailed program of observation, several conclusions were reached—all in general agreement with our results on the East Fork. It was found that 65 percent of all the rocks moved during the season, even though none of the nine streams reached bankfull discharge. The distance moved was relatively small during any one movement, usually less than a few meters. Some rocks moved more than once, and a few as many as four times. About the same percentage of the large rocks, D_{84}, moved as did the smaller, D_{35}, size.

Sand Marked by Fluorescent Dye

The alternate scour and fill of pool and riffle sections has been detailed by Emmett and others (1983). Further detail on this process is provided by our measurements of particles marked with fluorescent dye. Sand so marked was placed as a line source across the channel section at 3,037 m upstream from the bedload trap. There was surprisingly little difference in the distance moved as a function of particle size. For example, 16 days after injection, the peak number of particles of various sizes was recorded at the following distances downstream from the point of injection:

Particle size (millimeters)	Distance moved (meters)
0.25 - 0.5	450
0.5 - 1.0	350
1.0 - 2.0	380
2.0 - 4.0	260
Larger than 4.0	280

In this study, the daily downstream displacement of the peak concentration (approximate centroid) for tracer particles of size 0.5 to 1.0 mm was about 30 m. During the full runoff season in 1979, which lasted 22 days, the total movement of the bulk of marked particles of this size was 650 m (Emmett and others, 1983; Emmett and Myrick, 1985).

Thus, the downstream speed of sediment particles is slow, on the order of 0.01 to 0.1 percent of the mean flow velocity. The volume of material scoured and moved is large, but because of its slow downstream velocity, the total distance moved is limited. These details have been shown quantitatively by the data collected on the East Fork, much of which has been published (see especially the references in Emmett and others, 1983).

Water-Surface Topography

Cross-Channel Profile

In a straight reach of river, there usually is a topographic ridge in the water surface near the centerline of the channel. This ridge has been observed in every survey we have made where it was possible to measure with sufficient accuracy to show such detail. Examples are shown in Leopold and others (1964, p. 283) and Leopold (1982b). The East Fork is another example.

Cross-channel profiles were measured from the suspension bridge at the bedload trap (shown in fig. 29 at high flow). Elevations were surveyed at the centerline of each gate of the trap.

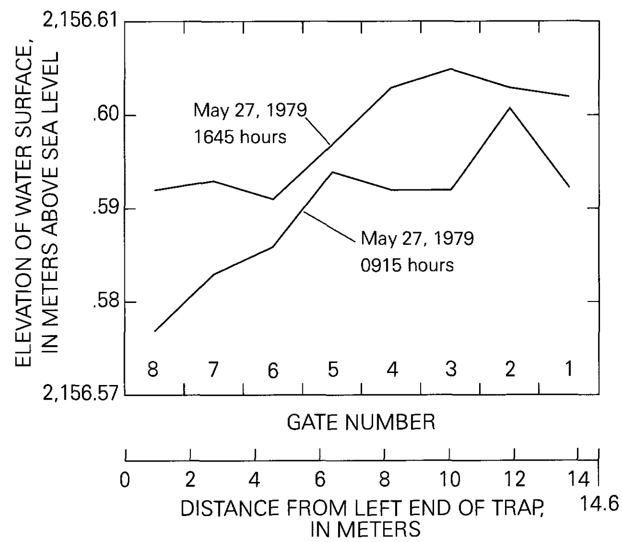


Figure 29. Cross-channel profiles of the water surface, East Fork River at bedload trap, May 27, 1979. Average discharge for May 27 was 28.5 cubic meters per second.

The water-surface elevation was low at the left bank and increased 13 to 24 mm toward the right bank, then decreased 3 to 9 mm in the last several meters. Although the channel is relatively straight at the bedload project site, the last bend upstream from the highway bridge was toward the left, so the general rise of water surface toward the right side of the channel may be due to the residual superelevation from that bend upstream. The marked drop in elevation in the right one-quarter of the channel must be attributed to some other mechanism, overcoming the residual superelevation due to curvature.

As postulated by Gibson (1909), and elaborated with river measurements by Leopold (1982b), we believe that the topographic high is attributable to two circulation cells in which water at the surface converges near the river centerline, and water at the bed diverges. These two cells do not remain of equal strength, and the position of the topographic ridge depends on the relative size and strength of the two cells. In very wide rivers there are several cells, some being drivers and some being driven.

Topography in a Straight Reach

In the East Fork between Muddy Creek and the project site, there are two prominent straight reaches of channel. One is 250 m or 17 widths in length, including three riffles and two pools of unequal length. The plan view of that reach is shown in figure 30. On four occasions during the 1979 spring runoff season, leveling sur-

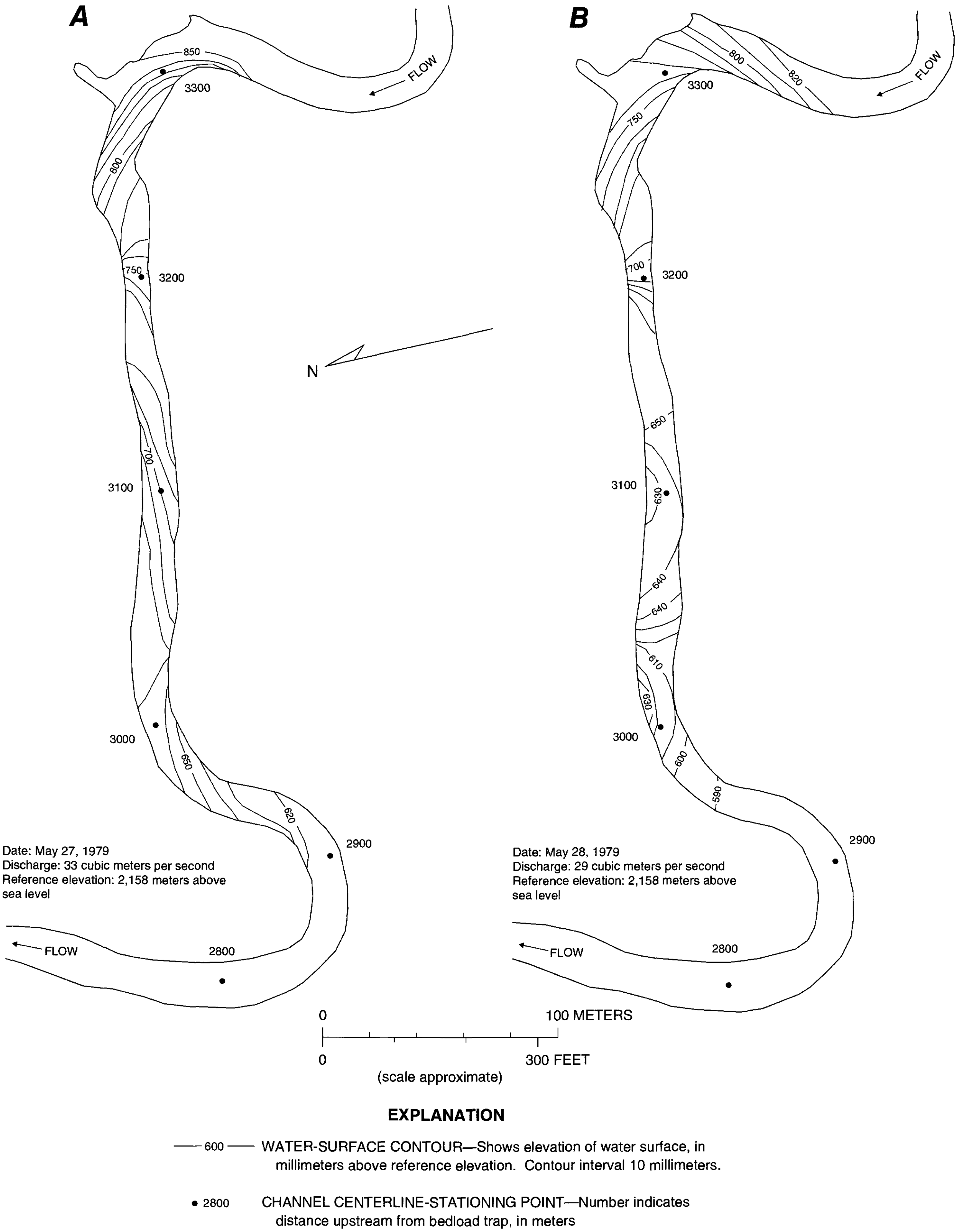


Figure 30. Water-surface contours for decreasing values of discharge in a straight reach of East Fork River about 3 kilometers upstream from bedload trap. ***A***, May 27, 1979. ***B***, May 28, 1979. ***C***, June 5, 1979. ***D***, June 21, 1979.

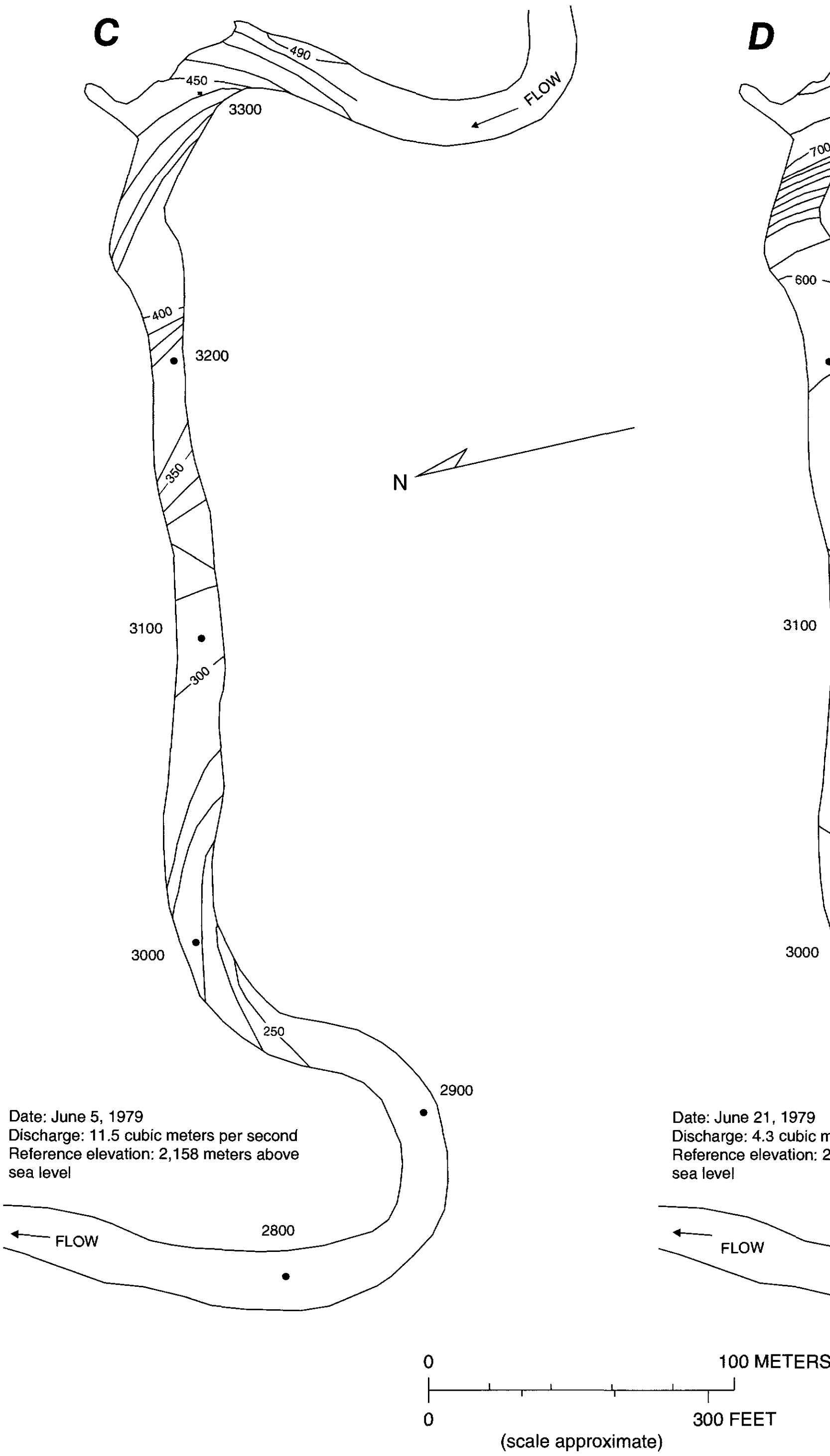


Figure 30. (Continued)

veys of water surface along both right and left banks were made, including: high flow, flow above bankfull, and low flow. Elevations were read to nearest millimeter at points averaging 20 m apart. On the maps in figure 30, contours are drawn on the water surface with an interval of 10 mm. This choice of contour interval is larger than the precision of measured values. The variance due to random survey error, temporal stage changes, and minor local inconsistencies are thus not significant.

The four maps (fig. 30) show water-surface topography for decreasing values of discharge. The first obvious characteristic is the superelevation due to curvature, prominent between stations 3250 and 3330 and between stations 2900 and 3000; the amount of superelevation is greatest at the highest discharge. A second characteristic is the tendency for the water surface to be steeper along the convex than along the concave bank, in agreement with the findings of other workers. At the highest discharge (fig. 30A), local steepening of water surface at station 3200 in this reach was caused by a pile of logs and flood debris against the right bank.

Note that the distance between the positions along the channel from superelevation on one bank to superelevation on the opposite bank is about eight channel widths. For example, the distance from station 3250 to station 3100 is 150 m, and the average width, bankfull, is about 19 m. This is close to the range usually stated, 5 to 7 widths.

It has long been known, especially to the engineers associated with the maintenance of navigation channels on large rivers such as the Mississippi, that riffles, shallows, or crossings fill at high flow, while pools or deeps get even deeper by scour. At low flow, riffles or crossings scour. One could surmise that the reason for this scour is that the water surface becomes steeper as flow and depth decrease. In other words, the water-surface slope at low flow is small in the pool and steep over the riffle. With increasing flow, the slope steepens over the pool and flattens over the riffle until, at some high stage, the longitudinal profile becomes more or less straight or, in some cases, the pool slope may exceed that of the riffle. Measurements of this change in slope have been presented by Emmett and others (1983).

We were somewhat surprised when early measurements showed considerable bedload transport continuing in some locations, even when discharge had decreased to small values. Measurements of water-surface topography showed that the phenomenon described above was operative. The river at station 3250 in figure 30A is a shallow, being the downstream end of a point bar. Between stations 3250 and 3300, the water surface is strongly superelevated against the concave bank, and the steepest water surface is along the convex bank. When the discharge had decreased to a low value, 4.3 m^3/s, the water-surface slope in the vicinity of the section at station 3250 had increased dramatically, and this shallow (riffle) was being scoured and deepened at low flow (fig. 30D). The scoured sediment was deposited in the pool immediately downstream near the section at station 3225. Thus, the changing topography of the water surface explains and illuminates the process of deposition or fill in shallows at high flow followed by scour at low flow.

Descriptions of longitudinal profiles of water surfaces at various discharges are uncommon in the literature, and even those are insufficient to indicate important details of river action. Note on figure 30A that at high flow the superelevation against the right bank at station 3300 becomes zero downstream, so that at the succeeding riffle section at station 3100 the superelevation is against the left bank, even though the channel has no curvature to cause it. At the section at station 2980, the superelevation is again against the right bank, here explained by the curvature of the channel. Thus, the occurrence of bars on alternate sides of a channel in a straight reach seems to be associated with the rhythmic alternation of water surface cross-channel slope. The superelevation against one bank creates a cross-channel component of velocity near the bed away from that bank, and bed material is thus carried toward the bank opposite the side with superelevation. The bedload transport rate is then also greatest near the bank toward which the velocity component near the bed is directed.

The data indicate that in this manner the locus of bedload transport moves alternately from one side of the channel centerline to the other and is on the side where the channel is shallow; that is, the transport is greatest over the alternate bars rather than in the deepest part of the channel. This alternation of the locus of bedload transport has been demonstrated with measurement data by Leopold (1982b, figs. 13, 14).

CONCLUDING STATEMENT

Data from the East Fork bedload trap have been compiled and printed in a series of open-file reports, all of which are listed in the references at the end of this paper. The total number of numerical values tabulated and printed for this project is estimated to exceed 1 million. All of the bedload data and corresponding hydraulic parameters are listed in table 3. It is our firm belief that publication of all the actual data from a scientific investigation of this sort is necessary if the results are to have long-term value to other researchers in the future. It is the present custom to print only graphs or short discussions and omit the tabulated data, in order to save space in the publication. But considering the fact that personnel, equipment, and field costs exceed by far the cost of printing the results, the present practice is short-sighted. Perhaps science needs fewer minor investigations and fewer papers, but those printed should be accompanied by the actual data.

The most important contribution made by the careful measurements on the East Fork River is that they provided the actual bedload amounts moving in a real river, against which the new Helley-Smith sampler was compared. No rating of such a device in a flume has the value of the comparison of total bedload movement in a river and simultaneous sampling by a sediment-sampling device. This comparison, consisting of thousands of samples and years of real bedload measurement, has not been equaled by any other sampler calibration.

The project has several restrictions and shortcomings. It is, first, a sample of the action of only one river. That river carries primarily sand, with only a minor amount of gravel as bedload. Therefore, the many things we would like to know about gravel-bed rivers are unanswered and may be surmised only by inference.

The sand carried by the river has a somewhat bimodal size distribution. Thus, the selection of what grain size might best characterize the bedload is not obvious. Analysis of the data indicates that the representative size probably should be dependent on the discharge and is not a constant that applies to all flow conditions. This is an important matter because in all formulas for computing bedload transport rate, a representative size and size distribution is either specified or tacitly assumed. Using the measured concurrent values of velocity, depth, and slope, computed values of bedload transport rate using a constant grain size are too small for high discharges and too large for low discharges. Measured changes in slope do not account for this difference. We conclude that for reasons not clear, the representative grain size should be smaller at high discharges than at low discharges. This idea needs to be further explored in other rivers.

In the East Fork, the sediment transport was not concentrated in the deepest part of the channel, where the depth-slope product would be greatest. The greatest transport was in the shallower parts of the channel over or near the minor gravel bar just left of the channel centerline. The transport-rate distribution closely follows the distribution of local shear stress, as explained in detail by Dietrich and Smith (1984). They computed local shear stress from measurements of local velocity close to the bed and simultaneously measured transport rate with a miniature Helley-Smith sampler. As shown especially in their figure 16 (p. 1369), shear stress is greatest near the convex bank as the water approaches the point bar and gradually shifts toward the concave bank at the end of the curve and as the crossover point is reached. Thus, the East Fork observations are well explained by the Dietrich-Smith analysis.

Finally, actual measurement data on movement of individual sand grains and of gravel clasts supplement heretofore meager data on distance moved in individual excursions and during a whole flow season. When the flow is competent to move a rock of a given size, only a few of the many available will be moved at one time. The fluorescent-tracer experiments allowed us to mark and follow individual grains of sand. The data indicate that downstream movement usually is limited to only a short distance on any individual excursion. The downstream rate of bedload movement is surprisingly slow as a result.

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BEDLOAD DATA AND HYDRAULIC PARAMETERS

Table 3. Bedload data and hydraulic parameters measured at the bedload trap, East Fork River, Wyoming, 1973-79

[Q, effective water discharge; u, mean velocity; d, mean depth; D_{50}, median particle size; i_b, unit transport rate; ω, unit stream power; ω_0, stream power at initial motion; ω-ω_0, excess stream power; u_*, shear velocity; m^3/s, cubic meters per second; m/s, meters per second; m, meters; kg/m·s, kilograms per second per meter of width. Water-surface slope, S, = 0.0007. Width of flow, w, = 14.6 meters. No measurements during 1977.]

Date	Q (m^3/s)	u (m/s)	d (m)	D_{50} (m)	i_b (kg/m·s)	ω (kg/m·s)	ω_0 (kg/m·s)	$\omega-\omega_0$ (kg/m·s)	u_* (m/s)	u/u_*
					1973					
5/26/73	16.1	1.06	1.04	0.00135	0.008	0.772	0.059	0.712	0.085	12.5
6/01/73	16.1	1.06	1.04	.00045	.012	.772	.013	.759	.085	12.5
6/02/73	17.8	1.09	1.11	.00074	.015	.847	.026	.821	.087	12.5
6/03/73	16.6	1.07	1.06	.00071	.015	.794	.024	.770	.085	12.5
6/06/73	11.3	.96	.81	.00056	.0083	.544	.017	.527	.075	12.9
6/07/73	15.9	1.06	1.03	.00060	.016	.764	.019	.745	.084	12.6
6/08/73	19.2	1.19	1.17	.00098	.014	.975	.039	.936	.090	13.3
					1974					
5/25/74	5.34	.76	.48	.00054	.003	.255	.015	.240	.057	13.2
5/26/74	9.92	.92	.74	.00059	.051	.477	.018	.458	.071	12.9
5/27/74	21.5	1.15	1.27	.00103	.110	1.02	.042	.981	.093	12.3
5/28/74	29.8	1.28	1.60	.00140	.140	1.43	.065	1.37	.105	12.2
5/29/74	41.5	1.41	2.01	.00152	.182	1.98	.075	1.91	.117	12.1
5/30/74	32.2	1.31	1.68	.00151	.049	1.54	.073	1.47	.107	12.2
5/31/74	22.9	1.18	1.33	.00140	.040	1.10	.064	1.03	.096	12.3
6/01/74	24.3	1.20	1.38	.00094	.013	1.16	.037	1.12	.097	12.3
6/02/74	25.5	1.22	1.43	.00099	.0081	1.22	.040	1.18	.099	12.3
6/03/74	29.7	1.27	1.59	.00088	.011	1.41	.034	1.38	.104	12.1
6/04/74	27.9	1.25	1.52	.00092	.018	1.33	.036	1.29	.102	12.2
6/05/74	26.5	1.23	1.47	.00081	.019	1.27	.030	1.23	.100	12.2
					1975					
5/27/75	2.44	.61	.28	.00070	.0013	.119	.021	.099	.044	13.9
6/02/75	5.82	.78	.51	.00074	.030	.278	.024	.255	.059	13.2
6/03/75	9.13	.90	.70	.00078	.049	.441	.027	.414	.069	13.0
6/04/75	10.0	.92	.74	.00116	.051	.477	.046	.430	.071	12.9
6/05/75	10.7	.94	.78	.00126	.061	.513	.052	.461	.073	12.8
6/06/75	20.0	1.13	1.21	.00136	.195	.957	.061	.896	.091	12.4
6/07/75	24.8	1.21	1.40	.00128	.129	1.19	.057	1.13	.098	12.3
6/08/75	25.6	1.22	1.44	.00141	.108	1.23	.065	1.16	.099	12.3
6/09/75	24.3	1.20	1.38	.00135	.052	1.16	.061	1.10	.097	12.3
6/10/75	14.4	1.03	.96	.00111	.022	.692	.045	.647	.081	12.7
6/11/75	10.1	.92	.75	.00102	.0069	.483	.039	.444	.072	12.8
6/13/75	15.8	1.06	1.02	.00050	.017	.757	.015	.742	.084	12.7

Table 3. Bedload data and hydraulic parameters measured at the bedload trap, East Fork River, Wyoming, 1973-79—Continued

Date	Q (m^3/s)	u (m/s)	d (m)	D_{50} (m)	i_b (kg/m·s)	ω (kg/m·s)	ω_0 (kg/m·s)	$\omega-\omega_0$ (kg/m·s)	u_* (m/s)	u/u_*
				1975—Continued						
6/14/75	25.7	1.22	1.44	0.00127	0.058	1.23	0.057	1.17	0.099	12.3
6/15/75	29.0	1.27	1.57	.00105	.074	1.40	.044	1.35	.104	12.2
6/16/75	30.3	1.28	1.62	.00119	.074	1.45	.052	1.40	.105	12.1
6/17/75	22.2	1.17	1.30	.00136	.050	1.06	.062	1.00	.094	12.4
6/18/75	12.8	.99	.88	.00059	.0066	.610	.018	.591	.078	12.7
6/19/75	10.1	.92	.75	.00073	.0060	.483	.024	.459	.072	12.8
6/21/75	7.23	.84	.59	.00070	.0020	.347	.022	.325	.064	13.2
6/22/75	7.01	.83	.58	.00064	.0029	.337	.020	.317	.063	13.1
6/23/75	8.24	.87	.65	.00077	.0039	.396	.026	.370	.067	13.0
6/24/75	10.8	.94	.78	.00098	.012	.513	.037	.476	.073	12.8
6/25/75	21.7	1.16	1.28	.00110	.052	1.04	.046	.994	.094	12.4
6/26/75	13.1	1.00	.90	.00099	.025	.63	.038	.592	.079	12.7
7/01/75	23.1	1.18	1.34	.00163	.135	1.11	.079	1.03	.096	12.3
7/08/75	21.5	1.16	1.27	.00091	.020	1.03	.035	.996	.093	12.4
				1976						
5/18/76	9.87	.87	.78	.00098	.052	.475	.037	.438	.073	11.9
5/19/76	14.8	1.00	1.01	.00104	.085	.707	.041	.666	.083	12.0
5/20/76	18.9	1.09	1.19	.00096	.073	.908	.037	.870	.090	12.1
5/20/76	19.6	1.10	1.22	.00104	.080	.939	.042	.897	.092	12.0
5/21/76	22.4	1.15	1.33	.00152	.111	1.07	.072	1.00	.096	12.0
5/22/76	17.5	1.06	1.13	.00156	.047	.84	.073	.765	.088	12.0
5/26/76	9.77	.87	.77	.00071	.008	.469	.024	.445	.073	11.9
5/27/76	14.3	.99	.99	.00059	.014	.686	.019	.667	.082	12.0
5/27/76	13.7	.97	.96	.00061	.019	.652	.019	.632	.081	12.0
5/27/76	13.0	.96	.93	.00077	.014	.625	.027	.598	.080	12.0
5/28/76	18.8	1.08	1.18	.00095	.027	.892	.037	.855	.090	12.0
5/28/76	19.8	1.10	1.23	.00111	.028	.947	.046	.901	.092	12.0
5/29/76	20.5	1.12	1.25	.00130	.044	.980	.058	.922	.093	12.0
5/29/76	20.9	1.12	1.27	.00167	.038	.996	.082	.914	.093	12.0
5/30/76	20.9	1.12	1.27	.00129	.048	.996	.057	.939	.093	12.0
5/31/76	16.6	1.04	1.09	.00109	.039	.794	.044	.749	.087	12.0
5/31/76	15.8	1.02	1.06	.00098	.025	.757	.038	.719	.085	12.0
6/01/76	14.3	.99	.99	.00081	.023	.686	.029	.657	.082	12.0
6/01/76	13.9	.98	.97	.00080	.020	.665	.028	.637	.082	12.0

Table 3. Bedload data and hydraulic parameters measured at the bedload trap, East Fork River, Wyoming, 1973-79—Continued

Date	Q (m^3/s)	u (m/s)	d (m)	D_{50} (m)	i_b (kg/m·s)	ω (kg/m·s)	ω_0 (kg/m·s)	$\omega-\omega_0$ (kg/m·s)	u_* (m/s)	u/u_*
					1976—Continued					
6/02/76	17.9	1.07	1.15	0.00094	0.036	0.861	0.036	0.825	0.089	12.0
6/02/76	17.8	1.06	1.14	.00104	.029	.846	.030	.607	.088	12.0
6/03/76	21.6	1.14	1.30	.00118	.052	1.04	.050	.987	.094	12.1
6/04/76	21.8	1.14	1.30	.00140	.054	1.04	.064	.973	.094	12.1
6/05/76	21.4	1.13	1.29	.00176	.057	1.02	.088	.932	.094	12.0
6/05/76	22.4	1.15	1.33	.00151	.049	1.07	.071	.999	.096	12.0
6/06/76	22.6	1.16	1.33	.00130	.057	1.08	.058	1.02	.096	12.1
6/07/76	24.6	1.19	1.41	.00135	.054	1.17	.061	1.11	.098	12.1
6/08/76	21.1	1.13	1.28	.00124	.036	1.01	.054	.958	.094	12.0
6/09/76	18.8	1.08	1.18	.00103	.032	.892	.041	.851	.090	12.0
6/09/76	18.9	1.09	1.19	.00108	.021	.875	.044	.830	.090	12.1
6/10/76	18.2	1.07	1.16	.00106	.018	.869	.043	.826	.089	12.0
6/11/76	13.8	.98	.97	.00084	.016	.665	.030	.635	.082	12.0
6/11/76	14.5	.99	1.00	.00105	.018	.693	.042	.651	.083	11.9
6/11/76	15.7	1.02	1.05	.00102	.017	.750	.040	.709	.085	12.0
6/11/76	15.2	1.01	1.03	.00107	.039	.728	.043	.685	.084	12.0
6/11/76	14.4	.99	.99	.00079	.015	.686	.028	.658	.082	12.1
6/12/76	13.1	.96	.93	.00081	.011	.625	.029	.596	.080	12.0
6/12/76	12.5	.94	.90	.00077	.010	.592	.027	.565	.079	11.9
6/12/76	11.2	.91	.84	.00081	.010	.535	.029	.507	.076	12.0
6/12/76	10.5	.89	.81	.00082	.0090	.505	.029	.476	.075	11.9
6/12/76	9.64	.86	.76	.00082	.0066	.458	.029	.429	.072	11.9
6/12/76	8.50	.83	.70	.00077	.0052	.407	.026	.381	.069	12.0
6/13/76	6.55	.76	.59	.00049	.0017	.314	.014	.300	.064	11.9
6/14/76	4.97	.69	.50	.00041	.0014	.242	.010	.231	.059	11.8
6/14/76	4.65	.67	.47	.00053	.0012	.220	.015	.206	.057	11.8
6/15/76	3.87	.64	.42	.00066	.0002	.188	.020	.168	.054	11.9
6/15/76	3.44	.61	.39	.00088	.0002	.167	.029	.137	.052	11.3
6/16/76	4.97	.69	.50	.00050	.0006	.242	.014	.228	.059	11.8
6/18/76	3.90	.63	.42	.00042	.0004	.185	.011	.175	.054	11.7
6/19/76	4.20	.65	.44	.00044	.0006	.200	.011	.189	.055	11.8
6/20/76	4.57	.67	.47	.00043	.0014	.220	.011	.209	.057	11.8
6/21/76	9.53	.86	.76	.00068	.011	.458	.022	.435	.072	11.9

Table 3. Bedload data and hydraulic parameters measured at the bedload trap, East Fork River, Wyoming, 1973-79—Continued

Date	Q (m^3/s)	u (m/s)	d (m)	D_{50} (m)	i_b (kg/m•s)	ω (kg/m•s)	ω_0 (kg/m•s)	$\omega-\omega_0$ (kg/m•s)	u_* (m/s)	u/u_*
					1978					
5/24/78	9.21	0.84	0.75	0.00079	0.045	0.441	0.027	0.414	0.072	11.7
5/25/78	8.38	.80	.71	.00096	.058	.401	.035	.365	.070	11.6
5/26/78	7.47	.77	.67	.00109	.028	.357	.042	.315	.068	11.4
5/27/78	7.52	.77	.67	.00107	.020	.360	.041	.319	.068	11.4
5/28/78	9.07	.83	.75	.00102	.019	.434	.039	.395	.072	11.6
5/28/78	8.65	.82	.72	.00088	.014	.413	.031	.382	.070	11.7
6/07/78	20.5	1.14	1.23	.00145	.060	.982	.067	.915	.092	12.4
6/08/78	26.3	1.26	1.43	.00144	.080	1.26	.067	1.19	.099	12.7
6/09/78	27.8	1.28	1.48	.00148	.085	1.33	.070	1.26	.101	12.7
6/10/78	30.7	1.33	1.58	.00143	.082	1.47	.067	1.40	.104	12.8
6/14/78	26.8	1.27	1.45	.00090	.067	1.28	.035	1.25	.100	12.7
6/15/78	26.5	1.26	1.44	.00117	.046	1.27	.050	1.22	.099	12.7
6/16/78	26.0	1.25	1.42	.00136	.037	1.24	.062	1.18	.099	12.7
6/21/78	15.4	1.02	1.03	.00092	.015	.735	.035	.700	.084	12.1
6/24/78	19.6	1.12	1.20	.00120	.040	.939	.051	.888	.091	12.3
6/25/78	17.6	1.07	1.12	.00138	.043	.842	.063	.781	.088	12.2
6/25/78	17.9	1.08	1.13	.00138	.035	.854	.062	.792	.088	12.3
6/29/78	13.5	.97	.95	.00122	.012	.648	.051	.559	.081	12.0
6/29/78	14.1	.99	.98	.00087	.018	.679	.032	.647	.082	12.1
6/29/78	13.7	.98	.96	.00125	.021	.659	.053	.606	.081	12.1
6/30/78	13.7	.98	.96	.00125	.023	.654	.053	.601	.081	12.1
6/30/78	13.9	.98	.97	.00117	.021	.665	.048	.617	.082	12.0
					1979					
5/20/79	10.9	.87	.85	.00077	.052	.518	.027	.491	.076	11.4
5/21/79	12.6	.92	.94	.00094	.071	.605	.035	.570	.080	11.4
5/23/79	20.9	1.09	1.31	.00138	.069	.999	.063	.937	.095	11.5
5/24/79	22.8	1.13	1.38	.00130	.049	1.09	.058	1.03	.097	11.6
5/25/79	21.8	1.11	1.34	.00149	.048	1.04	.070	.971	.096	11.6
5/26/79	22.0	1.11	1.35	.00147	.032	1.05	.069	.980	.096	11.5
5/27/79	28.5	1.22	1.60	.00171	.048	1.37	.086	1.28	.105	11.6
5/28/79	26.2	1.18	1.51	.00111	.026	1.25	.047	1.20	.102	11.6
5/30/79	17.2	1.02	1.14	.00100	.013	.814	.039	.774	.088	11.5
5/31/79	8.48	.80	.72	.00085	.004	.403	.030	.373	.070	11.4
6/01/79	5.77	.71	.56	.00050	.0002	.278	.014	.264	.062	11.4

Table 3. Bedload data and hydraulic parameters measured at the bedload trap, East Fork River, Wyoming, 1973-79—Continued

Date	Q (m^3/s)	u (m/s)	d (m)	D_{50} (m)	i_b (kg/m·s)	ω (kg/m·s)	ω_0 (kg/m·s)	$\omega-\omega_0$ (kg/m·s)	u_* (m/s)	u/u_*
					1979—Continued					
6/04/79	8.42	0.80	0.72	0.00047	0.002	0.403	0.013	0.390	0.070	11.4
6/05/79	13.0	.93	.95	.00047	.006	.618	.013	.605	.081	11.5
6/06/79	14.8	.97	1.04	.00050	.009	.706	.015	.691	.084	11.5
6/07/79	13.0	.93	.95	.00050	.018	.618	.015	.603	.081	11.5
6/08/79	6.95	.75	.63	.00103	.009	.331	.039	.292	.065	11.4
6/13/79	12.2	.91	.91	.00067	.013	.580	.022	.558	.079	11.5
6/14/79	15.5	.99	1.07	.00122	.026	.741	.052	.689	.085	11.5
6/15/79	14.0	.95	1.00	.00100	.025	.665	.039	.626	.083	11.5
6/16/79	8.26	.80	.71	.00079	.012	.398	.038	.360	.070	11.4
6/17/79	6.71	.74	.62	.00094	.008	.321	.034	.287	.065	11.3

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