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Literature Review for Texas Department of Transportation Research Project 0–4695: Guidance for Design in Areas of Extreme Bed-Load Mobility, Edwards Plateau, Texas

Open-File Report 2005–1234
(TxDOT Research Report 0–4695–1)

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16. Abstract

A review of the literature addressing sediment transport in gravel-bed river systems and structures designed to control bed-load mobility is provided as part of Texas Department of Transportation research project 0–4695: Guidance for Design in Areas of Extreme Bed-Load Mobility. The study area comprises the western half of the Edwards Plateau in central Texas. Three primary foci of the literature review are journal articles, edited volumes, and government publications. Major themes within the body of literature include deterministic sediment transport theory and equations, development of methods to measure and analyze fluvial sediment, applications and development of theory in natural channels and flume experiments, and recommendations for river management and structural design. The literature review provides an outline and foundation for the research project to characterize extreme bed-load mobility in rivers and streams across the study area. The literature review also provides a basis upon which potential modifications to low-water stream-crossing design in the study area can be made.

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Conversion Factors

The literature reviewed uses inch/pound (U.S. customary) and SI (metric) units of measurement. The authors have explicitly chosen to remain consistent with the original references in respect to the principal unit of measurement used. Furthermore, units are not abbreviated within the text.

Factors for converting inch/pound units to SI units:

Multiply	By	To obtain
cubic foot	0.01832	cubic meter
cubic foot per second	0.01832	cubic meter per second
foot	0.3048	meter
foot per second	0.3048	meter per second
inch	25.40	millimeter
mile	1.609	kilometer
pound (mass) per foot	1.488	kilogram per meter

Temperature in degrees Fahrenheit (°F) is converted to degrees Celsius (°C) as follows:

°C = (°F - 32)/1.8

Factors for converting SI units to inch/pound units:

Multiply	By	To obtain
centimeter	0.3937	inch
cubic meter	35.31	cubic foot
cubic meter per second	35.31	cubic foot per second
gram per liter	0.062427	pound per cubic foot
kilometer	0.6214	mile
meter	3.281	foot
millimeter	0.03937	inch
millimeter per hour	0.03937	inch per hour
newton per square meter	0.020885	pound (force) per square foot
square kilometer	0.3861	square mile

Temperature in degrees Celsius (°C) is converted to degrees Fahrenheit (°F) as follows:

°F = (1.8 x °C) + 32

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Literature Review for Texas Department of Transportation Research Project 0–4695: Guidance for Design in Areas of Extreme Bed-Load Mobility, Edwards Plateau, Texas

By Franklin T. Heitmuller[1], William H. Asquith[1], Xing Fang[2], David B. Thompson[3], and Keh-Han Wang[4]

Abstract

A review of the literature addressing sediment transport in gravel-bed river systems and structures designed to control bed-load mobility is provided as part of Texas Department of Transportation research project 0–4695: Guidance for Design in Areas of Extreme Bed-Load Mobility. The study area comprises Edwards, Kimble, and Real Counties in the Edwards Plateau in central Texas. The primary focus of the literature review is on journal articles, edited volumes, and government publications. The literature review provides an outline and foundation for the research project to characterize extreme bed-load mobility in rivers and streams across the study area. The literature review also provides a basis for potential modifications to low-water stream-crossing design in the study area. Major themes within the body of literature include deterministic sediment transport theory and equations, development of methods to measure and analyze fluvial sediment, applications and development of theory in natural channels and flume experiments, and recommendations for river management and structural design. A variety of methods are used to study gravel-bed river characteristics, including surveying channel geometry, particle tracing, bed-material and bed-load sampling, and developing sediment discharge rating curves, among others. Additionally, efforts to manipulate the transport of sediment in gravel-bed rivers include construction of debris traps, velocity control structures, or flow diversion structures. Extensive collection and analysis of field and geographic data, and subsequent parameterization of numerical and physical models, is the most appropriate approach to understanding bed-load transport and structural design in the Edwards Plateau.

[1] U.S. Geological Survey, Austin, Texas
[2] Lamar University, Beaumont, Texas
[3] Texas Tech University, Lubbock, Texas
[4] University of Houston, Houston, Texas

Introduction

Gravel-bed rivers are inherently dynamic features and provide a unique challenge for engineers and river management specialists. Activities in gravel-bed rivers can span a wide spectrum of scales, from culvert design to river restoration. A successful investigation of gravel-bed rivers must consider flow processes, sediment characteristics and transport, and channel adjustment potential. Extensive research of the physical characteristics and processes of gravel-bed rivers has been conducted by hydraulic engineers, geomorphologists, hydrologists, and stream ecologists. This research has produced a large body of literature in numerous books and journals specific to particular disciplines. In spite of the difficulties encountered in understanding and predicting form and process in gravel-bed rivers, an appreciable knowledge of the system components is available. In some cases, desired results of engineering and river management activities along gravel-bed rivers have been achieved. The successful implementation of a project involving gravel-bed rivers requires knowledge of the existing research literature.

A consortium of researchers at Texas Tech University, Lamar University, the University of Houston, and the U.S. Geological Survey (USGS) was selected to research the bed-load phenomena as part of Texas Department of Transportation (TxDOT) research project 0–4695: Guidance for Design in Areas of Extreme Bed-Load Mobility. This project was initiated to address the considerable reconfiguration of gravel during high-magnitude flows and the associated structural problems and maintenance along low-water (road) crossings (LWCs) in the study area. The study area (fig. 1) for the project comprises Edwards, Kimble, and Real Counties in the Edwards Plateau in central Texas. A major project objective was the assessment of the literature. A summary of the literature review is provided in this report. The primary focus for the university researchers are journal articles and books; whereas the USGS researchers focused on government documents.

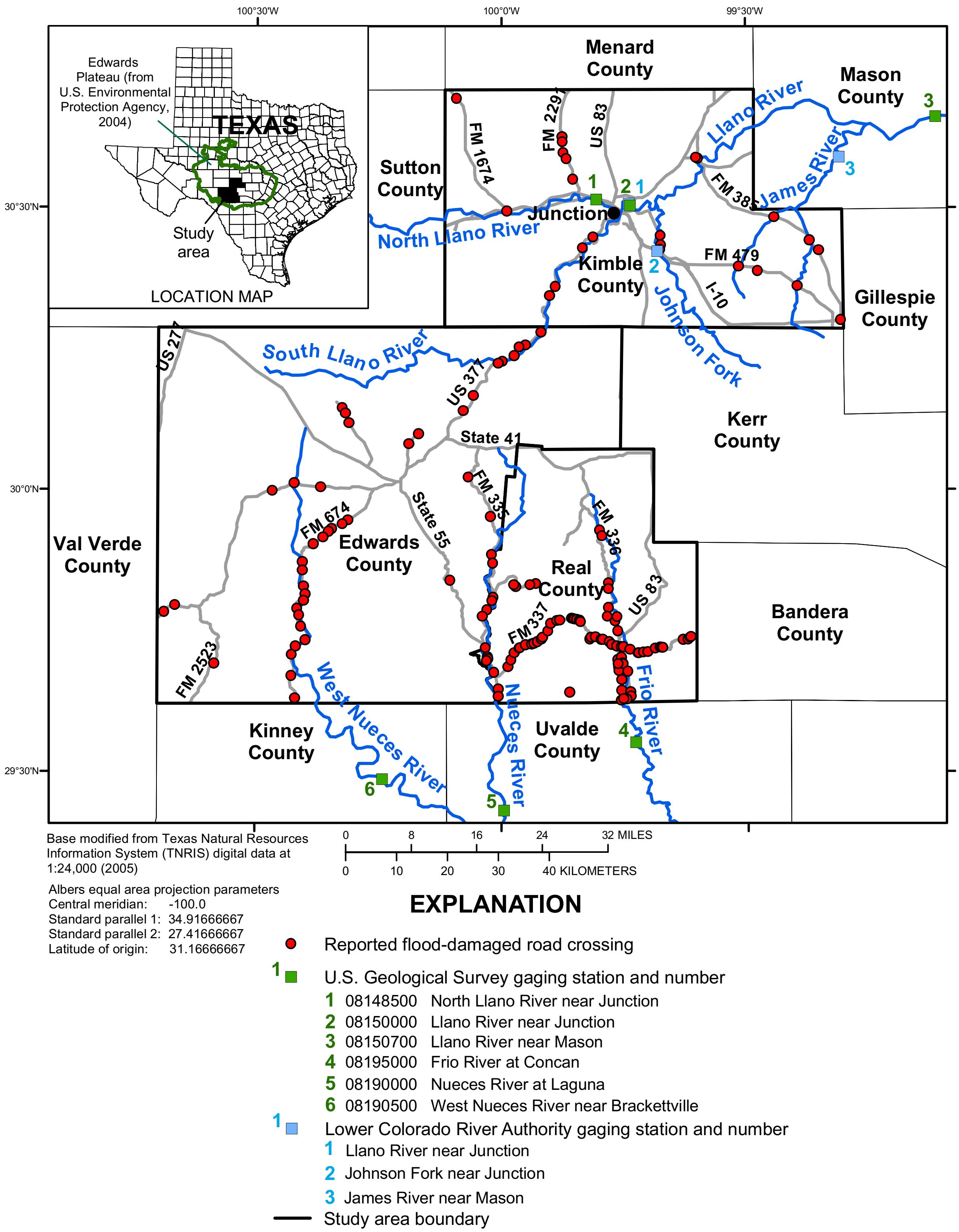


Figure 1. Study area for Texas Department of Transportation research project 0–4695.

Low-water crossings are low-height structures that provide acceptable passage as stream crossings over seasonal rivers or streams with relatively low normal-depth flow and are designed to allow flooding during high flow events. LWCs are a common alternative to traditional bridges in rural areas and along road segments expected to receive low maintenance because they generally are less expensive to design and build (Molauskas, 1988; Pienaar and Visser, 1995; and Lohnes and others, 2001). In areas that experience substantial bed mobility, LWCs built with no provision of debris-flow management during high streamflow rates are subject to structural erosion, sediment clogging, burial under several feet of debris, and complete structural washout.

Numerous LWCs have been built within the Edwards Plateau region of central Texas. During flood flow, LWCs often are buried under several to tens of feet of sediment, and the culverts are clogged with gravel- and cobble-size material. Additional damages include severe and rapid abrasion of the concrete culvert parapet and the pavement. Structural failure on relatively small LWCs, which originally was anticipated to have limited hydraulic effect on streams, has occurred as recently as the June 2004 flood on the Plateau.

The purpose of this report is to provide a review of the relevant literature through an annotated bibliography and additional description for some of the more informative citations. Furthermore, this literature review documents and synthesizes the extensive body of literature associated with the characteristics, entrainment, and transport of sediment in gravel-bed rivers as well as structural modifications to control sediment mobility. This work serves as a reference for researchers and engineers to increase their understanding of gravel-bed river morphology and sediment transport phenomena. Although very few publications directly address the defined problem at LWCs, many are of benefit to this investigation, such as structural designs to minimize adverse affects of debris flows. This literature review incorporates different subjects applicable to the problem. Most of the literature consists of journal articles, chapters in edited volumes, and government documents. For readers new to the topic, textbooks covering fluvial geomorphology, surface-water hydrology, and the principles of open-channel flow also are recommended. Not all references listed in this report were reviewed because of the large volume of available literature. References deemed most pertinent to the project scope were thoroughly reviewed and are summarized in pages preceding the bibliography.

Detailed Literature Review of Selected References

Although a wide variety of journals contain articles on sediment transport in gravel-bed rivers, a handful distinguish themselves as the preeminent sources for this type of information, including *Bulletin of the Geological Society of America*; *Earth Surface Processes and Landforms*; *Geomorphology*; *Journal of Geology*; *Journal of Hydraulic Engineering* (*Journal of the Hydraulics Division*); *Journal of Hydrology*; *Sedimentology*; and *Water Resources Research*. The emphasis of journal articles tends toward the development of theories defining the controls of gravel entrainment and movement, resultant depositional forms, channel adjustment to the sediment regime, and structural designs to control sediment mobility. Five edited volumes on gravel-bed rivers include Hey and others (1982), Thorne and others (1987), Billi and others (1992), Klingeman and others (1998), and Mosley (2001). These volumes contain a variety of chapters discussing sediment transport theory and research methods. Finally, U.S. government documents that pertain to sediment transport in gravel-bed rivers are most frequently published by the USGS and the U.S. Army Corps of Engineers. Early government publications introduced theories of bed-load transport and channel adjustment, and more recent publications discuss project applications involving bed-load transport and provide methodological guidance.

Literature Reviews by Lamar University Researchers

Sediment Transport Mechanism in Gravel-Bed Rivers

The definition of "sediment transport" is the transport of granular particles by fluid. As such, it embodies a type of two-phase flow, where one is fluid and the other is a solid composed of granular particles. Flow condition, grain-size distribution, and boundary shear stress are the main factors affecting the sediment transport mechanism. Gravel-bed streams usually have a bed surface, referred to as "pavement," markedly coarser than the substrate (Milhous, 1973; Parker, Klingeman, and McLean, 1982). Although the name may be misleading, pavement is mobile and differs from an immobile armored layer. The grain-size distribution for Oak Creek in Oregon is listed in table 1, and

Table 1. Grain-size range for Oak Creek in Oregon (from Parker, Dhamotharan, and Stefan, 1982).

[mm, millimeters; f_i, subpavement; f_{pi}, surface pavement; <, less than; --, no data]

Range (mm)	Grain diameter (mm)	f_i (percent)	f_{pi} (percent)
203–102	152	0	7.7
102–76	88.9	4	18.4
76–51	63.5	15	26.4
51–38	44.4	10	13.0
38–25	31.8	15	12.8
25–19	22.2	6.5	6.7
19–9.5	14.3	13	6.1
9.5–4.8	7.14	11.5	3.5
4.8–2.4	3.57	10	1.8
2.4–1.2	1.79	8	1.1
1.2–.59	.890	4	.9
.59–.30	.444	1.9	1.0
.30–.15	.223	.7	.3
.15–.74	.112	.2	.2
<.74	--	.2	.1

the data confirm that surface pavement has much coarser sediment than subpavement. Table 2 lists pavement and subpavement data for several gravel-bed rivers; median grain diameters of pavement ranged from 44 to 76 millimeters. Typical flow conditions in several gravel-bed rivers previously examined are listed in table 3 (Hollingshead, 1971; Jones and Seitz, 1980). The beds of paved streams require only infrequent flow conditions to activate the bed motion; therefore, the bed is active for at least several days in most years (Parker, Klingeman, and McLean, 1982). Milhous (1973) determined that the pavement is first “broken” at a critical water discharge of about 1.1 cubic meters per second (about 40 cubic feet per second). During such periods, all or nearly all sizes, including the coarsest pavement grains, often are found in motion (Hollingshead, 1971; Milhous, 1973). Many gravel-bed streams can transport essentially all available grain sizes during sufficiently large floods and yet show the same pavement at low flow (Parker and Klingeman, 1982). Parker and Klingeman (1982) propose two hypotheses:

Table 2. Pavement and subpavement data for several gravel-bed rivers (from Parker, Dhamotharan, and Stefan, 1982).

[mm, millimeters; D_{90}, grain size at which 90 percent of sediment is finer; D_{50}, grain size at which 50 percent of sediment is finer; *, sand bars on top of the pavement are frequent.]

Stream name	Pavement D_{90} (mm)	Pavement D_{50} (mm)	Bed material D_{50} (mm)	Percent sand in bed
Oak Creek	86	54	20	12
Elbow River	132	76	28	67
Snake River	137	54	27	14*
Clearwater River	143	72	18	19*
Vedder River	90	44	19	16

Table 3. Typical flow conditions in several gravel-bed rivers (from Parker, Dhamotharan, and Stefan, 1982).

[m, meters; ft^3/s, cubic feet per second]

Stream name	Water-surface slope	Water-surface width (m)	Average depth or hydraulic radius (m)	Discharge (ft^3/s)
Oak Creek	0.0097–0.0108	5.0–6.1	0.31–0.45	1.16–3.40
Elbow River	.00745	38–49	0.64–0.86	35–109
Snake River	.00094–.00121	184–198	4.6–5.9	2,200–3,500
Clearwater River	.00035–.00062	142–149	4.9–6.4	1,500–3,100
Vedder River	.00195	85–90	1.34–1.66	216–370

1. During floods capable of moving pavement grains, the pavement ceases to exist or is greatly modified. As flow wanes, it reforms.

2. Pavement is present even during floods capable of moving all available grains. Its structure during such floods differs little from that at low flow.

Parker, Klingeman, and McLean (1982) conducted experiments that show that the second hypothesis is the correct one. Pavement formed readily and could be maintained indefinitely under constant flows, even though all grain sizes were represented in the bed load. In other words, pavement is a mobile bed phenomena (Parker and Klingeman, 1982). Parker and Klingeman (1982) state that pavement is a regulator that enables a stream to transport the coarse one-half and fine one-half of its bed-load supply at equal rate. More specially, pavement forms just so as to render all available grain sizes of nearly equal mobility. Parker and Klingeman (1982) state that if the size distributions of bed load and bed material are almost similar, the coarse one-half of the subpavement could move through the reach at the same rate as the fine one-half if a reach is to be in equilibrium.

Parker and Klingeman (1982) consider a phenomenon called “hiding,” previously noted by Einstein (1950) and Egiazaroff (1965). The “microscopic” hiding depends on the relative placement of individual grains. The isolated protrusions offered by coarser surface grains in a mixture render them more mobile than they are in a uniform sediment composed exclusively of the coarse size (Parker and Klingeman, 1982). It means that in a mixture, due to microscopic hiding, finer surface grains are less mobile, and coarse grains are more mobile in comparison to a uniform sediment condition. Microscopic hiding helps reduce the intrinsic difference in mobility between coarser and finer surface grains (Parker and Klingeman, 1982). The surface pavement also provides a macroscopic hiding effect, so that gravel-bed streams eliminate the remaining mobility difference by means of the pavement itself. No matter what percentage of finer grains of a given size are stored in the subpavement, none can be entrained if none are contained in the pavement (Parker and Klingeman, 1982). The authors also explain the vertical winnowing of fine particles. Each time a large grain is dislodged, it leaves a “hole” of comparable size in the bed. Small grains that fall into the hole might work their way below the pavement and reduce their probability of re-erosion. This was also described by Milhous (1973).

Parker, Klingeman, and McLean (1982) use similarity analysis to study the size distribution in paved gravel-bed streams and conclude that all grain-size ranges are of about equal transportability when the critical condition for breaking the pavement is exceeded. When discharge exceeds the critical value, more and more of the pavement is moved, exposing the finer gravels below and making them available for transport. Bed-load transport is governed by hydraulic conditions rather than availability.

Parker, Dhamotharan, and Stefan (1982) performed laboratory experiments with a poorly sorted gravel bed and intended to provide a mechanistic model for two paved streams

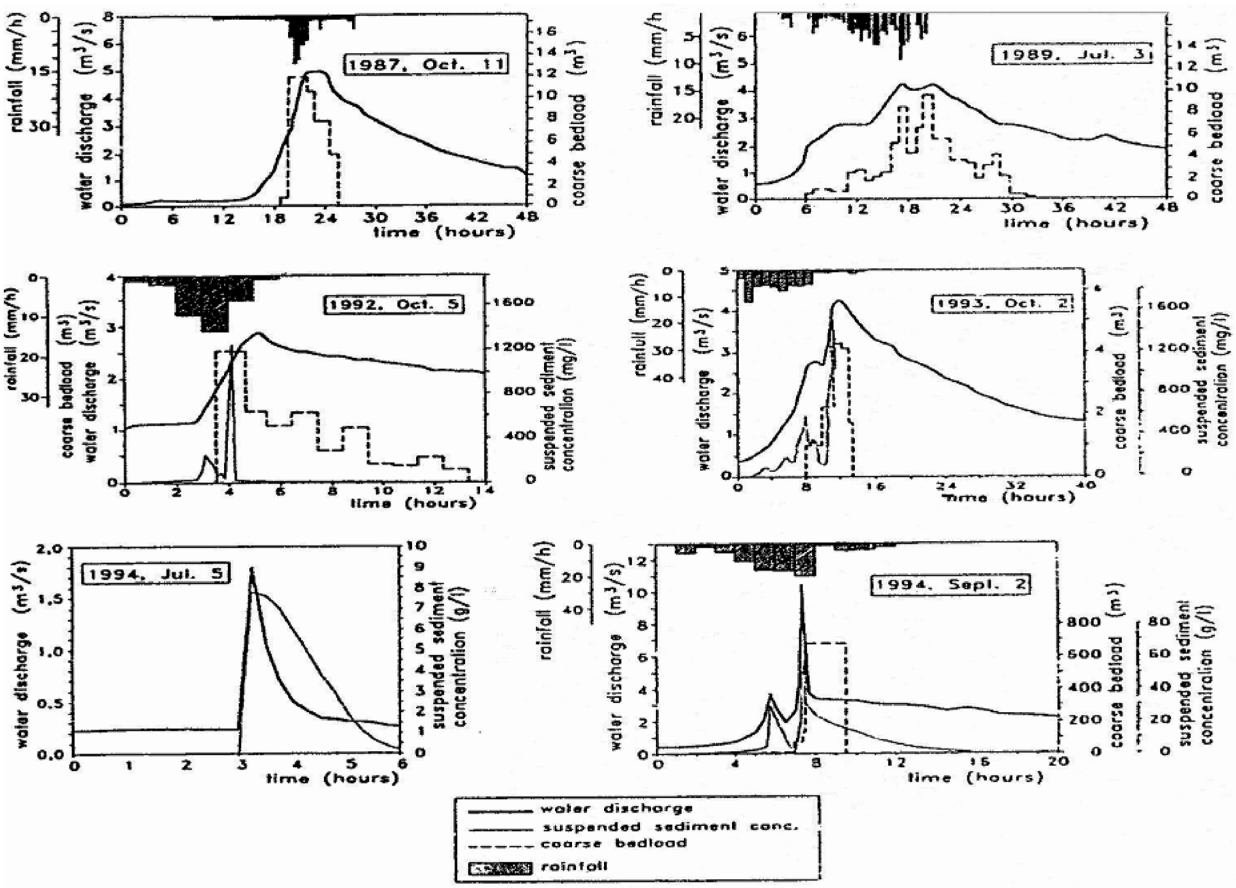


Figure 2. Rainfall hyetographs, streamflow hydrographs, and sediment transport rates for recorded floods (from Billi and others, 1998).

for which bed load had been measured. These streams are the Elbow River in Alberta, Canada (Hollingshead, 1968) and Oak Creek in Oregon (Milhous, 1973). Both have a steep downstream water-surface slope (S) (0.0075, Elbow River; 0.010, Oak Creek). The results reveal that pavement is a mobile bed phenomenon, but the pavement can coexist with the motion of all available grain sizes. Because of its episodic or sporadic motion, at any given time only a small percentage of surface grains are actually in motion. Therefore, particles in the immediate subpavement are only occasionally mobilized and deeper particles are rarely moved, even during floods. It was found that pavement imbrication is ubiquitous, even though pavement and bed load exchange with each other; at higher flow there was weak formation of bars.

Kuhnle (1992) documents bed-load transport during rising and falling stages on two small streams. At higher flow strengths, mean bed-load transport rates were greater during rising stages than during falling stages. One of the streams showed evidence for greater transport rates for low flows as the stage declined. However, experiments from Sutherland and coworkers (Griffiths and Sutherland, 1977; Bell and Sutherland, 1983; and Phillips and Sutherland, 1989, 1990) show that unsteady flow does not affect the rate of bed-load transport unless the bed is degrading.

Billi and others (1998) investigate channel morphology processes and bed load in a high altitude alpine torrent in the Rio Cordon catchment. The authors use sediment transport measurements to study relations between slope erosion processes, bed morphology adjustment, and sediment transport. The study area has the following characteristics: watershed area, 52.0 square kilometers; main channel slope, 17 percent; annual precipitation, 1,100 millimeters; and average annual temperature, 2.0 °C.

Table 4 lists sediment transport values from eight floods (Billi and others, 1998). Peak discharges range from 1.8 to 10.4 cubic meters per second (or 64 to 370 cubic feet per second), two critical discharges for bed-load entrainment occur at 2 cubic meters per second (or 70 cubic feet per second), and median particle size of coarse bed load (D_{50}) ranges from 25.8 to 82.6 millimeters (1.0 to 3.3 inches). Figure 2 depicts hyetographs, hydrographs, coarse bed load, and suspended load during the floods. The flood on September 14, 1994, the most severe flood recorded, was caused mostly by high intensity rainfall (maximum rainfall rate 7.2 millimeters/5 minutes, 16.4 millimeters/15 minutes, and 25.3 millimeters/30 minutes). The recurrence interval was assessed to be between 35 and 50 years. Two flood waves occurred, with the second having a higher peak discharge (10 cubic meters per second). The volume of

Table 4. Hydrologic, hydraulic, and sediment data of recorded floods (modified from Billi and others, 1998).

[m^3, cubic meters; m^3/s, cubic meters per second; h, hours; m^3/h, cubic meters per hour; mm, millimeters; g/L, grams per liter; (1)(2), first and second part of flood; --, not available; [ ], assessed value]

Sediment transport characteristic[1]	Oct. 11, 1987	July 3, 1989	June 17, 1991	Oct. 5, 1992	Oct. 2, 1993	May 19, 1994	July 18, 1994	Sept. 14, 1994 (1)	Sept. 14, 1994 (2)
$R_e(10^3m^3)$	79.90	103.36	57.89	21.52	30.69	5.41	0	4.71	21.93
$Q_p(m^3/s)$	5.15	4.4	4.0	2.9	4.3	1.80	1.8	3.74	10.4
$Y_b(m^3)$	50.0	85.0	39.0	9.3	10.2	1.00	0	10	890
T(h)	8	27	20	10	[6]	12	0	1.42	2.75
$Q_b(m^3/h)$	6.25	3.15	1.95	.93	[1.7]	.08	0	7	323.6
D_{50}(mm)	--	82.5	35.5	31.1	43.1	25.8	--	--	82.6
D_{84}(mm)	--	152.0	64.0	77.0	96.0	37.0	--	--	168.0
D_{90}(mm)	--	173.0	84.0	117.0	133.0	43.5	--	--	207.0
$Q_{cr1}(m^3/s)$	1.8	2.2	[2.0]	1.9	[2.3]	1.60	--	1.8	1.8
$Q_{cr2}(m^3/s)$	3.8	2.7	[2.4]	2.1	[3.7]	1.61	--	1.8	3.3
C_{max}(g/L)	--	--	--	1.2	1.65	.1	7.8	30	58

[1]Definition of symbols:

R_e = effective runoff;
Q_p = peak discharge;
Y_b = deposited volume of coarse bed load;
T = bed-load transport duration;
Q_b = average transport rate of coarse bed load;
D_{50} = median particle size of coarse bed load;
D_{84}, D_{90} = particle sizes for which 84 and 90 percent, respectively, of coarse bed-load material is finer;
Q_{cr1} = discharge at bed-load entrainment;
Q_{cr2} = discharge at bed-load transport end;
C_{max} = maximum suspended sediment concentration.

coarse sediment transported was about 900 cubic meters, much larger than the volumes measured for the previous floods, which commonly were less than 100 cubic meters. It also was observed that bed-load transport occurs at two different scales of magnitude. Typical bed loads are associated with peak flow discharges less than 5 cubic meters per second with a return period not exceeding 5 years and bed-load transport rates of 7 cubic meters per hour. During larger floods with return period exceeding 30 years, the bed-load transport rate is as much as 324 cubic meters per hour, or 50 times the transport of a typical bed load.

Sechet and Le Guennec (1999) introduce the bursting phenomenon concept associated with the incipient motion of the solid particles in bed-load transport. They conducted an experiment to visualize the displacement of solid particles on the smooth bottom of a hydraulic channel and calculated trajectories with the laser doppler anemometry measurement of the instantaneous velocity near the bottom. Sechet and Le Guennec (1999) conclude that there coexist two transport modes at the wall: one is transport by sweeps and the other is through ejection. Transport by the ejection has the dominating effect, and the particle transport by sweeps needs further investigation.

McEwan and Heald (2001) examined the stability of randomly deposited sediment beds by using a discrete particle model in which individual grains are represented by spheres. The results indicate that the threshold or critical entrainment shear stress for cohesionless uniform size sediments in flat beds cannot be adequately described by a single-value parameter; rather, it is best represented by a distribution of values. They state that a distinct threshold for the initiation of motion does not exist but a value of 0.06 traditionally has represented the threshold condition for the uniform size sediment. There are two types of sheltering that occur in the sediment bed: direct sheltering and remote sheltering. In the case of direct sheltering, particles upon which a particular grain is resting reduce the grain's effective area and, hence, alter the fluid force acting upon it. This condition will remain as long as the grain is static in its resting condition. Remote sheltering is a consequence of non-uniformity of the bed flow that occurs over complex roughness. For remote sheltering, other upstream particles, potentially located a number of diameters upstream, modify the fluid velocity in the vicinity of the grain and, hence, influence the fluid forces acting on it. They also state that remote sheltering and direct sheltering, the supporting grain arrangement, and the influence of remote sheltering by upstream grains dominate the critical shear stress distribution. Direct sheltering is less influential, comparatively.

Parker and Toro-Escobar (2002) conclude that there are two hypotheses on the concept of equal mobility of gravel transport. The weak hypothesis states that to transport the coarse one-half of the mean annual gravel load through a river reach at a rate equal to the fine one-half, the coarse material must be overrepresented on the bed surface, giving rise to mobile bed armor. The strong hypothesis states that the grain-size distribution of the gravel portion of the bed load should be similar to that of the substrate and finer than that of the surface layer. A rigorous test in the laboratory under some controlled conditions, which is almost similar to the field condition, was conducted. The results of the experiment strongly support the weak hypothesis; the surface layer was substantially coarser than the bed-load material. The strong hypothesis is also supported by the experiment, in that the size distribution of the "gravel" substrate was nearly identical to the size distribution of the "gravel" portion of the load (Parker and Toro-Escobar, 2002). The gravel substrate was, however, slightly but measurably coarser than the gravel load, a tendency that has been observed in the field (Parker and Toro-Escobar, 2002).

Hydraulic Geometry of Gravel-Bed Rivers

Parker (1979) discusses active gravel rivers that satisfy the following criteria: (1) channel is straight and laterally symmetrical; (2) perimeter is composed of loose, coarse gravel that is of similar composition in both bed and banks and that cannot be suspended; (3) most particles, including those much coarser than median size, are mobile at bankfull or dominant conditions; and (4) self-formed channel has stable width and is in grade. Parker (1979) reveals that wide gravel-bed rivers have larger loads in comparison to the narrow channels. The relations regarding the effect of bed-load material on channel geometry and vice versa are given by the following equations.

$$Q^* = \frac{Q_s}{D_{50}^2\sqrt{\lambda g D_{50}}} = 1.02\times10^{-5}{H^*_c}^{0.275}B^*, \quad (1)$$

$$H^*_c = 0.866\left(\frac{\bar{Q}}{B^*}\right)^{0.830}, \text{ and} \quad (2)$$

$$H^*_c = 0.0553S^{-1.013}, \quad (3)$$

where Q_s is the volumetric gravel discharge of bed material; $\lambda = \rho_s/(\rho - 1)$ is the submerged specific gravity of the sediment with ρ and ρ_s as densities of water and sediment; g is the acceleration of gravity; D_{50} is the median grain diameter at the surface pavement layer; $H^*_c = H_c/D_{50}$ is the dimensionless depth at the channel central region; $B^* = B/D_{50}$ is the dimensionless channel width; and $\bar{Q} = Q/(\sqrt{\lambda g D_{50}}D_{50}^2)$ is the dimensionless water discharge.

Sediment Transport Equations for Gravel-Bed Rivers

Four principal approaches have emerged in the design of bed-load transport equations (Gomez and Church, 1989), on the basis of bed shear stress (DuBoys, 1879), stream discharge (Schoklitsch, 1934), stochastic functions for sediment movement (Einstein, 1950), or stream power (Bagnold, 1980). A formal or theoretical relation was derived to link the bed-load transport rate to hydraulic and sedimentological quantities from field data, laboratory data, or mechanical/physical principals. Many equations have been modified in light of their performance against data not included in the initial analysis. Most of the equations have been assessed tentatively on the basis of limited amount of field data. No completely adequate methodology has been developed to assist the investigator in selecting the best equation for a particular hydraulic and sediment condition. If no sediment transport information is available for a river, none of the selected equations are capable of generally predicting bed-load transport in gravel-bed rivers (Gomez and Church, 1989). Several recent equations that have been reviewed and summarized follow.

Parker, Klingeman, and McLean (1982) analyzed data from Oak Creek and conclude that for conditions in excess of the critical stress of the pavement, the bed-load size distribution is to a first-order approximation the same as the subpavement size distribution. Empirical relations for total bed-load material as a function of shear stress and subpavement median size were developed for poorly sorted gravel-bed streams. The dimensionless bed load (W_i^*) and shear stress (τ_i^*) for the *i*th size range are defined as:

$$W_i^* = \frac{\lambda g q_{Bi}}{f_i(\tau/\rho)^{3/2}} = \frac{\lambda q_{Bi}}{f_i\sqrt{g}(dS)^{3/2}} = \frac{q_{Bi}^*}{(\tau_i^*)^{3/2}}, \quad (4)$$

$$\tau_i^* = \frac{\tau}{\rho g \lambda D_i} = \frac{dS}{\lambda D_i}, \quad (5)$$

$$q_{Bi}^* = \frac{q_{Bi}}{f_i\sqrt{\lambda g D_i}D_i}, \text{ and} \quad (6)$$

$$\tau = \rho g d S, \quad (7)$$

where q_{Bi} is volumetric bed-load transport rate per unit channel width; f_i is fraction of the bed material; D_i is typical (mean) grain size, for *i* size range of bed load; *d* is the hydraulics radius or cross-sectionally averaged depth; $\lambda = (\rho_s/\rho - 1)$ is the submerged specific gravity of the sediment; and *S* is the downstream slope of energy grade line. After integration of all size ranges, the total bed-load relation is only a function of the subpavement median grain size.

$$W^* = 0.0025\exp[14.2(\phi_{50} - 1) - 9.28(\phi_{50} - 1)^2] \text{ for } 0.95 < \phi_{50} < 1.65, \text{ and} \quad (8)$$

$$W^* = 11.2(1 - 0.822/\phi_{50})^{4.5} \text{ for } \phi_{50} > 1.65, \quad (9)$$

where $\phi_{50} = \tau_{50}^*/\tau_{r50}^*$ is the normalized Shields stress; the reference value τ_{r50}^* was 0.0876 (Parker, Dhamotharan, and Stefan, 1982), which is associated with the reference W_i^* of 0.002. The substrate-based bed-load relation above strictly applies only to near-equilibrium mobile-bed conditions. It is useful for rough estimates of gravel yield even in disequilibrium conditions (Parker, 1990). A substrate-based relation is not suited to the computation of selective sorting driven by disequilibrium.

Parker and Klingeman (1982) introduce the relative mobility of different uniform materials. The relative mobility analysis reveals that, for the range of stresses typical of field gravel-bed streams, uniform coarser material is substantially less mobile than uniform finer material at the same fluid stress. However, when dimensionless Shields stress is greater than the critical Shields stress, the relative mobility is more or less independent of the grain-size ratio; therefore, approximate equal mobility is attained (Parker and Klingeman, 1982). The dimensionless bed load was normalized to be a function of the normalized Shields stress as:

$$W^*/W^*_{ref} = G(\phi) = G(\tau^*/\tau^*_r)$$
$$5.6\times10^3(1-0.853/\phi)^{4.5}\text{, and} \quad (10)$$

$$\tau^*_r = 1.17\tau^*_c\,, \quad (11)$$

where τ^*_c is the critical Shields stress, and W^*_{ref} was 0.002 for Oak Creek data (Parker and Klingeman, 1982). The total bed-load computation is given as:

$$q_{Bi} = [f_i\sqrt{g}(dS)^{2/3}]W^*_{ref}G(\phi)/(\lambda g)\,. \quad (12)$$

Parker (1990) derives the surface-based bed-load transport equation for gravel-bed rivers by using the data from Oak Creek in Oregon, because mobilization of the grains takes place from the exposed bed surface and is caused by the fluid force on the exposed grains. Substrate can participate as bed load only under the condition of local or global scour. The surface-based bed-load relation developed by Parker (1990) is:

$$W^*_{si} =$$
$$0.00218G\left[g_s\left(\frac{D_i}{D_{50}}\right)\phi_{50}\right] = \quad , \quad (13)$$
$$0.00218G[\omega_o\phi_{sgo}g_o(\delta_i)]$$

$$\phi_{sgo} = \tau^*_{sg}/\tau^*_{rsgo} = \tau^*_{sg}/0.0386\,, \quad (14)$$

$$g_o(D_i/D_{sg}) = (D_i/D_{sg})^{-0.0951}\,, \quad (15)$$

$$G(\phi) = 5474(1-0.853/\phi)^{4.5} \text{ for } \phi > 1.59\,, \quad (16)$$

$$G(\phi) = \exp[14.2(\phi-1)-9.28(\phi-1)^2] \text{ for}$$
$$1 \le \phi \le 1.59\text{ , and} \quad (17)$$

$$G(\phi) = \phi^{14.2} \text{ for } \phi < 1\,, \quad (18)$$

where W^*_{si} is the dimensionless bed load for the *i*th size range of surface grains; g_s is a "reduced" hiding function; D_{sg} is the geometric mean surface size; and $\omega_o(\phi_{sgo})$ is a straining function ranging from 1.011 for very coarse grains to 0.453, for which the equilibrium surface layer is considerably finer and poorly sorted.

Gomez and Church (1989) test the performance of the 12 bed-load sediment transport equations for gravel-bed channels with seven sets of data (four sets of river data and three sets of flume data). Gomez and Church (1989) conclude that none of the equations performed consistently well. Of seven complete comparisons, only three equations account for successful mean comparison: (1) Schoklitsch (1934), (2) Bagnold (1980), and (3) Einstein (1950). The Bagnold (1980) formula is predominantly more successful in comparison to others. To understand the magnitude of bed-load transport on the basis of limited hydraulic information, the stream power equation should be used (Gomez and Church, 1989). When local transport estimates are required and local hydraulic information is available, an equation should be selected that is sensitive to bed state or grain-size distribution, including the Einstein (1950), Parker (1979), and Ackers and White (1973) equations.

Bakke and others (1999) calibrate the Parker and Klingeman (1982) model to minimize the variance and bias. The model carries several assumptions; one assumption is that the bed load is in equilibrium with the bed material, and the system is neither aggrading nor degrading. The pavement layer is formed to establish an equilibrium between the bed load and the bed material. Parker and Klingeman (1982) use the "hiding factor" to predict bed load. This helps increase the critical shear stress required for motion of the smaller particles compared to that for a uniform bed, which slows down the transfer of smaller particles. The hiding force is described by the simple relation:

$$\frac{\tau^*_{ri}}{\tau^*_{r50}} = \left(\frac{D_i}{D_{50}}\right)^h\,, \quad (19)$$

where τ^*_{ri} and τ^*_{r50} are the reference Shields stresses associated with subpavement D_i and D_{50}, and h = -0.982 for Oak Creek. Bakke and others (1999) indicate that h ranged from -0.907 to -0.974 on the basis of sediment-transport data from seven Klamath River Basin streams. The authors suggest a calibration of h with site-specific data for application of the Parker-Klingeman equation. Lopez and Garcia (2001) used a probabilistic approach to analyze sediment transport.

Laboratory Experiments for Gravel Transport

B. Hofland, a Ph.D. student in the Fluid Mechanics Section, Faculty of Civil Engineering and Geosciences, Delft University of Technology, The Netherlands, conducted a series of laboratory experiments to study pressure and velocity fluctuations around a granular-bed element. In the study, rocks are used to prevent scouring of the underlying bed material (fig. 3). The stability of stones in such a granular filter is usually evaluated by means of the non-dimensional bed shear stress or Shields factor. This factor is a measure of the mobility of the bed; if higher than a certain threshold, the bed protection is subject to damage (B. Hofland, Delft University of Technology, The Netherlands, written commun., 2001). However, if the flow is not an equilibrium boundary-layer flow, this approach (using only the mean bed shear stress) does not apply. A good example is the flow behind a backward-facing step. At the reattachment point, the mean bed shear stress vanishes. Nevertheless, many stones are entrained at this location, because of the increased level of turbulence (B. Hofland, Delft University of Technology, The Netherlands, written commun., 2001). Hofland's research was aimed at gaining more insight into the interaction between the turbulence structure and the forces on the stones to develop new (physically based) design criteria to select appropriate rock sizes to prevent scouring of the underlying bed material.

Figure 4. Side view of flume and laser doppler used in experiments of B. Hofland (Delft University of Technology, The Netherlands, written commun., 2001).

Figure 3. Flume with bed rocks used in experiments of B. Hofland (Delft University of Technology, The Netherlands, written commun., 2001).

To get a good picture of the flow processes near and in a granular bed, a number of accurate pressure sensors were used with a laser doppler (fig. 4) (B. Hofland, Delft University of Technology, The Netherlands, written commun., 2001). The pressure sensors give a detailed view of the pressure field. In combination with velocity measurements, the position and kind of turbulence flow structures that create the extreme forces on stones are determined.

Martin Detert and several researchers at the Institute for Hydromechanics, University of Karlsruhe; the Interdisciplinary Center for Scientific Computing, University of Heidelberg; and the Federal Waterways Engineering and Research Institute, Germany, conducted laboratory experiments to study pressure fluctuations on and in a subsurface gravel layer caused by turbulent open-channel flow (fig. 5). The experiments were made to investigate riverbed stability and to quantify the influence of turbulence in the free surface flow to the pore flow. Pore flow was measured by tracking tracer particles with two flexible optic endoscopes (shown at left in fig. 6). Both velocity and pressure of pore flow were measured. Additional micropressure sensors allowed simultaneous gaging of pressure fluctuations within the gravel layer (shown at center in fig. 6). Results were presented in the Conference of River Flow 2004, at Naples, Italy, June 23–25, 2004 (Detert and others, 2004; Jehle and others, 2004).

Figure 5. Experimental flume for study of pressure fluctuations on and in a subsurface gravel layer (picture courtesy of Martin Detert, University of Karlsruhe).

Figure 6. Different devices used for study of pressure fluctuations on and in a subsurface gravel layer.

Lane and others (2004) document both an experimental and numerical study on coherent flow structures in shallow gravel-bed rivers. The authors used three-dimensional computational fluid dynamics, particle image velocimetry, and acoustic Doppler velocimetry to explore the nature of flow structures in a flume study of shallow gravel-bed rivers. This research is based on a new algorithm for representing very complex topography in structured grids. The model study effectively represented the changing flow field around an individual bed particle, and it has major potential benefits toward the understanding of flow-form interactions and the associated implications for sediment transport and shallow flow ecohydraulics.

Literature Reviews by Texas Tech University Researchers

Researchers at Texas Tech University made contributions to the literature review by coordinating responsibilities among the other research entities, communicating with TxDOT, and making an extensive, but unsuccessful, search for publications directly addressing problems associated with sediment mobility at LWCs. The lack of literature addressing LWCs could indicate either that problems may be unique to the Edwards Plateau or that research has not been conducted to understand the effects at these structures.

Literature Reviews by University of Houston Researchers

The objective of this section is to investigate current debris-flow management strategies that can be applied to alleviate LWC damage. Flows of water charged with substantial quantities of sediments ranging from fine clay sizes to boulders are termed “debris flows” (Pierson and Costa, 1987; Fiebiger, 1997; VanDine and others, 1997; Wieczorek and others, 1997). Debris-flow management is an important component of structural design in watersheds with substantial bed mobility. Planning and construction of countermeasures have evolved from consolidation and retaining functions (large debris dams) in the early 1970s to more elaborate and integrated systems that include initiation prevention, magnitude reduction, and flow diversion (Fiebiger, 1997).

Debris-Flow Management for Low-Water Crossing Protection

A debris-flow management system can be divided into prevention, which deals with watershed management, and control. There are two styles of control: passive and active. Passive control includes landscape management, forest management, and hazard and risk mapping. The purpose of such control is to avoid the effects of debris flow by zoning or warning (VanDine and others, 1997). Active control, which tries to minimize the areal extent of the debris flow, involves stabilization of debris sources, energy dissipators, dam systems, diversion structures, or discharge control features (Fiebiger, 1997). Active measures also are classified according to areas of application, including the source or initiation area, transportation zone, and deposition zone (Campbell, 1975; Baldwin and others, 1987; Hungr and others, 1987). Thus, active measures within source areas include landscape and forest management according to Hungr and others (1987). Their intended function is reduction of debris-flow production. Active control in the transportation zone would include energy dissipators and diversion structures. Energy dissipators reduce the flow magnitude and convey the debris surge to designated area. Finally, dam systems and the associated discharge and runoff control structures, which are designed to control the areal extent of the debris flow, would be classified as active measures applicable in the deposition zone. An integrated system can be built by combining several of the different management tools listed in table 5 to achieve an effective control structure. Selection and design criteria are site specific, taking into account the character of the flow, the channel, and the debris fan. The complexity of the design depends on the structure or entity to protect and on the available capital (VanDine and others, 1997). The following sections discuss flow management methods relevant to the project that prompted this investigation. Watershed, landscape, and forest management will not be presented because their implementation is beyond the scope of the project.

Passive-control hazard mapping and zoning starts by the recognition of destruction patterns of debris flows: direct impact, indirect impact, and flood zones (Hungr and others, 1987). The direct impact zone is delineated by high energy and destructive, rapidly moving, high-discharge pulses that influence the deposition area just downstream of transportation zones. The direct impact zone, where deposition begins, is located in areas where slopes decrease below the transportation critical level, which is very site specific. Inspection of nearby deposits that are evidence of debris flow should give an indication of the critical slope. In selecting that slope, attention should be paid to channel confinement, which can be more critical than the slope (Hungr and others, 1987). Indirect impacts, including burial of structures, result from deposition of large debris

Table 5. Debris-flow management system diagram (Hungr and others, 1987; Fiebiger, 1997; VanDine, 1997).

Debris-flow prevention	Debris-flow control	
Watershed management	Passive control	Active control
	1. Landscape management (source zone) 2. Forest management (source zone) • reforestation/controlled harvest • forest road construction control 3. Hazard and risk mapping (source, transport, and deposition zone)	1. Debris source stabilization • source area grading • riprap • baffles • check dams • creek channel linings 2. Energy dissipaters (transportation zone) • debris-flow breakers • debris-flow screens or rakes 3. Dam systems (deposition zone) • debris-flow structure • retention dams • steel grid dams • open debris basin • close debris basin 4. Diversion structures (transportation zone) • deflection walls • deflection berms • terminal berms 5. Discharge control features

volumes moving at low velocities after passing the direct impact zone. Those deposits can develop bars and temporary earth dams that divert the flow to an unexpected area and create flood zones. Indirect impacts and flood zones are linked to the runout length, which in turn is related to the volume of debris, magnitude at the beginning of the deposition zone, nature of the debris flow, and slope of the deposition area. Equations to derive deposition thickness and runout length are presented by Innes (1983), Jeyapalan and others (1983), and Hungr and others (1984). Once the hazard map is created, development in dangerous areas is restricted by zoning the areas as hazardous, park land, or agricultural areas (Hungr and others, 1987). Mapping also can contribute to public infrastructure design by determining areas of high sediment loads.

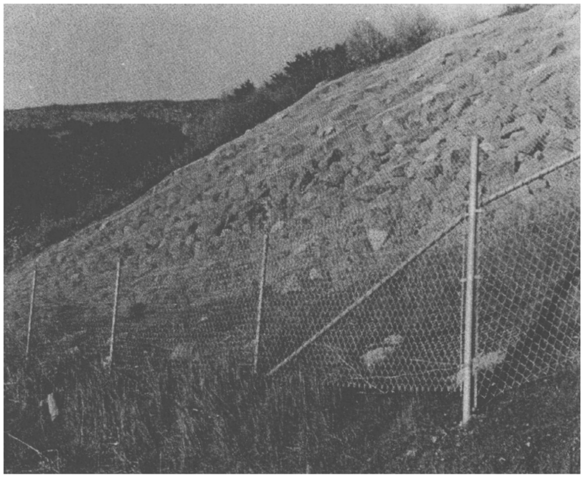
Active control consists of debris source stabilization, energy dissipators, dam systems, diversion structures, discharge control features, and combinations of one or more of those structures.

Debris source stabilization is important. Steep slopes are one of the control elements in the initiation and amplification of debris-flow magnitude. Grading the source area to a more uniform and smooth slope is a common practice to mitigate sliding hazard. However, the soil cementing vegetation requires seeding in spring or early summer to allow full growth before the arrival of heavy rains to prevent severe erosion (Baldwin and others, 1987). Riprap also can be used on over-steepened slopes (fig. 7). As shown in the figure, the riprap needs to be keyed into the bedrock at a recommended depth of about 1 meter to avoid sliding. When the finished slope is greater than 50 percent, Baldwin and others (1987) recommend covering the surface with chain-link fence.

Scour of loose blocks of sediment and slides of channel banks are an important supply of debris flow (Hungr and others, 1987; Fiebiger, 1997). Scour and slides can be reduced by elevating the water surface level. This is achieved by building check dams along steep channels. The method is very efficient but quite expensive. As alternatives, steel cable nets (DeNatale, 1997) and steel bags of cobbles (Baldwin and others, 1987) often are used.

Baffles can be built in the transportation zone to deflect, check, or regulate debris flows. Baffles usually are made of treated timber or steel. Baffles also have been used as temporary energy dissipators, designed to fail at the impact while offering some resistance to the incoming flow. In this case, baffles are set up in a sand-filled foundation rather than in concrete (Baldwin and others, 1987).

Channel lining is used to stabilize the bed, protect the banks, and maintain channel alignment. These stabilizations are important for LWC abutment protection. The lining can be made of riprap that subsequently is grouted with concrete. To limit lining damage from debris slides and bank slumps, excessive velocities generated by the smoothness of concrete,



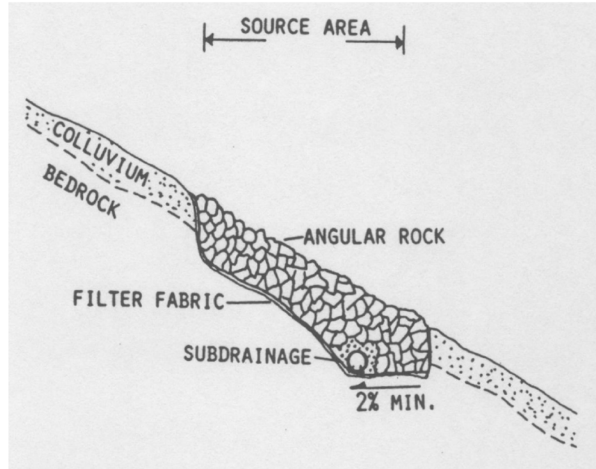


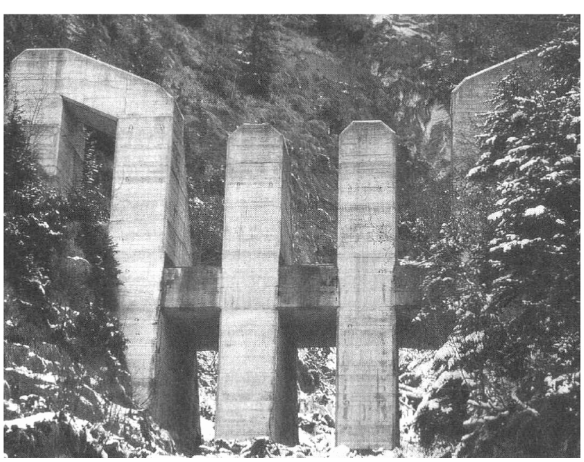
Figure 7. Riprap (left) on hillside in Pacifica, California, and riprap design recommendation (right) (from Baldwin and others, 1987).

and maintenance because of abrasion, masonry linings are used in Europe and boulders embedded in steel fiber-reinforced concrete are used in British Columbia (Hungr and others, 1987).

Energy dissipaters decrease the energy of the incoming flow by means of flow breakers that can stand alone (fig. 8) or can be coupled with other structures to enhance efficiency or accomplish other controls. When built as stand-alone structures, flow breakers are made of massive concrete piers raised at a design height across the channel bed. The combination of flow breakers with debris dams dramatically reduces debris-flow rates and thus decreases the size needed for the structure. The combination also can serve as debris traps to retain oversize material. Low-rise flow breakers also can be built at the bottom of settling basins to serve as deposit structures. Sediment can be removed after each flood.

Dam systems shown in figure 9 can have a complex structure or consist of a simple excavation and piled up berms around the selected site, known as debris dams. Debris dams often are coupled with other debris-flow control structures, such as flow breakers and rakes or screens, to accomplish several functions, such as stabilizing the channel bed and decreasing slope erosion, by elevating the water surface level, sorting oversize material, and retaining debris overload.

Open debris basins are designed with a large surface area to maximize deposition area and minimize depth so that some downstream sediment supply still occurs. The basins



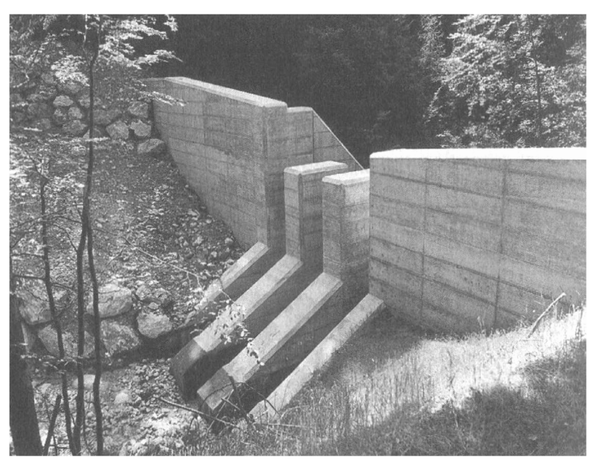
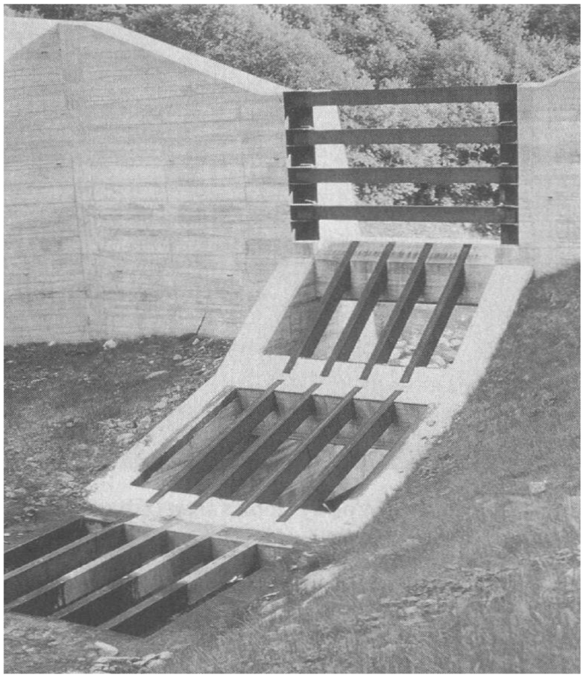


Figure 8. Stand-alone flow breakers (left) and flow breakers in debris dam (right) (from Fiebiger, 1997).



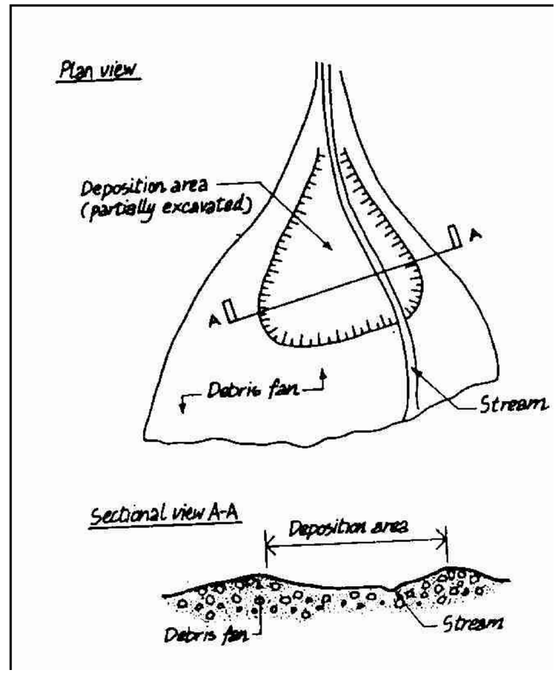


Figure 9. Debris-flow dam with a screen of steel beams (left, from Fiebiger, 1997) and open debris basin design (right, from VanDine, 1997).

are built across the existing channel path when diversion is not necessary.

Closed debris basins (fig. 10) have a more complex structure. In addition to the excavated basin and the containing berms, they have debris straining features that are built on-line. The debris straining features can be raised at the end run of deflection berms, which would canalize debris flows toward them. To protect the community of Lions Bay, British Columbia, from debris flows in Harvey Creek, a closed debris basin was built in the mid-1980s. The basin can contain 2,648,600 cubic feet of debris and the dam is 49 feet high. It is an earth-filled structure with a complex and heavy reinforced

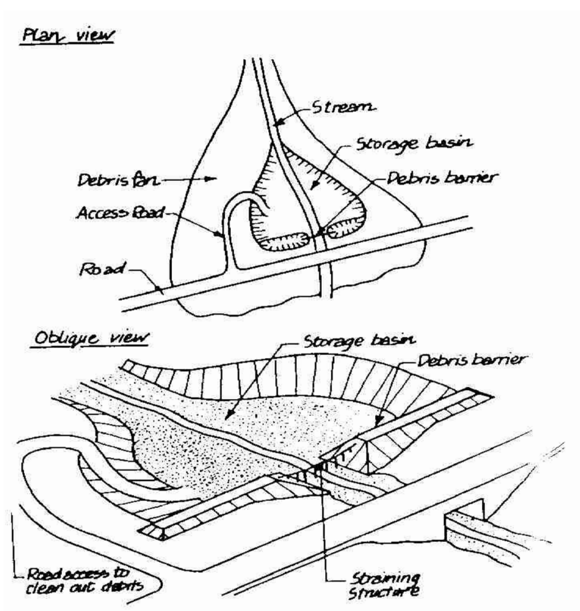


Figure 10. Closed debris basin schematic (left) and closed debris basin on Harvey Creek in British Columbia (right) (from VanDine, 1997).

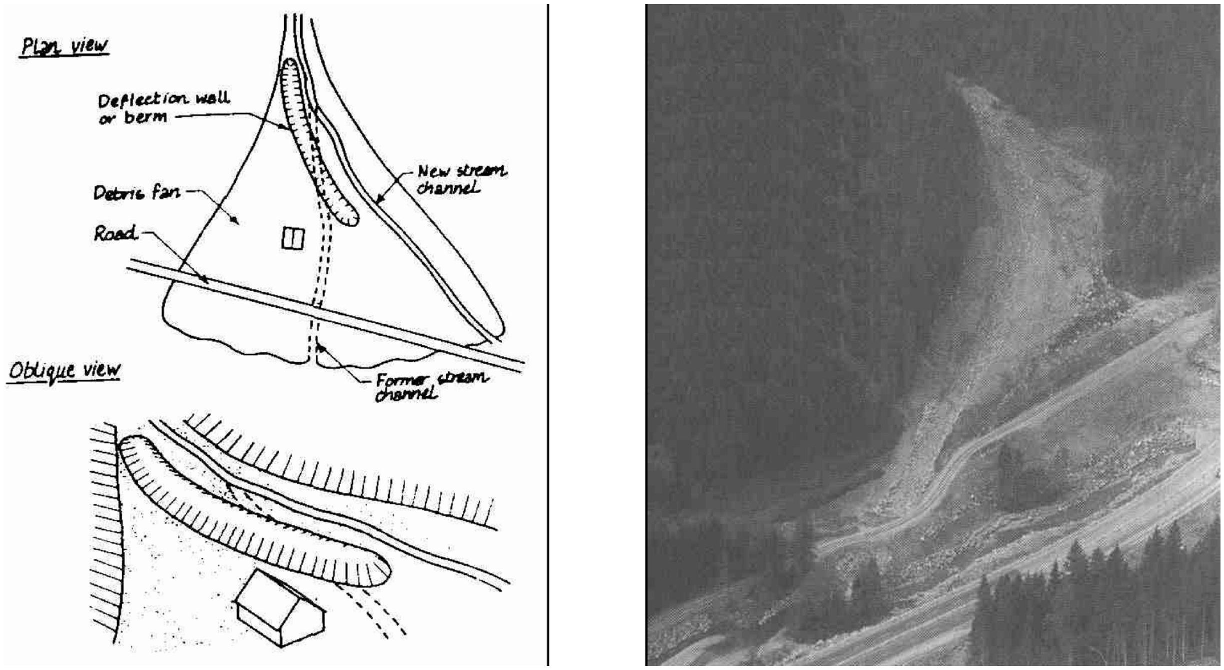


Figure 11. Deflection berm schematic (left) and deflection berm on Boulder Creek in British Columbia (right) (from VanDine, 1997).

concrete face that allows passage of the normal creek and strained debris flows.

Diversion structures are composed of deflection and terminal berms and open and closed debris basins (VanDine and others, 1997). Deflection berms (fig. 11) are built to deflect the flow path while providing lateral boundaries to avoid areal spreading of debris. The figure also shows a deflection berm built on Boulder Creek, British Columbia (Hawley, 1989; VanDine and others, 1997), to prevent debris flows from overtopping the highway. The berm was 10 to 56 feet high and 1,640 feet long, the lower end composed of riprap. The structure was designed to handle about 530,000 cubic feet of debris.

Steel wire bags of cobbles can be used as deflection devices (fig. 12). The bags are effective in sustaining high impact forces. The bags are deformed during high-magnitude debris flows. However these deformations do not affect bag efficiency. The bags are easily replaced and can be reused after maintenance. As shown in figure 12, high segments are designed to sustain impacts and decrease potential for overtopping. The lower segments should be embedded into the bedrock to avoid sliding.

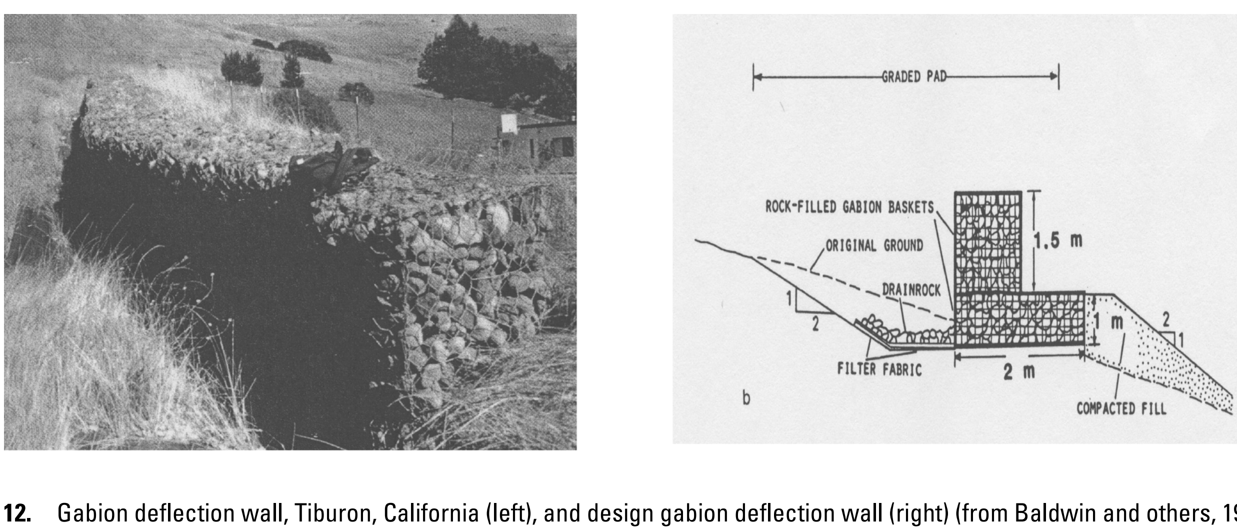


Figure 12. Gabion deflection wall, Tiburon, California (left), and design gabion deflection wall (right) (from Baldwin and others, 1987).

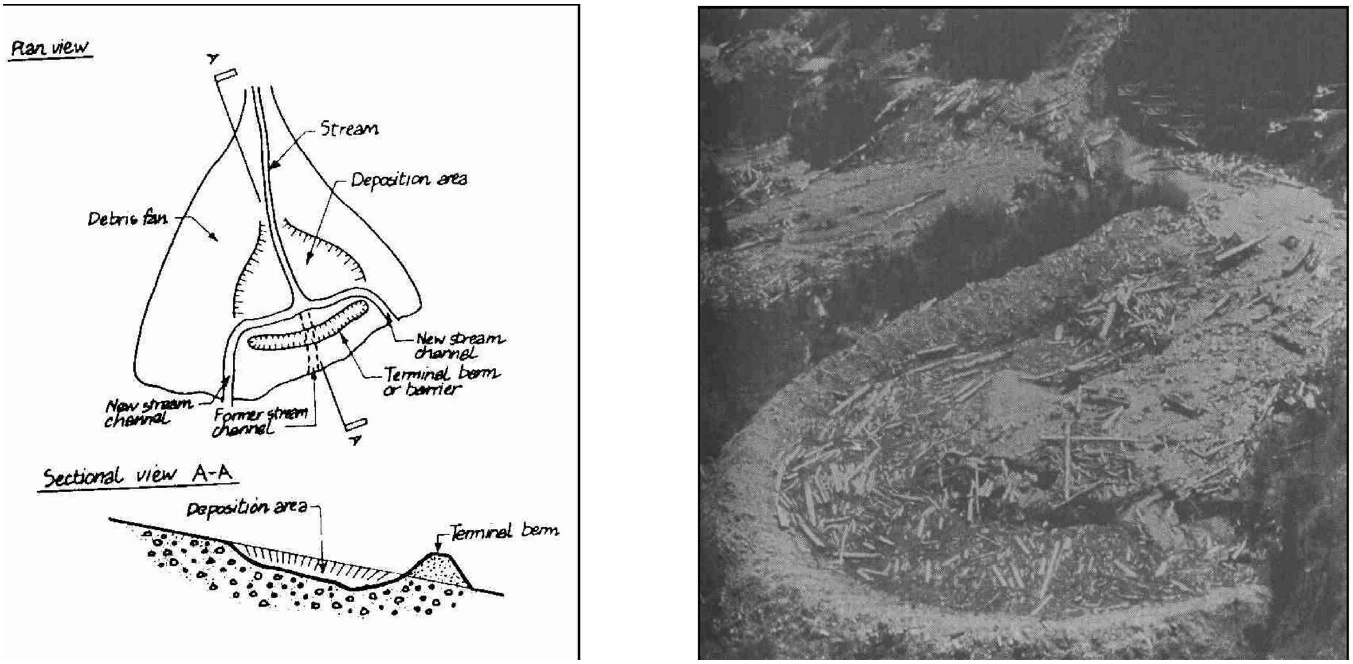


Figure 13. Terminal berm schematic (left) and terminal berm on Cypre Creek in British Columbia (right) (from VanDine, 1997).

Terminal berms (fig. 13) are earth-filled debris trap belts built as far down as possible from the avalanche scarp to maximize deposition area and decrease impact force. The berms are built on-line of the existing channel, enclosing a deposition area big enough to contain the expected maximum volume of debris. Weirs are made on the sides to allow the creation of secondary channels that would move relatively low debris-loaded flows downstream. Figure 13 shows a terminal berm constructed on the west coast of Vancouver Island in 1989 on a seasonal tributary to Cypre Creek. It is 656 feet long and 11.5 feet high and withstood a debris-flow volume of 176,573 cubic feet.

Research on Debris-Flow Countermeasures

Flexible wire rope barriers have been used successfully in controlling debris flows. Wire ropes were used in Pacifica, California, as fences in baffle systems, which were designed to reduce flow velocity (Baldwin and others, 1987). They also served as debris straining structures in closed debris basins (VanDine and others, 1997). In 1994, a flexible wire rope prevented about 2,100 cubic feet of debris flows from causing damage to California State Route 41. Following the incident, the USGS conducted field experiments to study the response of flexible wire rope barriers to debris-flow charges (DeNatale and others, 1997). A reinforced concrete flume tilted at a 5-percent slope was installed near Blue Forest, Oregon. The channel was 6.5 feet wide, 312 feet long, and 3.9 feet deep. A run-out pad, 82 feet long was mounted at the flume exit. The pad was tilted at a 5-percent slope (fig. 14). The system could deliver 44 cubic feet of debris flow moving at 32.8 feet per second. In order to create a soil slurry that would be similar to debris-flow composition and properties and that would fit within the flume operational constraints, the experimental soil was artificially made of 42.1-percent gravel, 73.9-percent sand, and 2.0-percent silt and clay. The typical grain-size diameter was 6.2 millimeters and the effective grain size was 0.35 millimeter.

Four models of barriers were tested. The first two models were wire rope netting 8 by 30 feet with chain links to create nets of 12 by 12 inches and 8 by 8 inches (fig. 15). Ropes of 0.75-inch diameter were used for the frame and the columns were W4 by 13-inch steel. The latter two models were both 8 by 30 inches with a 0.75-inch diameter rope frame and W8 by 48-inch steel support columns. The 6-by 6-inch clear opening of the third model was made with chicken wire. The fourth model had 12-inch opening interlocking rings and a silt screen as an additional feature. Flow velocities were measured using 1-square-meter gridlines marked on the run-out pad, a time-stamped videotape recorder, and an overhead camera. Movement of markers, including sprayed gravels and chunks, were recorded. Barrier deformations were measured with a cable extensometer attached to the nets. After running multiple debris flows into the barriers, only models 3 and 4 did not suffer column or anchor-cable connection failure. Deformations were less than 6.6 feet and only 0.05 percent of debris passed underneath the barriers. The investigators (DeNatale and others, 1997) recommended that wire rope barriers could be used to mitigate small debris flows.

Flow breakers are energy dissipaters that decrease the energy of the incoming flow. They can be used as stand-alone structures or be coupled with other control measures. Chen and

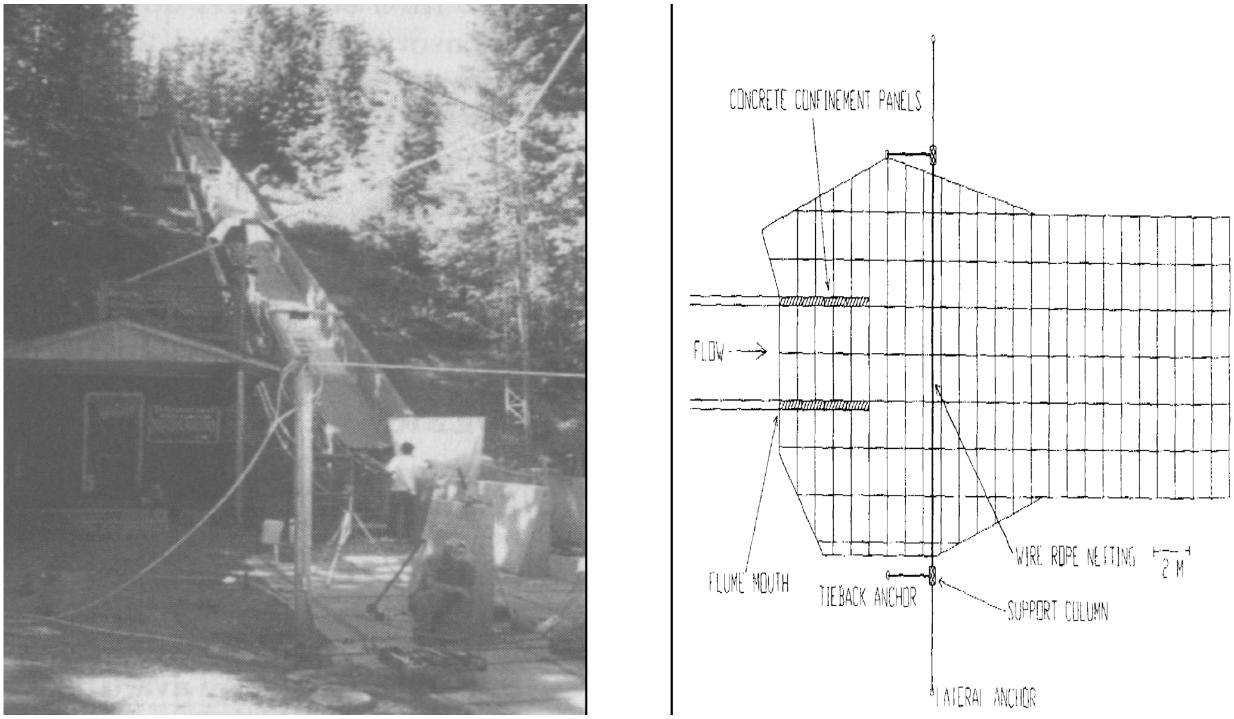


Figure 14. U.S. Geological Survey flume on Blue River at Blue Forest, Oregon (left), and schematic of the experiment to study the response of flexible wire rope barriers to debris-flow charges (right) (from DeNatale and others, 1997).

Ho (1997) studied effects of four different types of flow breakers that the authors referred to as “dams” (gravitational, grid, step-grid, and column) on debris flows. As shown in figure 16, a gravitational flow breaker is a heavy reinforced concrete structure. The model used for experiments had a 5:3 front slope, clear openings, and heights 1.5 and 5 times greater than the largest grain of the experimental debris flow. The largest grain diameter was 38 millimeters. Grid and step-grid flow breakers were piles of steel-bar cubes with openings 1.5 times greater than the largest particle size. Different numbers of layers, or square units making up a cube, were tested. The column flow breaker was made of equally spaced steel bars of a length 3 times greater than the maximum diameter size.

A slurry, used as debris flow, was prepared and compacted to a concentration of about 119 pounds (mass) per foot with 4-percent water and placed at the top of a flume 6.7 feet long, tilted at 34 percent (fig. 17). After compaction, the slurry was saturated with water for 24 hours (VanDine, 1986; Baldwin and others, 1987). The compacted slurry then was flushed downward as water rushed in the flume at about 49 cubic feet per second.

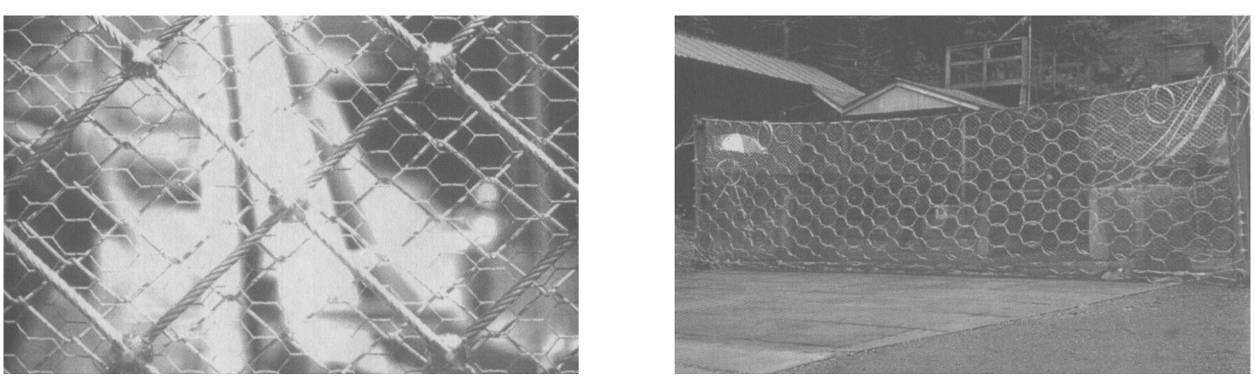


Figure 15. Flexible wire rope barriers with netting (left; models 1, 2, and 3) and with interlocking rings (right; model 4) (from DeNatale and others, 1997).

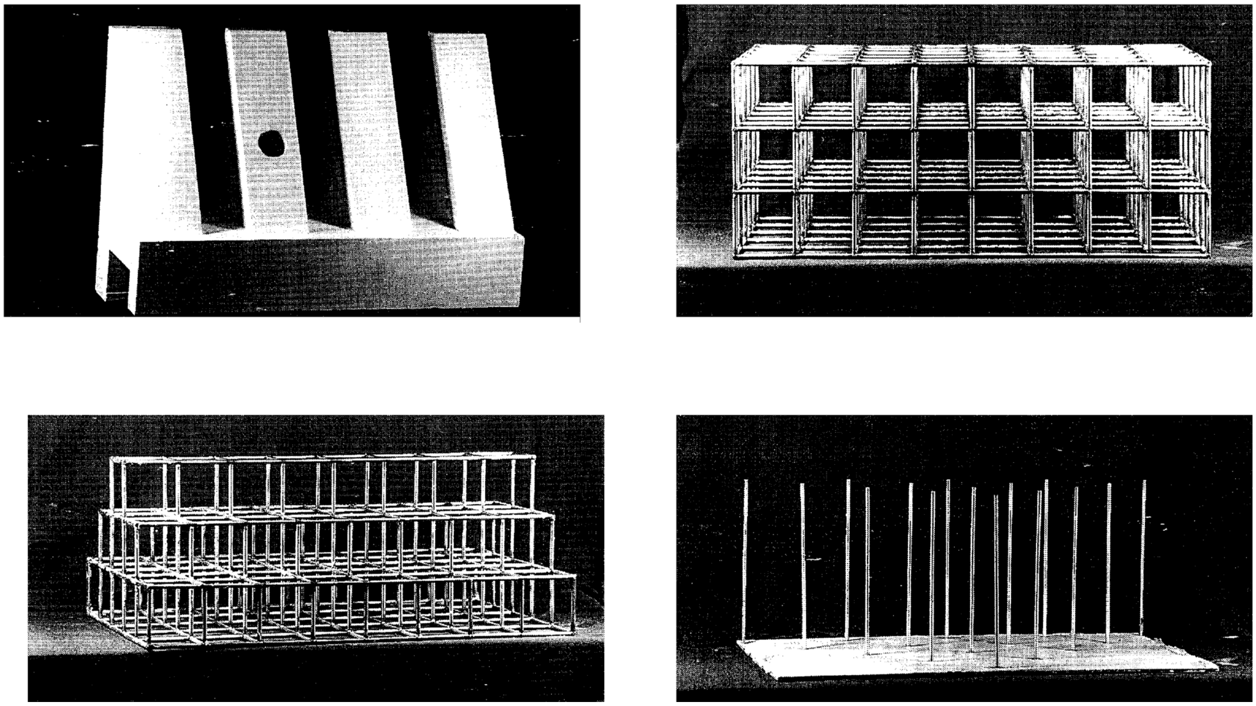


Figure 16. Gravitational flow breaker (top left), five-layer grid flow breaker (top right), step-grid flow breaker (bottom left), and column flow breaker (bottom right) (from Chen and Ho, 1997).

Results showed that the more layers (cubes) the grid flow breakers were made of, the more debris could be retained. However there is a number of layers above which retaining efficiency could not be improved. The column debris-flow breaker was the most efficient in decreasing debris-flow energy but did not retain debris. Experiments also revealed that gravitational flow breakers were best suited as a structure outlet. Fiebiger (1997) had the same conclusion about gravitational flow breakers.

Lin and others (1997) studied retaining rates and segregation efficiency of three types of flow breakers (fig. 18)—the column, which Chen and Ho (1997) also studied, the horizontal column referred to as a beam, and a more elaborated version of the step-grid Chen and Ho (1997) studied. In Chen and Ho (1997) experiments, column and grid flow breakers have clear openings 3 and 1.5 times as large as the largest grain-size diameter, respectively. In Lin and others (1997), the openings of the horizontal column and grid

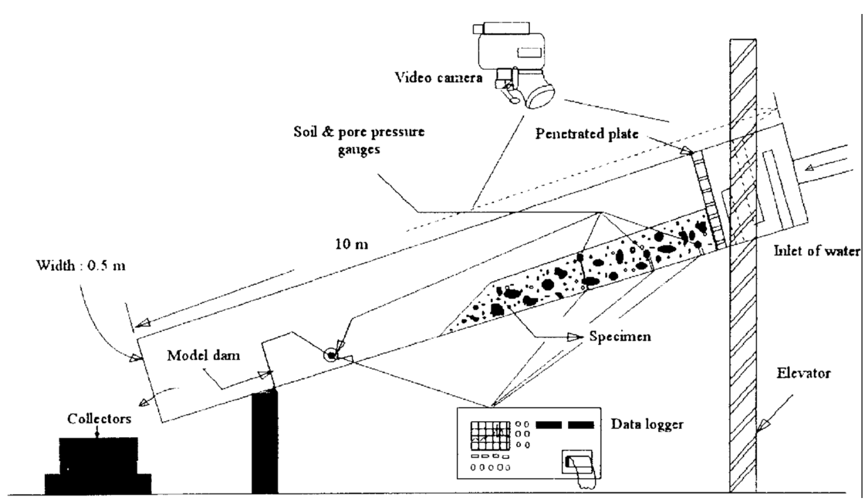


Figure 17. Flume test apparatus (from Chen and Ho, 1997).

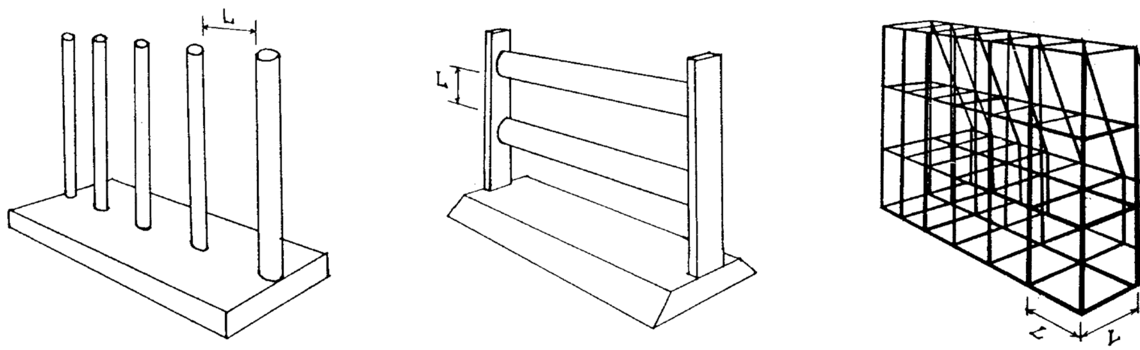


Figure 18. Column flow breaker (left), beam flow breaker (center), and grid flow breaker (right) (from Lin and others, 1997).

flow breakers are 2 times greater than the largest grain-size diameter.

A debris-flow slurry was made by compaction of the sediment, submersion for 2 hours, then drainage. Successive tests were run using sediments with maximum grain-size diameters of 25.4 and 50.8 millimeters. The slurry was placed in the upper part of a flume tilted at 23, 27, 31, and then 35 percent. Debris flows were triggered with water flushed in at flow rates of 0.07 and 0.14 cubic feet per second, successively.

The retaining rate (R) was defined as the ratio of weight of sand retained to the sum of sand passed and sand retained. Segregation efficiency was quantified by the separation index, defined as the ratio of average grain size of sand that passed to average grain size of the original sample. Experiments showed through regression analysis that retaining rate was highly correlated to flume tilt as was the ratio of flow breaker opening to maximum grain size (L/D_{max}); whereas, separation index was well correlated to L/D_{max}. Other important conclusions are that pore pressure is controlled by seepage, not static water pressure, and that impact force magnitude increases drastically when coarse sediment strikes the flow breakers. The authors of this report also noted that recorded dynamic impact forces were more than 2 times as much as theoretical values.

Mizuyama and Mizuno (1997) noticed that flow breakers were used more often because of their ability to allow for a sufficient sediment supply downstream as well as for fish to pass through the openings. However, because material of appreciable size can pass through flow breakers, prediction of the flow hydrograph and sediment content is necessary. The authors set up an experiment to compare measured instantaneous sediment discharge to a theoretically derived passing hydrograph. The peak sediment reduction rate (P) is defined as:

$$P = 1 - R, \tag{20}$$

where R is the retaining rate (see Lin and others, 1997) defined as:

$$R = \frac{Q_{sp}}{Q_{spo}}, \tag{21}$$

where Q_{sp} is the peak sediment flow without structure, and Q_{spo} is the peak sediment flow with structure. From previous studies, Mizuyama and Mizuno (1997) noted that the reduction rate (P) was a function of L/D_{max} (see Lin and others, 1997) and sediment concentration (C) and then established an empirical equation relating these parameters,

$$P = 1 - 0.11\left[\frac{L}{D_{max}} - 1\right]C^{-0.93}, \tag{22}$$

where $P = 1 - Q_{sp}/Q_{spo}$. Assuming that the flow was not influenced by deposits inside the flume and that trapped sediment never flowed out, Mizuyama and Mizuno (1997) established the following equation:

$$Q_s(t) = 0.11\left[\frac{L}{D_{max}} - 1\right]C^{-0.93}Q_{so}(t), \tag{23}$$

where $Q_s(t)$ is the predicted instantaneous debris-flow discharge through a structure, and $Q_{so}(t)$ is the instantaneous debris-flow discharge without a structure. D_{max} is taken as D_{95}. For experimental verification, the authors (this report) set up a wooden flume that was 13 feet long and 6 inches wide, tilted at 17, 27, and 36 percent. Mizuyama and Mizuno (1997) measured $Q_{so}(t)$ and $Q_{s-measured}(t)$; the authors (this report) subsequently computed $Q_{s-computed}(t)$ and find good agreement between computed and measured debris-flow hydrographs.

Conclusions

Numerous debris-flow mitigation strategies have been proposed around the world. The strategies span from simple piling of berms used as low-cost flow deflectors or debris trap basins to more complex structures that exceed millions of dollars.

Current research focuses on flow breakers that can be used as stand-alone structures or as discharge control structures. USGS experiments with the possibility of using flexible rope wires as barriers showed that 6- by 6-inch opening wire rope netting with chicken wire and interlocking-ring wire ropes were promising but should be limited to mitigation of small debris flows. Column debris-flow breakers are used more often because they stand out as the most efficient in decreasing debris-flow energy and allow both a sufficient sediment supply downstream and for fish to pass through the openings. Experiments also showed that retaining rates of column debris-flow breakers were highly related to hill slope, the ratio of flow breaker opening to maximum grain size (L/D_{max}), and sediment concentration. Material of considerable size can pass through flow breakers and affect downstream structures. To have better control over the inflow and outflow of debris movements, an attempt to predict the movement of debris flows past flow breakers was made and the results were encouraging.

Debris-flow magnitude should be alleviated with mitigation structures (discussed herein) before reaching LWCs. Countermeasures at LWCs should be limited to erosion and structural stability controls. Important considerations in designing debris-flow mitigation structures would be to quantify impact forces, the deposit volume per event, and the magnitude of discharges, frequency of events, and sediment size distribution of debris flows.

Literature Reviews by U.S. Geological Survey Researchers

Edwards and Glysson (1999) serves as the guide for USGS investigations involving the sampling of both suspended and bed sediment. Equipment description and technique discussions are included. This report is a comprehensive methodological guide. The authors distinguish bed-material sampling from bed-load sampling, the former associated with bed composition and the latter defined as “sediment that moves by sliding, rolling, or bouncing along on or near the streambed.”

Edwards and Glysson (1999) report that current equipment for bed-material sampling can accurately represent particles finer than 16 millimeters in diameter and only can accommodate particles finer than 30 to 40 millimeters. A variety of equipment is available for this purpose, including hand-held samplers and cable-and-reel samplers. Standard equipment for sampling bed material comprising gravel, cobbles, and boulders is not available, and apparatus designed for this purpose are experimental. For particles greater than 16 millimeters, the popular and randomized Wolman pebble count (Wolman, 1954) is recommended. The pebble count is conducted by establishing a grid of sample sites, after which 100 pebbles are chosen randomly at each site. The long, intermediate, and short axes of each clast are measured and recorded, the clast then is placed into a size interval, and the percentage of each interval provides a frequency histogram and a grain-size curve. Another method mentioned involves the use of a device known as a “Zeiss particle-size analyzer” in combination with photography of the streambed. Finally, the used of a “pipe dredge” is mentioned for non-wadable streams.

Edwards and Glysson (1999) report that bed-load sampling is difficult, as a device on or near the bed disturbs velocity distribution and rate of bed-load movement. Complicating this is the spatial and temporal variation of both the flow velocity near the bed and the bed load. For best results, a bed-load sampler must sample the mass or volume of particles through a given width in a specified period of time. Direct-collecting samplers fall within four categories: (1) box or basket, (2) pan or tray, (3) pressure difference, and (4) slot or pit samplers. The efficiency of bed-load-sampling devices is defined as the “ratio of the mass of bed load collected to the mass of the bed load that would have passed through the sampler width in the same time period had the sampler not been there.” For the greatest efficiency, the slot or pit sampler is preferred, however, extraction of the sample can be either difficult or costly. Pressure-difference samplers are hydrodynamically designed to maintain ambient entrance flow velocities by creating a pressure drop at the exit. The Helley-Smith bed-load sampler is the most popular type of pressure-difference sampler. It consists of an expanding 3- by 3-inch nozzle, sample bag, and frame, allowing for the collection of clasts less than 76 millimeters at mean velocities less than 9.8 feet per second. An enlarged 6- by 6-inch version is available for streams with larger particle sizes. These samplers are cumbersome and require a cable-reel suspension system. Helley-Smith bed-load samplers are categorized by the ratio of the entrance nozzle expansion, the original sampler having a 3.22 area ratio. The USGS endorses the use of a Helley-Smith bed-load sampler with a 1.40 area ratio of the expanding entrance nozzle, although data obtained with the original 3.22 area ratio will still be accepted. Efficiencies have been determined as about 1.0, however, it should be noted that the sampler has the potential to collect some particles moving in suspension.

Edwards and Glysson (1999) emphasize the temporal variability of bed-load transport, associated with its characteristic movement in the form of dunes, cycles, or slugs. Additionally, the cross-channel variation is typified by very little movement near the banks to maximum transport toward mid-stream or in the thalweg. To obtain a reasonable estimate of the mean cross-sectional bed-load discharge, the collection of about 40 rate measurements is recommended, subdividing the cross section into 20 verticals and making two passes. The time that the sampler rests on the bed should be equal for all verticals in a cross section but does not have to be the same for both passes. The sampling time is preferred to be no more than 60 seconds, but it should be short enough to fill no more than 40 percent of the sample bag from the vertical with the highest transport rate. This is referred to as the single equal-width-increment (SEWI) method. The multiple equal-width-increment (MEWI) method collects one sample at four or more evenly spaced verticals, followed by repeated passes until a total of 40 samples are collected. Finally, the unequal-width-increment (UWI) method collects one sample at four or more unevenly spaced verticals, followed by repeated passes until a total of 40 samples are collected.

Edwards and Glysson (1999) report that the bed-load transport rate at a vertical is:

$$R_i = K\frac{M_i}{t_i}, \quad (24)$$

where R_i is the bed-load transport rate at vertical i, in tons per day per foot; M_i is mass of sample collected at vertical i, in grams; t_i is the time the sampler was on the bottom at vertical i, in seconds; and K is a unit conversion factor used to convert grams per second per foot into tons per day per foot. For a 3-inch nozzle $K = 0.381$, and for a 6-inch nozzle $K = 0.190$.

The cross-sectional bed-load discharge is calculated using the total cross-section method, if the sample times at each vertical were equal, the verticals were evenly spaced, and the first sample was collected at one-half the sample width from the bank. If any of these conditions are not met, either the midsection or the mean-section method should be used. The total cross-section formula is:

$$Q_B = K\frac{W_T}{t_T}M_T, \quad (25)$$

where Q_B is the bed-load discharge, in tons per day; W_T is total width of stream, in feet; t_T is the total time that the sampler is on the bed, in seconds; M_T is the total mass of sample collected from all verticals samples in the cross section, in grams; and K is defined as in eq. 24.

Stevens and Yang (1989) provide a summary of fluvial sediment discharge equations, compare measured and computed results from the equations, and provide guidance to select equations for a variety of flow and sediment conditions. Sediment discharge equations fall into three categories: deterministic, probabilistic, and regression. The deterministic approach assumes a correlation between dependent and independent variables and is advantageous if the independent variables are known. Probability-based equations rely on predictions of particle motion, and regression analysis is used to derive empirical relations between sediment discharge rates and some other parameter. The authors include 13 fluvial sediment-discharge equations, five of which are bed-load discharge and eight are bed-material discharge. The bed-load discharge is the sediment moving in continuous contact with the bed. The bed-material discharge is the sediment readily exchangeable with the bed-material, moving both as bed load and in suspension.

Stevens and Yang (1989), through their review of sediment discharge equations accompanied by measured values, computed discrepancy ratios between equations and made recommendations regarding use of the equations. A discrepancy ratio, an indicator of the equation accuracy, is the ratio between computed and measured sediment discharges. Stevens and Yang (1989) conclude that reliable bed-load-discharge equations are available in Schoklitsch (1934) and Meyer-Peter and Müller (1948). Meyer-Peter and Müller (1948) is recommended for bed material coarser than 5 millimeters. The Einstein (1950) equation is best suited for bed-load-dominated rivers, and the Yang (1984) equation can be applied when most bed materials range from 2 to 10 millimeters. Stevens and Yang (1989) conclude that reliable bed-material-discharge equations are available in Yang (1973) (sand only), Engelund and Hansen (1967), Ackers and White (1973), and Yang (1984) (gravel only).

Elliott (2002) addresses a problem notably similar to that of TxDOT project 0–4695. In this study, the entrainment potential is computed for a river having a frequently mobile streambed composed of gravel, cobbles, and boulders. Cross-sectional surveys and water-surface elevations were used to compute the boundary shear stress at different locations, including the mean streambed, thalweg, and bar surfaces. The equation for boundary shear stress is:

$$\tau_o = \gamma DS, \quad (26)$$

where τ_o is mean boundary shear stress, in newtons per square meter; γ is specific weight of water (9,807 newtons per square meter); D is the mean depth of flow, in meters; and S is the energy gradient, in meters per meter. The slope of the water surface often is used as a substitute for S.

Elliott (2002) then uses the critical shear stress to describe the point at which entrainment of bed material is initiated. The critical shear stress is calculated with the following equation:

$$\tau_c = \tau_c^*(\gamma_s - \gamma)d_{50}, \quad (27)$$

where τ_c is the critical shear stress, in newtons per square meter; τ_c^* is the dimensionless critical shear stress or Shields parameter (Shields, 1936; Neill, 1968); γ_s is the specific weight of sediment (often taken as 2.65 times the specific weight of water); γ is the specific weight of water (9,807 newtons per square meter); and d_{50} is the median particle size, in meters.

Elliott (2002) concludes that sediment-entrainment potential for any given geomorphic surface or flow can be expressed as the ratio of boundary shear stress to critical shear stress (τ_o/τ_c). The condition at which the median particle size becomes entrained is referred to as the partial entrainment threshold ($\tau_o/\tau_c = 1$). The complete entrainment threshold ($\tau_o/\tau_c = 2$) describes the point at which complete or widespread mobilization of the median particle size occurs.

Gustavson (1978) is the only identified citation on gravel entrainment in the Edwards Plateau. Using historic streamflow data of the Nueces River in Texas, specifically for large floods, the author computed shear stresses to estimate stream competence. The results show that the magnitude of flow required to initiate movement of gravel with an intermediate diameter of about 0.5 inch (about 1.2 centimeters) occurs only 0.1 percent of the time each year, and a 12-percent probability exists each year for floods capable of transporting (initiating movement of) almost all of the bed material. Additionally, the river can transport over one-half of its bed material during flows with a relatively frequent recurrence interval (1- to 2-year annual peak

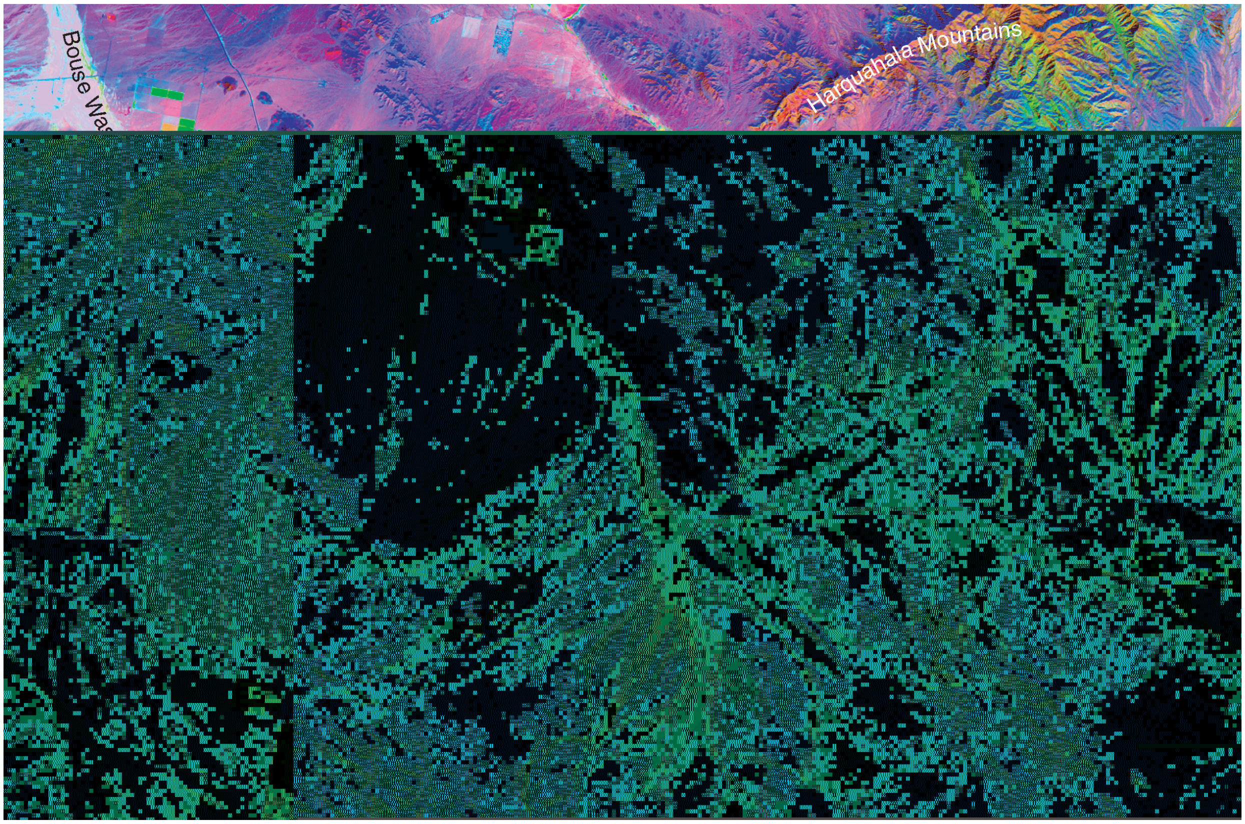


Figure 19. Processed Landsat Thematic Mapping scene for part of western Arizona (from Mayer and Pearthree, 2002, pl. 3). The image shows changes caused by Hurricane Nora in different colors. The colors result from processing bands 4 and 5 before and after the storm. The yellow color highlights areas in which flooding deposited fine-grained material. Mayer and Pearthree (2002) conclude that green and cyan colors probably highlight areas of vegetation growth.

discharge) and can mobilize more than 90 percent of its bed material once every 7 or 8 years.

Biedenharn and others (2000) provide practical guidance for calculation of the effective discharge of rivers. Effective discharge is defined as the streamflow able to transport the most sediment, specifically the bed-load material. Using data available from gaging stations, a standardized procedure was developed to calculate effective discharge. In general, the approach uses a flow-duration curve and a sediment-transport rating curve. For ungaged sites, nearby gaging stations within the same drainage basin can be used or a regionalized flow-duration curve must be developed. Following the creation of a flow-duration curve from measured discharge, a sediment-transport equation is used or a sediment-transport rating curve must be created through intensive data collection. The sediment-transport rating curve has sediment-load data (vertical axis) plotted against discharge (horizontal axis). A power function through regression often provides the sediment-transport equation. Finally, a bed-material load histogram is created to represent the total bed-material load transported by each discharge class. This histogram is produced by multiplying the bed-material load by the frequency of occurrence of its corresponding discharge. The effective discharge corresponds to the modal class of the histogram.

Mayer and Pearthree (2002) describe the use of standard Landsat Thematic Mapping (TM) data to detect sediment changes on the land surface caused by flooding in the deserts of the southwestern United States. Mayer and Pearthree (2002) also provide additional references for space-based flood mapping and resultant changes to landscape. The authors process Landsat TM scenes recorded in July 1997 and in October 1997 over the Tiger Wash area of southwestern Arizona (fig. 19). This area experienced widespread flooding as a result of Hurricane Nora in late September 1997. Landsat TM data is available from the USGS National Center for Earth Resources Observational Science (EROS). The Landsat satellites are about 700 kilometers above the earth and revisit the same area every 16 days.

Mayer and Pearthree (2002) process infrared bands 4 and 5. Each band has a spatial resolution of 30 meters. The authors processed the scenes to accentuate scene changes that are believed to reflect changes to sediment and vegetation. The processing is complex and includes adjustments for such factors as inherent differences in solar illumination and geographic referencing errors. Extensive field analysis was used to map regions of sediment change following the Hurricane Nora flooding event. Although the meaning of the changes in Landsat TM scenes on a pixel to pixel basis are clear, the changes between scenes are “strikingly” similar to the field mapping of sediment changes. Mayer and Pearthree (2002, pl. 3) provide an spectacular high-resolution color plate of a part of western Arizona showing the sediment and other changes caused by Hurricane Nora flooding. They conclude that Landsat TM data with specific processing can be used to detect regional changes to channels and overbank areas resulting from substantial flooding in ephemeral streams in the southwestern United States.

Mayer and Pearthree (2002) is a promising reference that describes application of geographic information systems (GIS) and remotely sensed data suitable to study the bed-load-transport phenomena in the Edwards Plateau area in Texas. Because of the substantial rearrangement of the bed during large floods in the area, new insights in the phenomena could be made through periodic processing of Landsat data or high-resolution digital orthophoto quarter-quadrangles (DOQQs). However, a specific methods and processing study of Landsat TM data over the Edwards Plateau in the context of bed-load transport is required before cost-effective periodic data processing is feasible. DOQQs might be the most cost-effective, high-resolution imagery to use in spatial and temporal analyses of bed-load-transport.

Summary

A review of the literature addressing sediment transport in gravel-bed river systems and structures designed to control bed-load mobility is provided as part of Texas Department of Transportation research project 0–4695: Guidance for Design in Areas of Extreme Bed-Load Mobility. The study area comprises Edwards, Kimble, and Real Counties in the Edwards Plateau in central Texas. The primary focus of the literature review is on journal articles, edited volumes, and government publications. The literature review provides an outline and foundation for the research project to characterize extreme bed-load mobility in rivers and streams across the study area. The literature review also provides a basis for potential modifications to low-water stream-crossing design in the study area.

The literature associated with sediment transport in gravel-bed rivers and application of theory to river management is extensive, global, and multi-disciplinary. Investigations focus on data derived from natural channels or experimental flumes, and approaches vary from deterministic to empirical. A variety of methods are used to study gravel-bed river characteristics, including surveying channel geometry, particle tracing, bed-material and bed-load sampling, and developing sediment-discharge rating curves, among others. Additionally, efforts to manipulate the transport of sediment in gravel-bed rivers include the construction of debris traps, velocity control structures, or flow diversion structures. Regardless of the method implemented to alter the sediment regime of gravel-bed rivers, a thorough knowledge of watershed characteristics, local processes governing the transport, and collection of data characterizing sediment mobility is essential for the success of any management practice.

An assessment of the literature provides a guide for research of sediment-transport problems in gravel-bed rivers. Problems associated with extreme bed-load mobility in rivers and streams of the Edwards Plateau would benefit from a robust geographic, field, and laboratory assessment of the phenomenon. Geographic techniques include geographic information systems (GIS) analysis of field data, aerial photographic interpretation and time-series analysis of sediment condition at selected sites, and measurement of channel and basin characteristics. Field procedures should include bed-material particle-size analyses; surveys of channel geometry, bed configuration, and slope; bed-load measurements accompanied by flow velocity values; and particle tracing. Especially important are measurements during high-flow events and post-flood comparisons to earlier conditions. Field measurements could be used to develop sediment-transport rating curves, calculate shear stresses and stream power, compare with channel geometry or bed reconfiguration, and facilitate the design of structures or improvements to stream crossings. In comparison with field assessments, laboratory flume investigations have the advantage of controlling desired parameters, such as particle-size or channel width, to test the response of other variables. Additionally, flume experiments involving structural models might be conducted to test the effectiveness of possible designs or improvements to stream crossings.

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This section contains a comprehensive list of references useful for TxDOT research project 0–4695. Each of the four research entities contributed its own reference list with emphasis on a particular direction in the literature. The sequence number for each reference is shown at the end of the reference on the right-hand margin; the numbering is reset at the beginning of TTU, UH, and USGS sections. It is important to note that some overlap between the agency or institutional sections in selected references exists; the research team has elected to leave overlapping references in place. Brief annotations for selected references are interlaced throughout the bibliography. If more specific review of the reference was made in the body of this report, that is indicated in the interlaced annotation. Finally, at the expense of brevity the researchers have elected, as needed, to specifically reference chapters in books instead of citing just the book.

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Parker, G., 1978, Self-formed straight rivers with equilibrium banks and mobile bed—Part 2—The gravel river: Journal of Fluid Mechanics, v. 89, no. 1, p. 127–146.

Parker, G., 1979, Hydraulic geometry of active gravel rivers: American Society of Civil Engineers, Journal of the Hydraulics Division, v. 105, no. HY09, p. 1,185–1,201.

Parker, G., 1990, Surface-based bed load transport relation for gravel rivers: Journal of Hydraulic Research, v. 28, no. 4, p. 417–435.

Parker, G., and Andrew, E., 1986, Time development of meander bends: Journal of Fluid Mechanics, v. 162, p. 139–156.

Parker, G., Dhamotharan, S., and Stefan, H., 1982, Model experiment on mobile, paved gravel bed streams: Water Resources Research, v. 18, no. 5, p. 1,395–1,407.

Parker, G., Seminara, G., and Solari, L., 2003, Bed load at low Shields stress on arbitrarily sloping beds—Alternative entrainment formulation: Water Resources Research, v. 39, no. 7, p. 1,183.

Parker, G., and Izumi, N., 2000, Linear stability analysis of channel inspection—Downstream-driven theory: Journal of Fluid Mechanics, v. 419, p. 239–262.

Parker, G., and Klingeman, P.C., 1980, Bar resistance of gravel-bed streams: American Society of Civil Engineers, Journal of the Hydraulics Division, v. 106, no. HY10, p. 1,559–1,575.

Parker, G., and Klingeman, P.C., 1982, On why gravel bed streams are paved: Water Resources Research, v. 18, no. 5, p. 1,409–1,423.

Parker, G., Klingeman, P.C., and McLean, D.G., 1982, Bed load and size distribution in paved gravel-bed streams: American Society of Civil Engineers, Journal of the Hydraulics Division, v. 108, no. 4, p. 544–571.

Parker, G., Paola, C., and LeClaire, S., 2000, Purely erosional cyclic and solitary steps over a cohesion bed: Journal of Hydraulic Engineering, v. 126, no. 11, p. 818–826.

Parker, G., and Toro-Escobar, C.M., 2002, Equal mobility of gravel in streams—The remains of the day: Water Resources Research, v. 38, no. 11, p. 1–8.

Phillips, B.C., and Sutherland, A.J., 1989, Spatial lag effect in bed-load sediment transport: Journal of Hydraulic Research, v. 27, p. 115–133.

Phillips, B.C., and Sutherland, A.J., 1990, Temporal lag effect in bed-load sediment transport: Journal of Hydraulic Research, v. 28, p. 5–23.

Pitlick, J., 1992, Flow resistance under conditions of intense gravel transport: Water Resources Research, v. 28, no. 3, p. 891–903.

Reid, I., and Laronne, J.B., 1995, Bed load sediment transport in an ephemeral stream and a comparison with seasonal and perennial counterparts: Water Resources Research, v. 31, no. 3, p. 773–781.

Schoklitsch, A., 1934, Der geschiebetrieb und die geschiebefracht: Wasserkraft und Wasserwirtschaft, v. 29, no. 4, p. 37–43.

Sechet, P., and Le Guennec, B., 1999, Bursting phenomenon and incipient motion of the solid particles in the bed-load transport: Journal of Hydraulic Research, v. 37, no. 5, p. 683–696.

Sutherland, A.J., 1987, Static armour layer by selective erosion, *in* Thorne, C.R., Bathurst, J.C., and Hey, R.D., eds., Sediment transport in gravel-bed rivers: New York, Wiley, p. 243–267.

Walter, C.M., 1999, High concentration granular shear flow: Journal of Hydraulic Research, v. 37, no. 2, p. 229–247.

Wiberg, P.L., and Smith, J.D., 1991, Velocity distribution and bed roughness in high-gradient streams: Water Resources Research, v. 27, no. 5, p. 825–838.

Wilcock, P.R., 2001, Toward a practical method for estimating sediment-transport rates in gravel-bed rivers: Earth Surface Processes and Landforms, v. 26, p. 1,395–1,408.

Wilcock, P.R., and Crowe, J.C., 2003, Surface-based transport model for mixed-size sediment: Journal of Hydraulic Engineering, v. 129, no. 2, p. 120–128.

Zedler, E.A., and Street, R.L., 2001, Large-eddy simulation of sediment transport—Current over ripples: Journal of Hydraulic Engineering, v. 127, no. 6, p. 444–451.

Annotated Bibliography by Texas Tech University Researchers

No references were submitted by Texas Tech University. Researchers at Texas Tech University made contributions to the literature review by coordinating responsibilities among the other research entities, by communicating with TxDOT, and by making an extensive, but unsuccessful, search for publications directly addressing problems associated with sediment mobility at LWCs.

Annotated Bibliography by University of Houston Researchers

This section contains the literature reviewed by researchers at the University of Houston. The researchers elected to construct the bibliography topically and then alphabetically.

Stability Assessment and Debris-Flow Initiation

Casadei, M., Dietrich, W.E., and Miller, N.L., 2003, Testing a model for predicting the timing and location of shallow landslide initiation in soil-mantled landscapes: Earth Surface Processes and Landforms, v. 28, no. 9, p. 925–950.

- The authors review general approaches for predicting and modeling debris-flow initiating storms. The authors linked a dynamic and spatially distributed shallow subsurface runoff mode to an infinite slope model. The authors provide a generalized flow modeling diagram. Finally, the authors conclude that a mechanistic model is better than an empirical model for prediction of landslide initiation. This reference is repeated in the Debris-Flow Modeling section.

Cheng, Kuang-Yen, Lin, Lee-Kuo, and Chang, Shou-Young, 1997, Field investigation and GIS application in a potential hazardous area of debris flow, *in* First International Conference on Debris-Flow Hazards Mitigation—Mechanics, Prediction, and Assessment, San Francisco, Calif., Aug. 7–9, 1997, Proceedings: American Society of Civil Engineers, p. 83–92.

- The authors conclude that if the maximum grain size is smaller than about 50 millimeters, grain size distribution has little effect on the flowing process. The authors detail sampling and sieving methods. MapInfo was used to store data related to sampling location. The authors recommend using global positioning system (GPS) and GIS in stability assessments.

Church, M.A., and Miles, M.J., 1987, Meteorological antecedent to debris flow in southwestern British Columbia—Some case studies, *in* Costa, J.E., and Wieczorek, G.F., eds., Debris flow avalanches, process, recognition and mitigation: Boulder, Colo., Geological Society of America, Reviews in Engineering Geology, v. 7, p. 63–79.

- The authors conclude that a rainfall threshold for debris-flow initiation does not exist. Little rainfall can induce slides. Antecedent moisture content is an important component of debris flow and slide potential.

Curran, J.H., 2003, Channel stability and water quality of the Alagnak River, southwestern Alaska: U.S. Geological Survey Water-Resources Investigations Report 02–4184, 64 p.

- The author provides aerial photograph analysis for channel history studies and aerial photograph analysis and field reconnaissance for bank erosion studies.

Day, R.A., 1997, Preliminary observations of turbulent flow at culvert inlets: Journal of Hydraulic Engineering, v. 123, no. 2, p. 116–124.

- Electromagnetic current meters (ECM) were used to measure velocity distribution components.
  Turbulence intensities were calculated using:
  N = Total number of readings during the sampling period at distance ‘x’ from the culvert and depth ‘h’
  Ui = Velocity readings = Average velocity at distance ‘x’ from the culvert and depth ‘h’
  Tui = Turbulence in longitudinal direction

Doyle, M.W., and Harbor, J.M., 2001, Rapid assessment of channel stability in vicinity of road crossing: Journal of Hydraulic Engineering, v. 127, no. 1, p. 85–87.

- The authors describe the spatial and temporal definition of stability.

Fannin R.J., Jaakkola J., Wilkinson, J.M.T., and Hetherington, E.D., 2000, Hydrologic response of soils to precipitation at Carnation Creek, British Columbia, Canada: Water Resources Research, v. 36, no. 6, p. 1,481–1,494.

- The authors describe observed upper limit piezometric pressures (independent of rainfall intensity and duration). The pressures are believed to be related to preferential underground flow paths.

Fannin, R.J., Wise, M.P., Wilkinson, J.M.T., Thomson, B., and Hetherington, E.D., 1997, Debris flow hazard assessment in British Columbia: *in* First International Conference on Debris-Flow Hazards Mitigation—Mechanics, Prediction, and Assessment, San Francisco, Calif., Aug. 7–9, 1997, Proceedings: American Society of Civil Engineers, p. 197–206.

- The authors attempt to present a unified assessment method.

Flanagan, S.A., Furniss, M.J., Ledwith, T.S., Thiesen, S., Love, M., Moore, K., and Ory, J., 1998, Methods for inventory and environmental risk assessment of road drainage crossings: U.S. Department of Agriculture, Forest Service Technology and Development Program 9877 1809–SDTDC., 46 p.

- The authors recommend using GPS and GIS in stability assessment.

Haan, C.T., Barfield, B.J., and Hayes, J.C., 1994, Design hydrology and sedimentology for small catchments: San Diego, Calif., Academic Press, 588 p.

- In a textbook format, the authors provide an overview on sediment transport basics. A rational system of channel classification is described; the system is important in predicting channel response and future transformation. An analytical method for predicting channel changes is described.

Harvey, A.M., 1987, Sediment supply to upland streams—Influence on channel adjustment, *in* Thorne, C.R., Bathurst, J.C., and Hey, R.D., eds., Sediment transport in gravel-bed rivers: New York, Wiley, p. 121–150.

- The author concludes that at low sediment inputs, channel morphology is closely related to drainage area and sediment size, which relate to runoff magnitude and roughness, respectively. Single meandering channels are characteristic of a low sediment input; whereas, wide unstable braided channels reflect high sediment supplies. Sediment diameter has little influence on the channel type (braided/not braided); however, the volume of coarse sediment supply has a substantial effect. Representative sediment diameter is obtained by measuring the b-axis of the fifth clast of the largest stones at 25 different locations. Aerial photographs show morphology changes. Statistical analysis is described.

Johnson, K.A., and Sitar, N., 1990, Hydrologic conditions leading to debris-flow initiation: Canadian Geotechnical Journal, v. 27, p. 789–801.

- The authors conclude that rainfall intensity-duration thresholds for debris-flow initiation are not reliable (see Church and Miles, 1987). Antecedent soil moisture condition is a more relevant variable in predicting the slips. A tensiometer was used in a field study to monitor site pore pressure. The authors use the pressure head before rain, and a site moisture-retention curve predicts debris-flow initiation.

Johnson, P.A., and Brown, E.R., 2000, Stream assessment for multicell culvert use: Journal of Hydraulic Engineering, v. 126, no. 5, p. 381–386.

- The authors conclude that a multicell culvert will not perform well in an incised channel.

Johnson, P.A., Gleason, G.L., and Hey, R.D., 1999, Rapid assessment of channel stability in vicinity of road crossing: Journal of Hydraulic Engineering, v. 125, no. 6, p. 645–652.

- The authors review several stability assessment methods and suggest a quantitative method with 13 stability indicators and a weight factor associated to each. The method advocated by the authors is available in the latest edition of Hydraulic Engineering Circular No. 20.

Kang, Zhicheng, 1990, A study on sediment transportation in debris flow, *in* French, R.H., ed., International Symposium on Hydraulics/Hydrology of Arid Lands, San Diego, Calif., July 30–Aug. 2, 1990, Proceedings: New York, American Society of Civil Engineers, p. 688–693.

- The author describes three stages of debris flow:
  1. Early fluid debris flow or sediment-laden flood—low concentration and low flow rates.
  2. Viscous flow with increased flow rates and concentration.
  3. Fluid debris flow—flow rate decreases, which permits sedimentation.

Kjartanson, B.H., Heilers, G.A., Lohnes, R.A., and Klaiber, F.W., 1998, Soil-structure interaction analysis of longitudinal uplift of culverts: Journal of Geotechnical and Geoenvironmental Engineering, v. 124, no. 2, p. 128–139.

- The authors use full-scale field testing and numerical analysis and conclude that backfill foreslope has a substantial effect on uplift response.

Lagasse, P.F., Schall, J.D., and Richardson, E.V., 2001, Stream stability at highway structures (3d ed.): U.S. Department of Transportation, Federal Highway Administration, Hydraulic Engineering Circular No. 20, 258 p.

- Three levels of watershed analysis are suggested. A six-step process was designed to lead to a stability assessment, which was recognized as the first level.

Lane, P.N.J., and Sheridan, G.J., 2002, Impact of an unsealed forest road stream crossing—Water quality and sediment sources: Hydrological Processes, v. 16, no. 13, p. 2,599–2,612.

- The authors provide an “environmental side view” of culvert damages.

Powell, D.M., Reid, I., and Laronne, J.B., 1999, Hydraulic interpretation of cross-stream variations in bed-load transport: Journal of Hydraulic Engineering, v. 125, no. 12, p. 1,243–1,252.

- The authors believe that variations thought to reflect lateral variations in shear stress are induced by sidewall drag and cellular secondary currents.

Reid, M, 1994, A pore-pressure diffusion model for estimating landslide-inducing rainfall: Journal of Geology, v. 102, no. 6, p. 709–717.

Roberds, W.J., and Ho, K., 1997, Quantitative risk assessment and risk management methodology for natural terrain in Hong Kong, *in* First International Conference on Debris-Flow Hazards Mitigation—Mechanics, Prediction, and Assessment, San Francisco, Calif., Aug. 7–9, 1997, Proceedings: American Society of Civil Engineers, p. 207–218.

- The authors provide an apparently good suggestion for debris-flow initiation simulation, but quantification and implementation of the method is not clear.

Simons, D.B., and Sentürk, F., 1992, Sediment transport technology—Water and sediment dynamics: Highlands Ranch, Colo., Water Resources Publications, 919 p.

- The fundamentals of sediment transport are described. A specific stability assessment is defined as a first level of watershed hydrologic analysis. The authors propose data that should be collected for analysis.

Wieczorek, G.F., 1987, Effect of rainfall intensity and duration on debris flows in central Santa Cruz Mountains, California, *in* Costa, J.E., and Wieczorek, G.F., eds., Debris flow avalanches, process, recognition and mitigation: Boulder, Colo., Geological Society of America, Reviews in Engineering Geology, v. 7, p. 93–104.

- On the basis of observation and measurements, the author establishes thresholds for debris-flow triggering. The number of slides and hence probability of slides increases with rain intensity and duration above threshold. The author proposes an empirical model for predicting initiation caused by rain.

Wieczorek, G.F., Mandrone, G., and DeCola, L., 1997, Influence of hillslope shape on debris-flow initiation, *in* First International Conference on Debris-Flow Hazards Mitigation—Mechanics, Prediction, and Assessment, San Francisco, Calif., Aug. 7–9, 1997, Proceedings: American Society of Civil Engineers, p. 21–31.

- The authors consider the definitive topographic factors that contribute to site failures, which initiate debris flows. The results of the study reveal that curvature measured just above the soil slip, distance to ridge, and drainage area were statistically significant.

Debris-Flow Rheology

Iverson, R.M., 1997, Hydraulic modeling of unsteady debris-flow surges with solid-fluid interactions, *in* First International Conference on Debris-Flow Hazards Mitigation—Mechanics, Prediction, and Assessment, San Francisco, Calif., Aug. 7–9, 1997, Proceedings: American Society of Civil Engineers, p. 550–561.

Major, J.J., Iverson, R.M., McTigue, D.F., Macias, S., and Fiedorowicz, B.K., 1997, Geotechnical properties of debris flow sediments and slurries, *in* First International Conference on Debris-Flow Hazards Mitigation—Mechanics, Prediction, and Assessment, San Francisco, Calif., Aug. 7–9, 1997, Proceedings: American Society of Civil Engineers, p. 249–259.

Ryashchenko, T., and Makarov, S., 1997, Debris-flow solid-phase formation, *in* First International Conference on Debris-Flow Hazards Mitigation—Mechanics, Prediction, and Assessment, San Francisco, Calif., Aug. 7–9, 1997, Proceedings: American Society of Civil Engineers, p. 158–164.

Debris-Flow Countermeasures

Baldwin, J.E., Donley, H.F., and Howard, T.R., 1987, On debris flow/avalanche mitigation and control, San Francisco Bay area, California, *in* Costa, J.E., and Wieczorek, G.F., eds., Debris flow avalanches, process, recognition and mitigation: Boulder, Colo., Geological Society of America, Reviews in Engineering Geology, v. 7, p. 223–236.

- The authors divide debris flow paths into 3 segments, (1)source area, (2)main track, and (3) deposition area. Specific countermeasures were suggested for each.

Brake, D., Molnau, M., and King, J.G., 1997, Sediment transport distances and culvert spacings on logging roads within the Oregon Coast Mountain Range: American Society of Agricultural Engineers Paper 975018, v. 3, 12 p.

Campbell, R.H., 1975, Soil slips, debris flows, and rainstorms in Santa Monica Mountains and vicinity, southern California: U.S. Geological Survey Professional Paper 851, 51 p.

Chen, R.H., and Ho, M.L., 1997, The effect of open dams on debris flows, *in* First International Conference on Debris-Flow Hazards Mitigation—Mechanics, Prediction, and Assessment, San Francisco, Calif., Aug. 7–9, 1997, Proceedings: American Society of Civil Engineers, p. 626–635.

- The authors describe laboratory flume-study of the effects of four different types of flow breakers on debris flows: (1) gravitational, (2) grid, (3) step-grid, and (4) column. More debris could be retained by cubes of grid flow breakers with more layers. Column flow breakers are most efficient in decreasing flow energy, and gravitational breakers are best sited at the structure outlet.

DeNatale, J.S., Fiegel, G.L., Iverson, R.M., Major, J.J., La Husen, R.G., Duffy, J.D., and Fisher, G.D., 1997, Response of flexible wire rope barriers to debris-flow loading, *in* First International Conference on Debris-Flow Hazards Mitigation—Mechanics, Prediction, and Assessment, San Francisco, Calif., Aug. 7–9, 1997, Proceedings: American Society of Civil Engineers, p. 616–625.

- Flow velocities were measured using 1-square meter grid-lines marked on the runout pad, a time-stamped videotape recorder, overhead camera, and marked gravels. A barrier with 6- by 6-inch clear opening of chicken wire and a barrier with 12-inch opening interlocking rings and a silt screen retained debris successfully.

Fiebiger, G., 1997, Structures of debris flow countermeasures, *in* First International Conference on Debris-Flow Hazards Mitigation—Mechanics, Prediction, and Assessment, San Francisco, Calif., Aug. 7–9, 1997, Proceedings: American Society of Civil Engineers, p. 596–605.

- The authors decompose debris-flow management into flow prevention, active control, and passive control. Different countermeasures also are presented.

Hawley, P.M., 1989, Identification, evaluation and mitigation of debris flow hazards in British Columbia, *in* 20th International Erosion Control Association Conference, Vancouver, Canada, 1989, Proceedings: p. 1–6.

Hungr, O., Morgan, G.C., and Kellerhals, R., 1984, Quantitative analysis of debris torrent hazards for design of remedial measures: Canadian Geotechnical Journal, v. 21, p. 663–677.

Hungr, O., Morgan, G.C., VanDine, D.F., and Lister, D.R., 1987, Debris flow defenses in British Columbia, *in* Costa, J.E., and Wieczorek, G.F., eds., Debris flow avalanches, process, recognition and mitigation: Boulder, Colo., Geological Society of America, Reviews in Engineering Geology, v. 7, p. 201–222.

- The authors decompose flow path into source, track, and deposition. They provide a classification and examples of debris-flow countermeasures, as well as a guide for hazard mapping.

Innes, J.L., 1983, Lichenometric dating of debris flow deposits in the Scottish Highlands: Earth Surface Processes and Landforms, v. 8, p. 579–588.

Jeyapalan, J.K., Duncan, J.M. and Seed, H.B., 1983, Analyses of flow failures of mine tailing dams: Journal of Geotechnical Engineering, v. 109, no. 2, p. 150–171.

Lin, P.S., Chang, W.J., and Liu, K.S., 1997, Retaining function of open-type sabo dams, *in* First International Conference on Debris-Flow Hazards Mitigation—Mechanics, Prediction, and Assessment, San Francisco, Calif., Aug. 7–9, 1997, Proceedings: American Society of Civil Engineers, p. 636–645.

Mizuyama, T., and Mizuno, H., 1997, Prediction of debris flow hydrographs passing through grid type control structures, *in* First International Conference on Debris-Flow Hazards Mitigation—Mechanics, Prediction, and Assessment, San

Francisco, Calif., Aug. 7–9, 1997, Proceedings: American Society of Civil Engineers, p. 74–82.

Pierson, T.C., and Costa, J.E., 1987, A rheologic classification of subaerial sediment water flows, *in* Costa, J.E., and Wieczorek, G.F., eds., Debris flow avalanches, process, recognition and mitigation: Boulder, Colo., Geological Society of America, Reviews in Engineering Geology, v. 7, p. 1–12.

Rothwell, R.L., 1983, Erosion and sediment control at road-stream crossings: The Forestry Chronicle, v. 59, no. 2, p. 62–66.

Taylor, S.E., Rummer, R.B., Yoo, K.H., Welch, R.A., and Thompson, J.D., 1999, Forest roads—What we know and don't know: Journal of Forestry, v. 97, no. 8, p. 12–17.

VanDine, D.F., 1986, Debris flow and debris torrents in the southern Canadian Cordillera: Canadian Geotechnical Journal, v. 22, p. 44–68.

- This paper describes pertinent characteristics, causes, and effects of debris flow. Mitigation methods and an explanation of critical discharge also are provided.

VanDine, D.F., Hungr, O., Lister, D.R., and Chatwin, S.C., 1997, Channelized debris flow mitigative structures in British Columbia, Canada, *in* First International Conference on Debris-Flow Hazards Mitigation—Mechanics, Prediction, and Assessment, San Francisco, Calif., Aug. 7–9, 1997, Proceedings: American Society of Civil Engineers, p. 606–615.

- A presentation of different countermeasures with construction costs is provided. The use of in-place material is simpler and less expensive.

Wilson, R.O., Little, C.D., Mendrop, K.B., Smith, J.B., and Montague, C.A., 1995, Channel stabilization methods in the demonstration erosion control project, *in* Domenica, M.F., ed., Integrated Water Resources Planning for the 21st Century, 22d Annual Conference, Cambridge, Mass., May 7–11, 1995, Proceedings: Reston, Va., American Society of Civil Engineers, p. 1,089–1,092.

Yoho, N.S., 1980, Forest management and sediment production in the South—A review: Southern Journal of Applied Forestry, v. 4, no. 1, p. 27–36.

Debris-Flow Magnitude

Cronin, V.S., Slosson, J.E., Slosson, T.L., and Shuirman, G., 1990, Deadly debris flows on I-5 near Grapevine, CA, *in* French, R.H., ed., International Symposium on Hydraulics/Hydrology of Arid Lands, San Diego, Calif., July 30–Aug. 2, 1990, Proceedings: New York, American Society of Civil Engineers, p. 78–83.

- Debris-flow rates can be 65 percent more and a 100-year storm runoff four times greater than those used for design. Magnitudes can be strong enough to sweep away loaded tractor-trailer rigs and cars.

Johnson, P.A., McCuen, R.H., and Hromadka, T.V., 1991, Magnitude and frequency of debris flows: Journal of Hydrology, v. 123, no. 1–2, p. 69–82.

- An empirical formula to predict debris-flow rate is presented. This formula does not incorporate a local geology factor. The authors did not use slope failure analysis for correlation because high variability of volume of debris generated at each event, and used a log-normal distribution instead. The burn factor, relief ratio, and hypsometric index were retained as major factors.

Melis, T.S., Webb, R.H., and Griffiths, P.G., 1997, Debris flows in Grand Canyon National Park—Peak discharges, flow transformations, and hydrographs, *in* First International Conference on Debris-Flow Hazards Mitigation—Mechanics, Prediction, and Assessment, San Francisco, Calif., Aug. 7–9, 1997, Proceedings: American Society of Civil Engineers, p. 727–736.

- The authors attempt to relate debris storm hydrographs to flow characteristics. Peak discharges were estimated using the superelevation method. Three steps in debris-flow discharge are suggested. A quantitative hydrograph is not provided.

Quick, M.C., 1991, Reliability of flood discharge estimates: Canadian Journal of Civil Engineering, v. 18, no. 4, p. 624–630.

- The slope-area method is presented. It is argued that this method is superior for flood discharge estimation because of errors in Manning's *n*, observed in post-flood channel cross-sectional measurements.

Slosson, J.E., and Slosson, T.L., 1990, Olacha debris flow—An example of an isolated damaging event, *in* French, R.H., ed., International Symposium on Hydraulics/Hydrology of Arid Lands, San Diego, Calif., July 30–Aug. 2, 1990, Proceedings: New York, American Society of Civil Engineers, p. 72–77.

- A description of damages caused by a debris flow is provided. Additionally, the lateral size distribution of the deposit is given.

Debris-Flow Modeling

Casadei, M., Dietrich, W.E., and Miller, N.L., 2003, Testing a model for predicting the timing and location of shallow landslide initiation in soil-mantled landscapes: Earth Surface Processes and Landforms, v. 28, no. 9, p. 925–950.

De Roo, A.P.J., 1998, Modelling runoff and sediment transport in catchments using GIS: Hydrological Processes, v. 12, no. 6, p. 905–922.

Egashira, S., Miyamoto, K., and Itoh, T., 1997, Constitutive equations of debris flow and their applicability, *in* First International Conference on Debris-Flow Hazards Mitigation—Mechanics, Prediction, and Assessment, San Francisco, Calif., Aug. 7–9, 1997, Proceedings: American Society of Civil Engineers, p. 340–349.

Jan, Chyan-Deng, 1997, A study on numerical modeling of debris flows, *in* First International Conference on Debris-Flow Hazards Mitigation—Mechanics, Prediction, and Assessment, San Francisco, Calif., Aug. 7–9, 1997, Proceedings: American Society of Civil Engineers, p. 717–726.

Nicholas, A.P., 2001, Computational fluid dynamics modelling of boundary roughness in gravel-bed rivers—An investigation of the effects of random variability in bed elevation: Earth Surface Processes and Landforms, v. 26, no. 4, p. 345–362.

Design and Construction of Low-Water Crossings

Aust, W.M., Visser, R., Gallagher, T., Roberts, T., and Poirot, M., 2003, Cost of six different stream crossing options in the Appalachian area: Southern Journal of Applied Forestry, v. 27, no. 1, p. 66–70.

Christopherson, A.B., Braun, K.W., Thieman, D.S., and Hardison, J.H., 2002, Performance of Kuparuk River submersible bridges and low water roadway, *in* Merrill, K.S., ed., Cold regions engineering—Cold regions impacts on transportation and infrastructure, 11th International Conference, Anchorage, Alaska, May 20–22, 2002, Proceedings: Reston, Va., American Society of Civil Engineers, p. 412–423.

Gu, R.R., McDonald, T.J., and Lohnes, R.A., 2003, Low-water stream crossings—The Iowa experience: Transportation Research Record, v. 2, no. 1819, p. 355–361.

Lohnes, R.A., Gu, R.R., McDonald, T., and Jha, M.K., 2001, Low water stream crossings—Design and construction recommendations: Center for Transportation Research and Education Project 01–78, Iowa Department of Transportation Project TR–453, 50 p.

Milauskas, S.J., 1988, Low-water stream crossing option for southern haul roads: Southern Journal of Applied Forestry, v. 12, no. 1, p. 11–15.

Pienaar, P.A., and Visser, A.T., 1995, Methodology for functional design of low-level river crossings in South Africa, *in* Modeling and model verification of testing pavement layers and materials, and low-cost drainage structures: National Academy of Sciences, Transportation Research Board, R1504, p. 112–117.

Tsihrintzis, V.A., 1995, Effect of sediment on drainage-culvert serviceability: Journal of Performance of Constructed Facilities, v. 9, no. 3, p. 172–183.

- The authors present a diagnosis of bad culvert design (slope, Manning's *n*, nature of flow considered).

Sediment Sampling and Analysis

Bunte, K., and Abt, S.R., 2001, Sampling frame for improving pebble count accuracy in coarse gravel-bed streams: Journal of American Water Resources Association, v. 37, no. 4, p. 1,001–1,014.

Butler, J.B., Lane, S.N., and Chandler, J.H, 2001, Automated extraction of grain-size data from gravel surfaces using digital image processing: Journal of Hydraulic Research, v. 39, no. 5, p. 519–529.

Church, M.A., and Hassan, M.A., 2002, Mobility of bed material in Harris Creek: Water Resources Research, v. 38, no. 11, p. 1,237.

Church, M.A., McClean, D.G., and Wolcott, J.F., 1987, River bed gravels—Sampling and analysis, *in* Thorne, C.R., Bathurst, J.C., and Hey, R.D., eds., Sediment transport in gravel-bed rivers: New York, Wiley, p. 43–88.

Crowder, D.W., and Diplas, P., 1997, Sampling heterogeneous deposits in gravel-bed streams: Journal of Hydraulic Engineering, v. 123, no. 12, p. 1,106–1,117.

DeVries, P., 2002, Bedload layer thickness and disturbance depth in gravel bed streams: Journal of Hydraulic Engineering, v. 128, no. 11, p. 983–991.

Eaton, B.C., and Lapointe, M.F., 2001, Effects of large floods on sediment transport and reach morphology in the cobble-bed Sainte Marguerite River: Geomorphology, v. 40, no. 3–4, p. 291–309.

Fraccarollo, L., and Marion, A., 1995, Statistical approach to bed-material surface sampling: Journal of Hydraulic Engineering, v. 121, no. 7, p. 540–545.

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- The author documents the operation of a facility designed to calibrate bed-load samplers. Data tables are available for measured bed-load transport rates.

Jaeggi, M.N.R., 1987, Interaction of bed load transport with bars, *in* Thorne, C.R., Bathurst, J.C., and Hey, R.D., eds., Sediment transport in gravel-bed rivers: New York, Wiley, p. 829–841.

- The author examines bar migration rates with respect to bed-load transport.

Jaeggi, M.N.R., 1992, Effect of engineering solutions on sediment transport, *in* Billi, P., Hey, R.D., Thorne, C.R., and Tacconi, P., eds., Dynamics of gravel-bed rivers: New York, Wiley, p. 593–605.

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- A number of small drainage basins were studied to estimate total sediment discharge. A suspended load curve and a bed-load equation were used.

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Jordan, P.R., 1965, Fluvial sediment of the Mississippi River at St. Louis, Missouri: U.S. Geological Survey Water-Supply Paper 1802, 89 p.

- The author provides figures, data tables, and a summary of an investigation of suspended sediment, flow resistance, and bed-load transport in the Mississippi River at St. Louis. Different equations were used and compared to estimate bed material and bed-load discharge.

Kellerhals, R., 1982, Effect of river regulation on channel stability, *in* Hey, R.D., Bathurst, J.C., and Thorne, C.R., eds., Gravel-bed rivers: New York, Wiley, p. 685–715.

Kircher, J.E., 1981, Sediment analyses for selected sites on the South Platte River in Colorado and Nebraska, and the North Platte and Platte Rivers in Nebraska—Suspended sediment, bedload, and bed material: U.S. Geological Survey Open-File Report 81–207, 48 p.

- The author provides figures and data tables of discharge, suspended sediment concentrations, bed-load transport rates, and bed-material and bed-load particle sizes.

Klingeman, P.C., Beschta, R.L., Komar, P.D., and Bradley, J.B., eds., 1998, Gravel-bed rivers in the environment: Highlands Ranch, Colo., Water Resources Publications, 832 p.

- A large edited volume of gravel-bed river processes, morphology, and applications.

Klingeman, P.C., and Emmett, W.W., 1982, Gravel bedload transport processes, *in* Hey, R.D., Bathurst, J.C., and Thorne, C.R., eds., Gravel-bed rivers: New York, Wiley, p. 141–179.

- The authors discuss advances in bed-material and bed-load measurement, as well as bed-load transport characteristics. Bed-load transport is indicated as noticeably different between rising and falling limbs.

Knott, J.M., and Dunnam, C.A., 1969, Sedimentation in upper Stony Creek Basin, eastern flank of the Coast Ranges of northern California—Sedimentation in small drainage basins: U.S. Geological Survey Water-Supply Paper 1798–F, 35 p.

- A suspended-sediment curve and estimate of bed-load transport using common formulas were developed for a creek in California.

Knott, J.M., Lipscomb, S.W., and Lewis, T.W., 1987, Sediment transport characteristics of selected streams in the Susitna River Basin, Alaska—Data for water year 1985 and trends in bedload discharge, 1981–85: U.S. Geological Survey Open-File Report 87–229, 51 p.

- Suspended-load and bed-load transport rating curves were developed for a few stations in Alaska. The annual total sediment load was determined and event-based trends in bed load were interpreted.

Kodama, Y., 1994, Downstream changes in the lithology and grain size of fluvial gravels, the Watarase River, Japan—Evidence of the role of abrasion in downstream fining: Journal of Sedimentary Research, v. A64, no. 1, p. 68–75.

- The author examines the downstream fining of gravel with respect to lithology.

Komar, P.D., 1987, Selective gravel entrainment and the empirical evaluation of flow competence: Sedimentology, v. 34, p. 1,165–1,176.

Komar, P.D., and Shih, S., 1992, Equal mobility versus changing bedload grain sizes in gravel-bed streams, *in* Billi, P., Hey, R.D., Thorne, C.R., and Tacconi, P., eds., Dynamics of gravel-bed rivers: New York, Wiley, p. 73–106.

- The authors discuss the assumption of equal mobility to evaluate bed-load transport rates. An interpretation of a transitional state when bed-load particle size approaches the bed-material size is made, and equal mobility is affected by pavement layers.

Kuhnle, R.A., 1992, Fractional transport rates of bedload on Goodwin Creek, *in* Billi, P., Hey, R.D., Thorne, C.R., and Tacconi, P., eds., Dynamics of gravel-bed rivers: New York, Wiley, p. 141–155.

Lamberti, A., and Paris, E., 1992, Analysis of armouring processes through laboratory experiments, *in* Billi, P., Hey, R.D., Thorne, C.R., and Tacconi, P., eds., Dynamics of gravel-bed rivers: New York, Wiley, p. 227–250.

Lane, S.N., Richards, K.S., and Chandler, J.H., 1995, Morphological estimation of the time-integrated bed load transport rate: Water Resources Research, v. 31, no. 3, p. 761–772.

Langbein, W.B., and Leopold, L.B., 1968, River channel bars and dunes—Theory of kinematic waves: U.S. Geological Survey Professional Paper 422–L, 20 p.

- Dunes and gravel bars might be considered kinematic waves or a grouping of moving objects in zones along a flow path through which the objects pass. This theory was tested through review of flume studies and particle-tracking techniques in the field.

Laronne, J.B., and Duncan, M.J., 1992, Bedload transport paths and gravel bar formation, *in* Billi, P., Hey, R.D., Thorne, C.R., and Tacconi, P., eds., Dynamics of gravel-bed rivers: New York, Wiley, p. 177–202.

- The authors use gravel tracers, cross-sectional surveying, and aerial photography to investigate variability of bar formation and bed reconfiguration.

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Leopold, L.B., 1992, Sediment size that determines channel morphology, *in* Billi, P., Hey, R.D., Thorne, C.R., and Tacconi, P., eds., Dynamics of gravel-bed rivers: New York, Wiley, p. 297–311.

Leopold, L.B., Bagnold, R.A., Wolman, M.G., and Brush, L.M., Jr., 1960, Flow resistance in sinuous or irregular channels: U.S. Geological Survey Professional Paper 282–D, p. 111–134.

- The authors discuss a flume study of the relation between flow resistance and velocity.

Leopold, L.B., and Emmett, W.W., 1997, Bedload and river hydraulics—Inferences from the East Fork River, Wyoming: U.S. Geological Survey Professional Paper 1583, 52 p.

- The authors document the installation and operation of a sophisticated cross-channel, bed-load trap and provide data tables and interpretations of the data for the period 1973–79, including differences in transport rates from pools to riffles and low- to high-flow.

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- The authors introduce the techniques of "hydraulic geometry," or power functions that relate channel geometry to hydraulic variables.

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- The author investigates the relation between the Manning roughness coefficient and particle sizes in natural channels.

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- The authors relate the estimated total sediment transport (1960–63) to basin characteristics, including geologic and topographic conditions.

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- The authors document an investigation of mean velocity, water-surface slope, bed-material size, and flow characteristics of a high-gradient, shallow-depth mountain stream. The paper consists mostly of data tables.

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- The reference is described in the body of this report.

Meade, R.H., Myrick, R.M., and Emmett, W.W., 1980, Field data describing the movement and storage of sediment in the

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- The authors provide a summary and data tables of bed elevations along one river reach during a snow runoff episode.

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Mundorff, J.C., 1964, Fluvial sediment in Kiowa Creek Basin, Colorado: U.S. Geological Survey Water-Supply Paper 1798–A, 70 p.

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- The authors provide a summary and interpretations of hydrologic data, sediment concentrations, and bed-material size distributions for six stations. Bed-load rates, calculated with the modified Einstein equation, were correlated to hydraulic variables. The use of one value for particle size might not account for streambeds with a bimodal distribution.

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- The author documents the use of a routing model for water and sediment in natural channels. The model was used in post-flood streambed analysis of three river reaches.

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Pickup, G., 1976, Adjustment of stream-channel shape to hydrologic regime: Journal of Hydrology, v. 30, p. 365–373.

Pitlick, John, 1992, Flow resistance under conditions of intense gravel transport: Water Resources Research, v. 28, no. 3, p. 891–903.

- A study of the North Fork Toutle River, Washington, was conducted using hydraulic and sediment-transport data for velocities up to about 9.8 feet per second and shear stresses up to 7 times critical values for bed-load transport. Weak bed-load transport over a plan gravel bed has little effect on flow resistance. At more than

3 times critical shear stress, irregular bed geometry emerges and flow resistance increases greatly. Additional discussion of logarithmic velocity profiles and flow resistance is made. This research could be important in assessing flow resistance in Edwards Plateau gravel-bed channels.

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- The authors place sediment supply and mobilization in context with the magnitude of hydrologic events and the sequence in which they occur.

Porterfield, George, 1972, Computation of fluvial-sediment discharge: U.S. Geological Survey Techniques of Water-Resources Investigations, chap. C3, book 3, 66 p.

Prestegaard, K.L., 1983, Variables influencing water-surface slopes in gravel-bed streams at bankfull stage: Geological Society of America Bulletin, v. 94, p. 673–678.

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Rathburn, R.E., Kennedy, V.C., and Culbertson, J.K., 1971, Transport and dispersion of fluorescent tracer particles for the flat-bed condition, Rio Grande conveyance channel, near Bernardo, New Mexico: U.S. Geological Survey Professional Paper 562–I, 155 p.

- The authors apply a fluorescent particle tracer technique to clasts of various sizes and specific gravities to track position, dispersion, and transport rates.

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Richards, K.S., 1973, Hydraulic geometry and channel roughness—a non-linear system: American Journal of Science, v. 273, p. 877–896.

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Schoklitsch, A., 1934, Der geschiebetrieb und die geschiebefracht: Wasserkraft und Wasserwirtschaft, v. 29, no. 4, p. 37–43.

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- The authors qualitatively and quantitatively describe the magnitude and effects of an unprecedented flood along the Rubicon River. Tractive force was determined indirectly to determine competency of the flow to transport boulders.

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- Methods are presented to estimate flow resistance, average velocity, and bed configuration of alluvial channels. The authors provide an extensive review of the relations between the variables above along with numerous relational figures.

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- A bed-load transport equation based on velocity and height of ripples and dunes is applied to flume observations with reasonable success.

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- The authors studied 12 gravel-bed streams in the Rocky Mountains of Colorado. The threshold for bed-load transport occurs, on average, at 34 percent of bankfull discharge, and flows up to and including the bankfull discharge transport an average of 69 percent of the total volume of bed load. The concepts of effective discharge, flow-duration curves, shear stress, and particle size (D_{84}) are considered.

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- The author discusses equations used to determine bedload transport rates.

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- A model for the velocity distribution over a poorly sorted bed is derived and applied to streams with high gradients and coarse gravel beds. The authors report that the values of mean velocity, normalized by shear velocity, are well represented by a simple log linear relation in terms of relative roughness D_{84}/h, where D_{84} is the 84th percentile particle diameter and h is depth of flow. This reference might have application for the 0–4695 project as well as the RMC3-Hydraulics TAP LRRP TASK 14.4.1 "Investigate Vertical Velocity Distribution in High Velocity Streams."

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- The author provides a critical review of typical methods to estimate sediment transport rates in gravel-bed rivers including equations and sampling campaigns. An alternative approach is described.

Williams, G.P., 1970, Flume width and water depth effects in sediment-transport experiments: U.S. Geological Survey Professional Paper 562–H, 37 p.

- The author summarizes a series of flume experiments with controlled sediment transport rates, particle size, depth, and width. Dependent variables were discharge, mean velocity, slope, and bed-form characteristics.

Williams, G.P., and Rosgen, D.L., 1989, Measured total sediment loads (suspended loads and bedloads) for 93 United States streams: U.S. Geological Survey Open-File Report 89–67, 128 p.

- The authors provide data tables for suspended load, bed load, water discharge, flow velocity, hydraulic geometry variables, suspended sediment concentration, water temperature, and particle-size distributions.

Wolman, M.G., 1954, A method of sampling coarse river-bed material: Transactions of the American Geophysical Union, v. 35, no. 6, p. 951–956.

- The author introduces the well-known "Wolman" method.

Wolman, M.G., and Miller, J.P., 1960, Magnitude and frequency of forces in geomorphic processes: Journal of Geology, v. 68, p. 54–74.

- The authors introduce the concept of "effective discharge," described as "a relatively frequent event and approximately corresponds to bankfull discharge (Emmett and Wolman, 2001)."

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- A comparison of two different approaches to sediment transport is made, including (1) the stream power approach, and (2) the unit stream power approach.

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8027 Exchange Drive
Austin, TX 78754–4733

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