APPENDIX D

Estimating Sediment Discharge

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D.1 INTRODUCTION

Sediment-discharge measurements usually are available on a discrete or periodic basis. However, estimates of sediment transport often are needed for unmeasured periods, such as when daily or annual sediment-discharge values are sought, or when estimates of transport rates for unmeasured or hypothetical flows are required. Selected methods for estimating suspended-sediment, bed-load, bed-material-load, and total-load discharges have been presented in some detail elsewhere in this volume. The purposes of this contribution are to present some limitations and potential pitfalls associated with obtaining and using the requisite data and equations to estimate sediment discharges and to provide guidance for selecting appropriate estimating equations.

Records of sediment discharge are derived from data collected with sufficient frequency to obtain reliable estimates for the computational interval and period. Most sediment-discharge records are computed at daily or annual intervals based on periodically collected data, although some partial records represent discrete or seasonal intervals such as those for flood periods. The method used to calculate sediment-discharge records is dependent on the types and frequency of available data. Records for suspended-sediment discharge computed by methods described by Porterfield (1972) are most prevalent, in part because measurement protocols and computational techniques are well established and because suspended sediment composes the bulk of sediment discharges for many rivers. Discharge records for bed load, total load, or in some cases bed-material load plus wash load are less common.

Reliable estimation of sediment discharges presupposes that the data on which the estimates are based are comparable and reliable. Unfortunately, data describing a selected characteristic of sediment were not necessarily derived—collected, processed, analyzed, or interpreted—in a consistent manner. For example, bed-load data collected with different types of bed-load samplers may not be comparable (Gray et al. 1991; Childers 1999; Edwards and Glysson 1999). The total suspended solids (TSS) analytical method tends to produce concentration data from open-channel flows that are biased low with respect to their paired suspended-sediment concentration values, particularly when sand-size material composes more than about a quarter of the material in suspension. Instantaneous sediment-discharge values based on TSS data may differ from the more reliable product of suspended-sediment concentration values and the same water-discharge data by an order of magnitude (Gray et al. 2000; Bent et al. 2001; Glysson et al. 2000; 2001). An assessment of data comparability and reliability is an important first step in the estimation of sediment discharges.

There are two approaches to obtaining values describing sediment loads in streams. One is based on direct measurement of the quantities of interest, and the other on relations developed between hydraulic parameters and sediment-transport potential. In the next sections, the most common techniques for both approaches are briefly addressed.

D.2 SUSPENDED-SEDIMENT CONCENTRATION INTERPOLATION METHOD

Suspended-sediment-discharge records are derived from analytical results of sediment samples and water discharge. Most are computed as daily time-series records. Some are computed on an annual basis, and some are computed for fractions of a day that can be summed to derive daily-value data.

The fundamental methods used by the U.S. Geological Survey (USGS) for collecting and computing daily suspended-sediment-discharge records have not changed since the 1940s. The most commonly used method is based on the derivation of a temporal relation by interpolating between measured suspended-sediment concentration values and using measured and estimated concentration values with time-weighted water-discharge values to calculate suspended-sediment discharges (Porterfield 1972). A temporal plot of suspended-sediment concentration values representative of the mean cross-sectional value at the time of collection is developed. A smooth curve, or in some cases a linear interpolation based on these values and other hydrologic information, is developed. Concentration values are merged with discharge values representing a selected time interval and summed to derive daily suspended-sediment discharges using the equation

$$Q_s = Q_w C_s k \qquad \text{(D-1)}$$

where

Q_s = suspended-sediment discharge, in tons per day or metric tonnes per day;
Q_w = water discharge, in cubic feet per second or cubic meters per second;
C_s = mean concentration of suspended sediment in the cross-section in milligrams/liter; and
k = a coefficient based on the unit of measurement of water discharge that assumes a specific weight of 2.65 for sediment, and equals 0.0027 in inch-pound units, or 0.0864 in SI units.

The suspended-sediment concentration relations based on linear interpolation and associated water discharges for two floods on the Mississippi River at Thebes, Illinois, are shown in Fig. D-1 (Holmes 1993).

Reliable suspended-sediment records cannot be obtained unless all concentration values used in the computation are representative of the mean cross-sectional value. Most suspended-sediment data in the United States are collected from only part of the stream cross-section, either manually as a surface dip or a single vertical, or automatically from a point in the stream. Because the derived concentration values may not represent the mean cross-sectional sediment concentration, they must be adjusted by empirically developed coefficients computed for the period of interest from concentrations obtained from partial-section samples and concurrently collected velocity- and depth-integrated, cross-sectional samples. It is seldom possible to collect a single cross-sectional sample in the length of time that it takes to obtain a sample with a pumping sampler, or to collect a single-vertical sample. Consequently, it is recommended that partial-section samples be collected immediately before and after one or more cross-sectional samples are collected. This procedure will serve to better define any changes in concentration that might occur during the time period necessary to collect the cross-sectional samples. If it is suspected that the concentration is changing rapidly during the collection of the cross-sectional samples, additional interim partial-section samples should be collected during the time that the cross-sectional samples are collected. Collection and comparison of these interim samples should be repeated during routine site visits, as well as during rising and falling stages, and during high flows for all seasons.

Cross-sectional coefficients usually are applied on a discharge-weighted or time-weighted basis. Increasing flow rates tend to be correlated with higher turbulence, more efficient mixing of sediment particles, and changes in the percentage of sand-size material in transport. Concentration values adjusted by discharge-weighted cross-sectional coefficients generally have been found to be more reliable and accurate than those adjusted by time-weighted coefficients. Regardless of the application method used, insufficient definition of these coefficients, or their subsequent misapplication, can result in substantial errors in the derivation of daily suspended-sediment-discharge records. A more detailed discussion of the development and application of cross-sectional coefficients is provided by Guy (1970) and Porterfield (1972) (also see Chapter 5 in this volume).

Computer software developed since the 1980s facilitates computational procedures and improves the accuracy of suspended-sediment-discharge records (Koltun et al. 1994; McKallip et al. 2001). The method of McKallip et al. (2001)

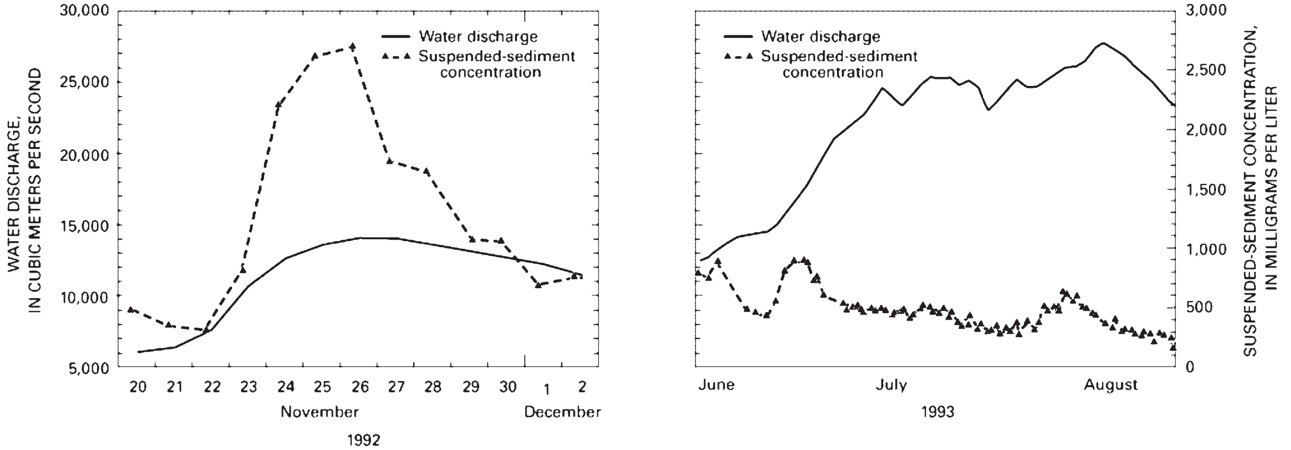

Fig. D-1. Water-discharge and suspended-sediment concentration graphs for two floods on the Mississippi River at Thebes, Illinois (USGS Streamgauging Station 07022000; Holmes 1993, p. 17).

provides advanced options for manipulating and portraying the sediment and flow data and for reliable development and application of cross-sectional coefficients.

D.3 TRANSPORT-CURVE METHOD FOR SUSPENDED SEDIMENT LOAD, BED LOAD, AND TOTAL LOAD

The empirical relation between water discharge and sediment concentration (or sediment discharge) at a site can be expressed graphically as a single average relation (Fig. D-2), and as a temporal relation (Fig. D-3). Such relations, referred to collectively as sediment-transport curves, are widely used to estimate sediment concentrations or sediment discharges for periods when water-discharge data are available but sediment data are not (Colby 1956). Sediment-transport curves can be classified according to either the period of the basic data that define the curve—instantaneous, daily, monthly, annual, or flood-period—or the kind of sediment discharge that the curve represents—suspended-sediment load, bed load, or total load (Glysson 1987).

Transport curves such as those in Figs. D-2 and D-3 are usually developed from logarithmically transformed data with water discharge as the independent variable and either sediment concentration or sediment discharge as the dependent variable. Bean and Al-Nassri (1988) consider use of sediment discharge as the dependent variable to be misleading because the goodness of fit implied by the relation is spurious.

Transport-curve relations are usually defined as a power function (Glysson 1987),

$$Q_s = aQ_w^{\,b} \tag{D-2}$$

where

Q_s = suspended-sediment discharge, in tons per day or tonnes per day;
Q_w = water discharge, in cubic feet per second or cubic meters per second;
a = the intercept; and
b = the slope.

The function can be formulated as either a linear or nonlinear model to find the solution for transport-curve parameters a and b. Formulation of the power function as a linear model requires a logarithmic transformation to linearize the function and subsequently correct for subunity bias in the retransformation of sediment-discharge or -concentration estimates (Crawford 1991). The degree to which constituent discharges are underestimated as a result of retransformation is a function of the goodness-of-fit of the regression line. Generally, increasing the data scatter around the regression line results in decreasing estimates of the value of the dependent variable.

Various methods are available for developing bias correction factors. Ferguson (1986) proposed a bias correction factor based on the standard error of the regression equation. Although satisfactory in many practical situations, Ferguson's (1986) method not only fails to eliminate bias but also can lead to severe overestimation of constituent loads (Cohn et al. 1989). Duan (1983) developed the "smearing estimator," which is insensitive to nonnormality in the distribution of regression residuals about the logarithmic model and avoids the overcompensation of Ferguson's (1986)

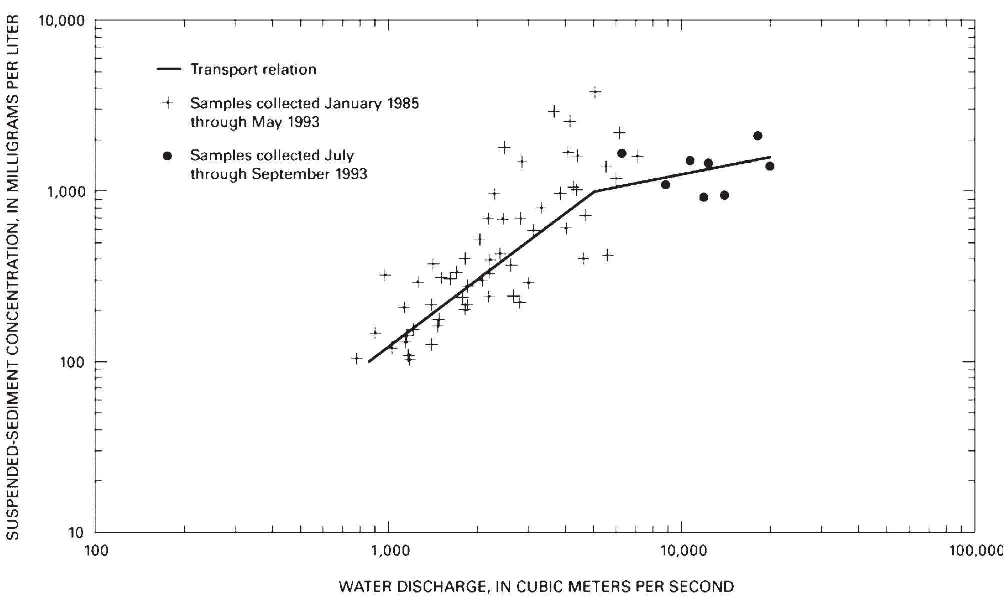

Fig. D-2. Relation between water discharge and suspended-sediment concentration for the Missouri River at Hermann, Missouri (USGS Streamgauging Station 06934500; Holmes 1993, p. 5).

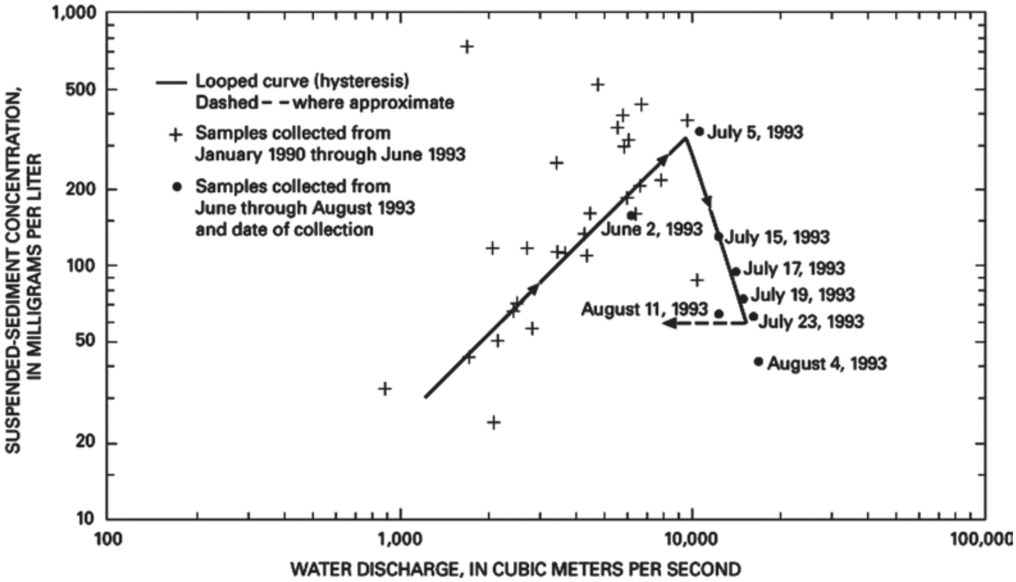

Fig. D-3. Relation between water discharge and suspended-sediment concentration for the Mississippi River below Grafton, Illinois (USGS Streamgauging Station 05587455; Holmes 1993, p. 4).

approach. A method proposed by Cohn et al. (1989) assumes normally distributed residuals about the logarithmic model and results in an exact minimum variance unbiased estimator and its variance.

A direct relation between Q_w and Q_s in streams is rarely present. A lack of synchronization between the peaks of water discharge and sediment concentration over a flood hydrograph is more the rule than the exception. That means that in parts of the hydrograph where sediment discharge is increasing, sediment concentration may be decreasing, and vice versa. That effect is clearly present in the 1993 Mississippi River flood at Thebes, Illinois (Fig. D-1), where in parts of the hydrograph not only are changes in the magnitude of water discharge not accompanied by associated changes in sediment concentration, but at times they show opposite trends.

A more complicated example of transport relations is demonstrated by a graph of instantaneous flow versus suspended-sand (0.062–2.0 mm) concentration data for the Colorado River near Grand Canyon, Arizona (USGS streamgauging station 09402500, Fig. D-4) (David Topping, U.S. Geological Survey, written communication, 2003), located 164 river km downstream from Glen Canyon Dam. General transport relations are depicted within three regions, or envelopes, on the graph. The left-most envelope encompasses the bulk of sand data for the period collected before closure of the dam in 1962. The right-most envelope encompasses most of the sand-concentration data collected after the upper river main channel sediment supply was essentially cut off following dam closure, through 1986. The central envelope encompasses most of the data for the period from 1991 to 2001. These general relations reflect a combination of dynamics in this river system, including natural variability in sand transport as a function of short-term (hours-to-days) flow fluctuations; cut-off of the main stem sediment supply 164 km upstream from the gauge; variability in the timing and rates of flow and sand transport from tributaries to the Colorado River in the reach between the dam and the gauge; and sand storage and redistribution patterns that occur over short- and long time-scales in that river reach.

The sediment-transport curve flow-duration method (Livesey 1975) was developed for sites where the duration of discharge record greatly exceeds the period for which sediment data are available. This method combines the transport-curve principle with streamflow records to develop a probability correlation between the sediment concentration and water discharge of a stream. It consists of determination of suspended-sediment-discharge values from the transport curve for corresponding increments of discharge from a flow-duration curve. Multiplication of the suspended-sediment load and discharge increments by the time-percentage interval results in a daily occurrence value. These daily average values can be summed to produce an estimate of annual suspended-sediment discharge.

Most sediment data obtained as part of monitoring programs tend to be associated with nonflood flows. The slope and intercept from linear regression analysis under these circumstances tend to be unduly affected by the large number of concentration values at low flows (Porterfield et al. 1978). Glysson (1987) describes a group-averaging method that determines the average—usually the arithmetic mean—of all values of the dependent variable (sediment discharge) for a small range of the independent variable (water discharge).

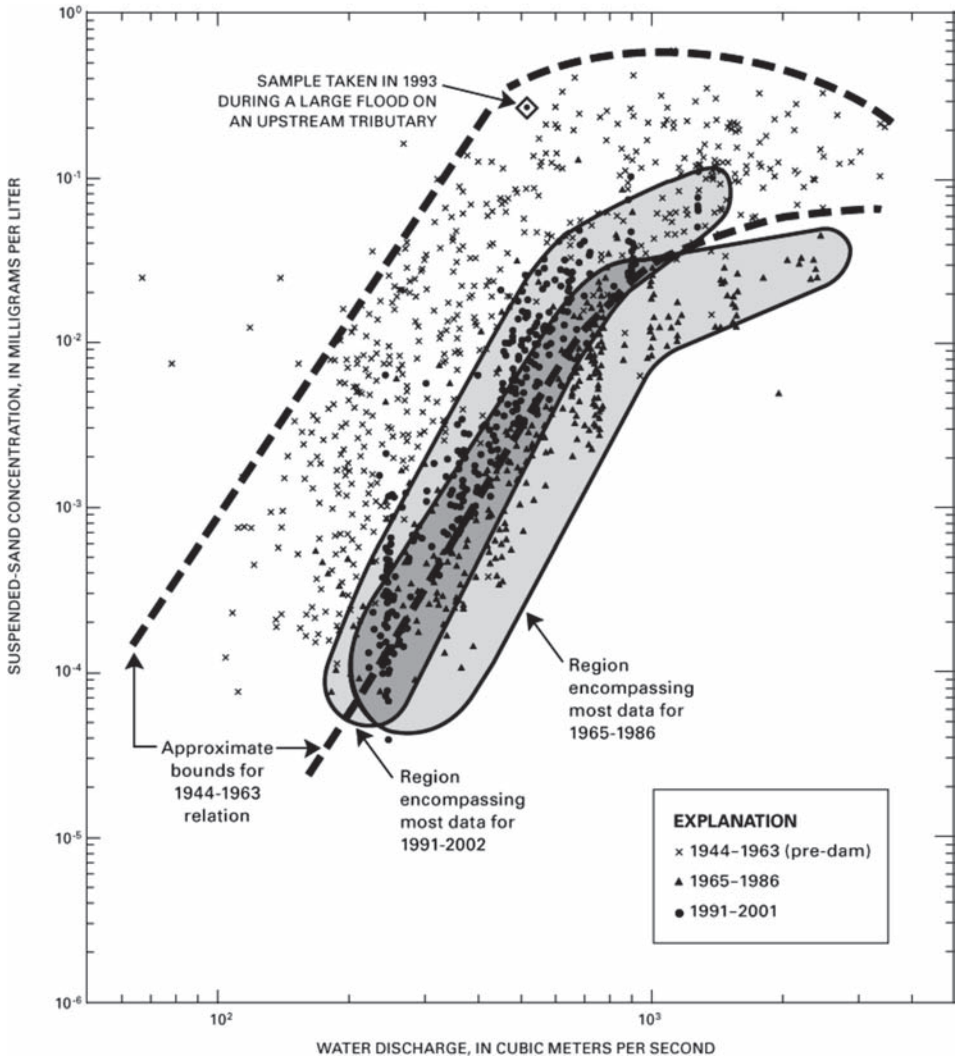

Fig. D-4. Relations between water discharge and suspended-sand (0.062–2.0 mm) concentrations for the Colorado River near Grand Canyon, Arizona (USGS Streamgauging Station 09402500; adapted from David Topping, USGS, written communication, 2003).

The average sediment discharge within each small range of water discharge then can be plotted against the average observed water discharge for that range. A transport curve then is fitted to these points in logarithmic space, such as that shown in Fig. D-5 for the Eel River at Scotia, California.

A combination of the suspended-sediment interpolation and suspended-sediment transport curve methods is referred to as the "hydrograph-shifting method" (Colby 1956). This empirical method requires daily water-discharge data and a sediment-transport curve for the same period and site. Daily suspended-sediment discharges (control points) estimated from the transport curve and daily mean water discharges are plotted on semilogarithmic coordinates. By viewing the curves on a light table or computer screen, the sediment-discharge hydrograph is moved vertically (shifted) to pass through or near the control points. After the base hydrograph is shifted to the control points, daily values are determined from the graph and are summed to give monthly and annual suspended-sediment discharges. Frost and Mansue (1984) estimated suspended-sediment discharges for 12 streams in Illinois using the hydrograph-shifting method with 2 yr of daily-flow and suspended-sediment record. Estimates of monthly and annual suspended-sediment discharges ranged from 16 to 326% and 41 to 136%, respectively, of measured values. This method is known to work well at sites with stable transport relations and where the transport curves indicate little or no hysteresis looping (G. Douglas Glysson, U.S. Geological Survey, written communication, 2000).

The reliability of sediment discharges computed from transport curves depends on a number of factors, including the range of discharges over which the data were collected to

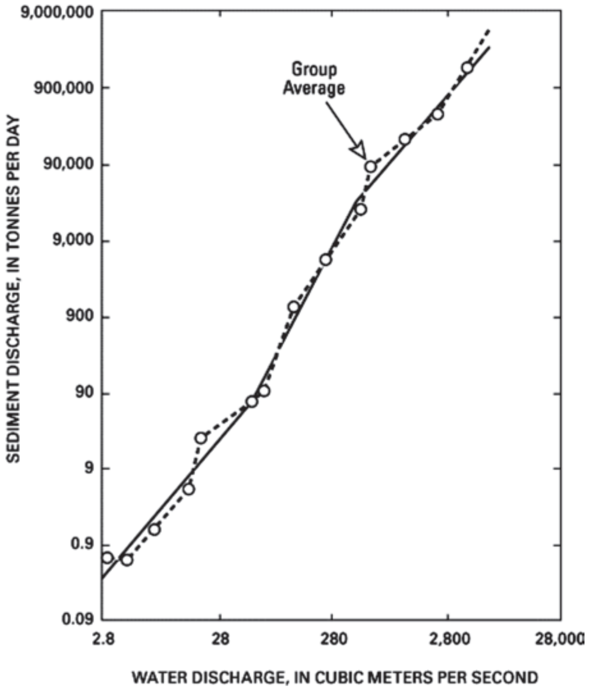

Fig. D-5. Sediment-transport curves based on the group averages method for Eel River at Scotia, California (USGS Streamgauging Station 11477000), 1958–1960 water years (Glysson 1987, p. 34).

define the curve, the number and reliability of the concentration-discharge relations used to define the curve, and whether the data are representative of water and sediment discharges for the computational period. The National Council for Air and Stream Improvement (NCASI 1999) considers "relatively good" suspended-sediment-discharge estimates from transport curves to be within 30% of the actual value. Meade et al. (1990) proffered that an average error of 50% for annual sediment-discharge estimates derived from sediment-transport curves.

Specification of a reference time interval has a direct bearing on the magnitude of errors in load estimates from transport curves. Walling (1977), using transport curves for the River Creedy, found that annual loads could be overestimated by as much as 30% even when the relations were refined for seasonal and stage effects, and monthly errors could vary from −80 to 900% of actual loads.

Glysson et al. (2001) compared transport-curve-generated suspended-sediment loads on daily, annual, and period-of-record intervals for 10 USGS streamgauging stations to loads computed by traditional techniques (Porterfield 1972) for the same stations and periods. Table D-1 shows the annual and total errors in the estimate of the suspended-sediment loads for the 10 stations used in this analysis. The magnitude of variations resulting from the use of regression analysis to estimate sediment loads decreased substantially with respect to those computed by traditional USGS techniques as the time frame associated with the estimated value increased. For example, errors between daily-sediment loads computed by regression versus traditional USGS techniques at the Rio Grande at Otowi Bridge station were as large as 4000%. However, the maximum error in the estimation of an annual load was 526%, and the error in the estimate of the total suspended-sediment load for 34 years of record at this station was within 38% of the traditionally derived value.

Glysson et al. (2001) concluded that estimates of suspended-sediment loads based on regression analyses are subject to significant errors. Because of the nature of sediment transport in open channels, there can be a large range in sediment concentrations at any given discharge. The fewer the number of concentration values available to define this range, the larger the potential errors can be. Although a well-defined, carefully constructed, and judiciously applied sediment-transport curve can be a useful tool for estimating sediment loads, load estimates derived from transport curves should not be considered a substitute for daily-sediment records computed by methods described by Porterfield (1972).

Because time-series data for bed load and total load are rare, the transport-curve method is more widely applied to estimate bed-load and total-load transport. Furthermore, for alluvial rivers, transport curves constructed for sediments that are characteristic of the bed will tend to be more accurate than those that include the wash-load component. Wash load is affected by watershed-wide processes that can vary with season, land use, rainfall, and other factors, whereas the bed-material load is primarily a function of the relation between river power and the availability of transportable bed sediments.

The empirical methods described in this and the previous section necessarily are based on direct measurements of sediment-transport rates using techniques described by Edwards and Glysson (1999) and samplers described by Davis and the Federal Interagency Sedimentation Project (2005), Childers (1999) and Edwards and Glysson (1999) and in other chapters of this volume. Depending on the phase of transport, the transport rate is either directly or indirectly dependent on water discharge, a quantity that can be measured with relative accuracy using conventional techniques (Buchanon and Somers 1969; Rantz 1982; USGS 2001). However, one or more factors can render these empirical methods difficult, impractical, or inappropriate to use and thus restrict their utility. On one hand, the sediment-transport curves thus obtained are valid only for the cross section or reach at which the data were collected, and for the watershed and channel conditions characteristic of those existing when the data were collected. On the other hand, information requirements for these empirical techniques, typically involving large amounts of data describing sediment and flow characteristics over a wide range of discharges and/or seasons, can be overwhelming to obtain with respect to available resources. Additionally, transport-rate estimates obtained from empirical techniques reflect a combination of errors

Table D-1 Summary Errors[a] in the Estimations of Annual Suspended-Sediment Loads[b] for the Period of Record for 10 USGS Streamgauging Stations

Site ID	Name	Years of record	Maximum annual error	Minimum annual error	Median annual error	Mean annual error	Error in total estimated load for period of record[c]
01463500	Delaware R. @ Trenton, NJ	32	126	−73	−30	−22	−5
05325000	Minnesota R. @ Mankato, MN	28	40	−57	−2	−8	−8
05406470	Brewery Cr. @ Cross Plains, WI	4	60	−36	−4	4	−3
05594100	Kaskaskia R. nr Venedy Station, IL	8	28	−49	11	2	6
05599500	Big Muddy R. nr Murphysboro, IL	8	34	−60	−18	−14	−13
06214500	Yellowstone R. @ Billings, MT	5	55	−35	−25	−3	8
06308500	Tongue R. @ Milles City, MT	8	−47	−87	−63	−63	−68
08313000	Rio Grande @ Otowi Bridge, NM	34	526	−91	−54	−4	−38
09368000	San Juan R. @ Shiprock, NM	31	259	−91	−30	−4	−38
12510500	Yakima R. @ Krona, WA	3	13	−32	−7	0	−8
		Mean = 16.1	Maximum = 526	Minimum = −91	Unweighted average = −22.2	Unweighted average = −11.2	Unweighted average = −16.7

Notes: Adapted from Glysson et al. (2001), 7.
[a]Error = 100 (estimated load – measured load)/measure load; all errors are expressed in percent.
[b]Suspended-sediment data (ASTM International 1997) were used in load calculations.
[c]The sum for the period of record of the measured load and the estimated load were used in this calculation.

inherent in the sampling and load-estimation techniques used. The magnitudes of these errors remain largely undefined and indefinable. Therefore, there is a need for sediment-transport estimation methods that can be used where field data are few or nonexistent and/or where exigency favors their application.

D.4 EQUATIONS FOR ESTIMATING BED LOAD AND BED-MATERIAL LOAD

Bed-load and bed-material transport have been studied systematically since the pioneering work of DuBoys in 1879. Since then, many empirical equations have been developed to estimate bed load and bed-material load and, at least in theory, they are straightforward to apply. These equations are predicated on the presence of specific relations among hydraulic variables, sedimentological parameters, and the rate at which bed load or bed-material load is transported.

Quantifying these relations has been problematic. On one hand, the theory supporting their derivations is incomplete, oversimplified, or nonexistent, with some empirical relations based entirely on data fitting. On the other hand, even the theoretically most complete equations rely on experimental data to determine the values of some of their coefficients, and their accuracy is often further undermined by the lack of reliable environmental data. Factors that may affect the usefulness of these equations are described in the following paragraphs.

D.4.1 Data Issues

The availability, reliability, and comparability of data to quantify coefficients for bed-load and bed-material-discharge equations cannot be taken for granted. Most estimating equations require data describing characteristics of the coarser sediment fractions in the channel. However, the preponderance of sediment data available from the USGS are for sand-size and finer material in suspension (Turcios et al. 2000; Turcios and Gray 2001). Data-collection techniques for coarser size fractions, such as those described by Bunte and Abt (2001), tend to be relatively costly and time-consuming. According to Wilcock (2001), estimates of sediment transport based on reliable local information require up to several days of nontrivial field work, and at least several return visits to collect the requisite data.

Bravo-Espinosa (1999) observed that many of the measured bed-load-transport rates used in his research were not particularly accurate. Leopold and Emmett (1997) state that "it would be highly desirable to have direct measurements of the bed-load transport in a natural river and of the concomitant hydraulic characteristics of the flow. The problem has been particularly intractable, because no sampling device has been available that would provide reliable and repeatable measurements of the debris load moving along the bed of the river." Gray et al. (1991) demonstrated that two types of pressure-difference-type bed-load samplers deployed simultaneously 2 m apart in the middle of the sand-bedded Colorado River under steady low-flow conditions (mean discharge 167 m^3/s) exhibited divergent sampling efficiencies (Fig. D-6). At-a-point bed-load-transport rates measured by the experimental BL-86-3 sampler with a nozzle outlet-to-inlet ratio of 1.40 were compared to those from a Helley-Smith sampler with a 3.22 ratio. Although short-

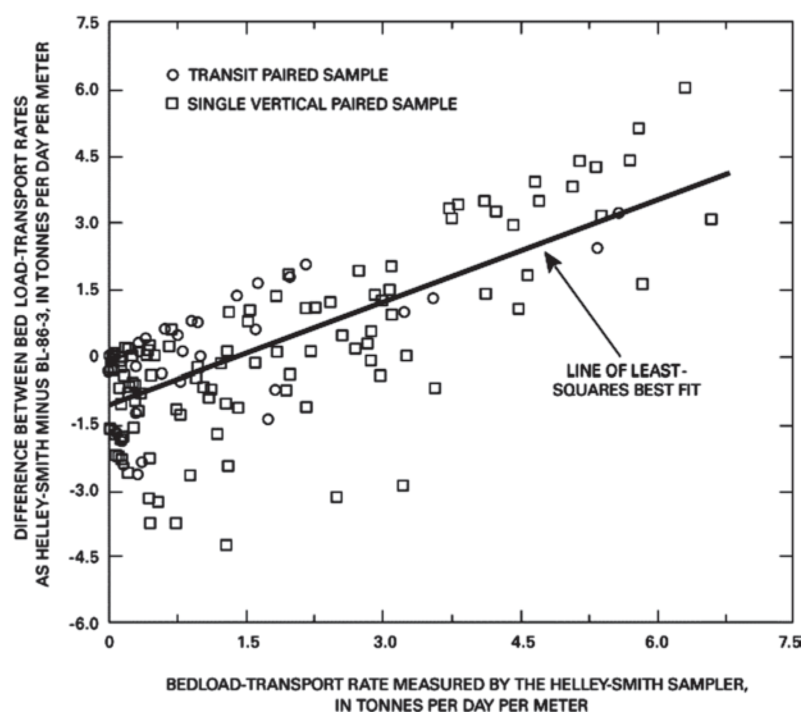

Fig. D-6. Differences in bed-load-transport rates concurrently measured with the Helley-Smith bed-load sampler (3.22 outlet-to-intake-nozzle ratio) and the experimental BL-86-3 bed-load sampler (1.40 outlet-to-intake-nozzle ratio) to those measured with the Helley-Smith sampler at the Colorado River above National Canyon, near Supai, Arizona (USGS Streamgauging Station 09404120; Gray et al. 1991, pp. 4–76).

term transport rates—minutes to hours—measured by both samplers were highly variable (Fig. D-7), the cross-sectional bed-load-transport relation based on results from all 390 bed-load samples collected over a 5-day period showed that the bulk of the bed-load transport occurred in the middle 15 m of the 76-m-wide river at a more or less uniform mean transport rate of 2.8 tn/day per meter of width (Fig. D-8). This study demonstrated potential inconsistencies in sampler performance and the need for large amounts of data to adequately describe spatial and temporal characteristics of bed-load transport even under steady-flow conditions.

Another indication of bed-load-sampler performance was provided by Childers (1999), who compared the relative sampling characteristics of six pressure-difference bed-load samplers in high-energy flows of the Toutle River at the Coal Bank bridge near Silver Lake, Washington (USGS Streamgauging Station 14242450). The sampling ratio of each pair of samplers tested was computed by dividing the mean bed-load-transport rate determined for one sampler by the mean rate for a second sampler. Ratios of bed-load rates between measured bed-load pairs ranged from 0.40 to 5.73, or more than an order of magnitude in differences of sampling efficiencies. Based on these tests, Childers (1999) concluded that the Toutle River-2 bed-load sampler appears to be capable of providing representative bed-load samples for material ranging from 1.0 to 128 mm median diameter.

Bunte (1996) attributes deficiencies in the understanding of coarse bed-load-transport processes to a "dearth of appropriate measuring techniques and data from natural streams." Emmett's (1980) solution to this problem was to construct a conveyor-belt bed-load trap in a concrete trough across the bed of the East Fork River of Wyoming. The trap caught all the bed load that dropped into the trough, conveyed it to the streambank for weighing and sampling, and returned it to the river downstream from the trough. The bed-load trap was used to collect bed-load data for 7 yr and to field-calibrate the Helley-Smith bed-load sampler. This work is as notable for its considerable success in quantifying the bed-load characteristics of the East Fork River and calibrating the Helley-Smith bed-load sampler as it is in highlighting difficulties and the considerable expense of obtaining reliable bed-load data.

Because of the difficulty of obtaining accurate field sediment-transport data, many researchers rely on laboratory flume data. The measurements of sediment-transport rates in the laboratory can be quite accurate, but do not represent natural river conditions well. Leopold and Emmett (1997) observed that a river's ability to adjust its cross section to a variety of flows is a characteristic not shared by a fixed-wall flume. The sediment in transport is determined by the geological and physiographic setting of the river and river basin; thus, sediment is not a controllable variable. The variety of conditions controlled in a laboratory experiment cannot be established in a natural river. Furthermore, bed-material transport in a flume is tantamount to total load, in that fine material typically is excluded from flume bed-load or bed-material-load experiments. In a river, total load is equal to bed-material load plus wash load. Bed-material equations

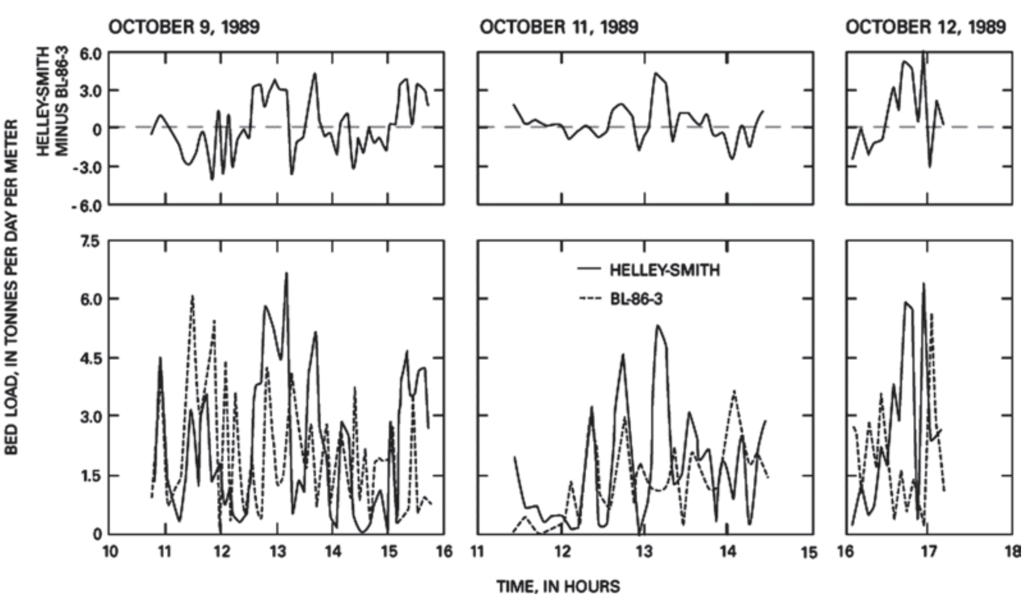

Fig. D-7. Temporal variability in bed-load-transport rates between the Helley-Smith bed-load sampler (3.22 outlet-to-intake-nozzle ratio) and the experimental BL-86-3 bed-load sampler (1.40 outlet-to-intake-nozzle ratio) at the Colorado River above National Canyon, near Supai, Arizona (USGS Streamgauging Station 09404120; Gray et al. 1991, pp. 4–68).

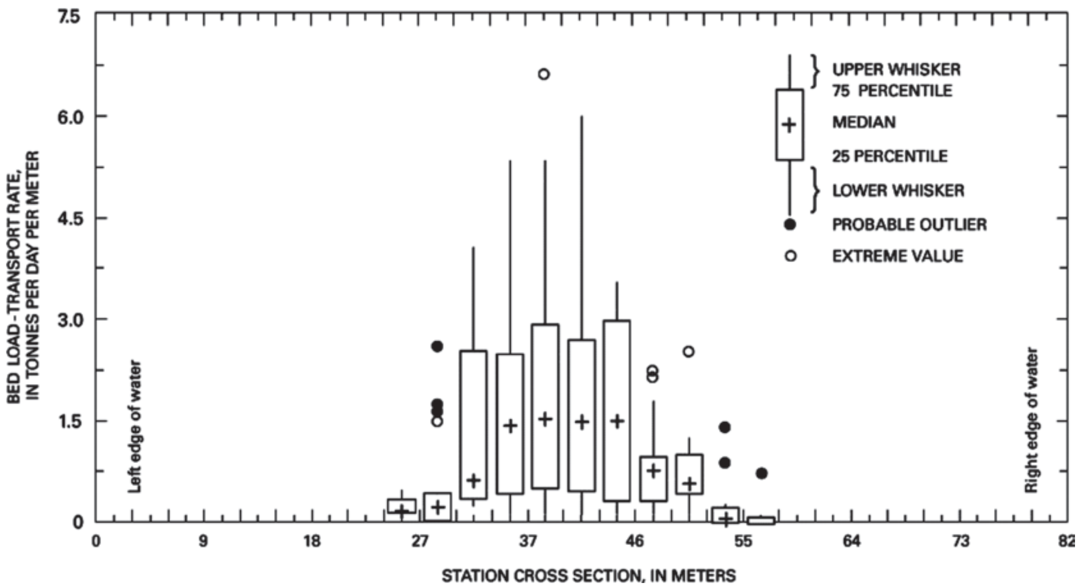

Fig. D-8. Box-and-whisker plots showing the cross-sectional distribution of bed load during steady flow of 165 m^3/s at the Colorado River above National Canyon, near Supai, Arizona (USGS Streamgauging Station 09404120; Gray et al. 1991, pp. 4–70).

calibrated on coarse-sediment flume data may substantially underestimate the total load when the wash-load component is comparatively large.

Based on the preceding information, it is not surprising that most bed-load and bed-material-load equations are derived from a comparatively restricted database, and their utility has been established on the basis of relatively few field data (Gomez and Church 1989). The disparate nature of much of the experimental data that are available, coupled with a dearth of reliable field data, seem to have encouraged the proliferation rather than the consolidation of transport equations. Ashworth and Ferguson (1986) point out that more data sets of integrated and intensive field measurements are needed if a better understanding of the functioning of active gravel-bed rivers is to be gained.

D.4.2 Sediment-Supply Issues

A key question in investigating sediment transport in natural flows is whether transport is limited by flow strength or sediment supply. The answer to this question determines whether research should focus on the relation between flow strength and sediment transport, the rate at which sediment of different grain sizes is supplied to the flow, or both (Rubin and Topping 2001).

Characteristics of sediment supply and transport affect the reliability of equations for estimating sediment discharge. Bed-load and bed-material-load equations are designed to estimate the actual transport of the watercourse. The transport capacity is the maximum tractive sediment load that the watercourse can convey for the given hydraulic and sedimentary conditions. However, the transport capacity calculated for a given stream and flow condition may differ substantially from the actual transport rate. For example, the natural processes of imbrication (longitudinal orientation of coarse surficial material in a fish-scale pattern) and/or armoring (coarse surficial material, such as boulders and cobbles, overlying finer material) can result in a calculated transport capacity substantially larger than the true capacity, because the flows may lack sufficient energy to move the bed material. Additionally, many streams are naturally or unnaturally in disequilibrium and are aggrading or degrading on time scales of years and decades—factors that may not be consistent with the estimating-equation requirements.

Besides the hydraulic factors, hydrological, geological, geographical, biological and other factors affect the sediment load of a stream. Some of a stream's sediment supply is derived from runoff from upland areas. Factors including season, snowmelt, rainstorm duration and intensity, watershed use, vegetation cover, watershed field slope, soil types, and human and animal activities determine the amount of sediment entering the stream and ultimately affect the sediment transported by the watercourse. Therefore, all of the assumptions on which most of the bed-load and bed-material-load equations are based may not be valid, or at least verifiable in a riverine setting. These include steady and uniform flow conditions and, as previously noted, an unlimited supply of sediment. Regarding the latter assumption, Bravo-Espinosa (1999) notes a need for a clear identification of sediment-supply conditions before a bed-load equation is applied. In summary, using equations to estimate sediment transport, particularly in gravel-bed rivers, remains problematic and is the focus of ongoing research.

D.4.3 Other Technical Issues

Difficulties in quantifying incipient motion—the initiation of bed-particle movement—pose another obstacle for the accurate estimation of sediment discharge. Determination of incipient motion in gravel-bed systems is complicated by a number of factors, including imbrication, armoring, and other nonhomogeneous distributions of bed material; determination of turbulent shear stress; and surface-packing density. Many sediment-transport equations, especially those for gravel-bed rivers, have a term that includes the critical shear stress, τ_c, which is the value of the bed shear stress for which initiation of bed motion occurs. This term is present as a coefficient in the form τ/τ_c, the associated uncertainty of which is the single largest source of error in the transport estimates. Wilcock (1997; 1998) presents a method, based on a calibrated approach, that is a compromise between the estimation methods of this section and empirical approaches for quantifying sediment transport presented previous to this chapter. This method emphasizes the measurement of the bed-material-transport rates under flow conditions close to incipient motion. A small number of accurate observations are used to identify the value of τ_c, thus reducing the error in τ/τ_c and resulting in transport estimates with higher accuracy.

Verifiably accurate estimation of wash-load transport rates remains an illusive goal. Most wash load other than that from bank caving originates in nonchannel parts of the watershed and is transported to the channel primarily by overland flow. It consists of fine material that flows through a reach without appreciable interaction with the bed, and represents the bulk of deposits in many lakes and reservoirs. Wash load tends not to be directly related to streamflow—except through rainfall, which is an important factor in detaching the sediment and producing the overland flow that delivers the wash load to the watercourse and adds to streamflow. This general lack of a direct relation between streamflow and wash load has complicated development of an analytic method to estimate wash-load-transport rates. Various watershed models have been developed to simulate runoff and wash load from the land surface. Although it is recognized that the sediment load of rivers and streams is composed of wash load and bed-material load, the equations described in this section are applicable only to the estimation of bed load or bed-material load, necessarily neglecting wash-load transport and its effects.

In spite of the problems associated with the derivation and application of bed-load and bed-material-load equations, they are necessary, because it is neither practical nor feasible to measure bed load or bed-material load at all desired sites and under all desired conditions. Numerous equations for estimating bed-load and bed-material-load transport have been developed based on four principal approaches:[1] shear stress or tractive force; energy; discharge or velocity; and probabilistic (Chang 1988; Yang 1996). These are described in the following paragraphs.

Shear Stress or Tractive Force: This approach assumes that the capacity of a stream to transport sediment varies directly with the shear stress acting on the bed, or with the difference between the shear stress acting on the bed particles and the critical shear stress for initiation of particle motion. The major difficulty of this approach is in determining the effective bed shear stress, which must be equal to the bed-form drag, a quantity that differs from the grain roughness and from the total bed shear stress. The determination of the initiation of motion poses another difficulty for this method (usually, the Shields τ_c is used, but the issue has not been satisfactorily resolved). The lift forces acting on the sediment particles also are ignored, which may constitute another source of error.

Energy: The energy approach is based on considerations of the energy carried by the flow and the energy necessary to carry the sediment particles. This approach may include considerations based on equating the work done by the flowing water and the rate of sediment transport or based on a balance of forces acting on the sediment particle. It includes equations based on unit stream power (power per unit of weight of water), which is expressed as the product of average velocity and channel gradient, and equations based on the stream power, which is the product of bed shear stress and average flow velocity, expressed as stream power per unit bed area.

Discharge or Velocity: This method uses the critical unit water discharge as a criterion for initiation of bed-load transport. It is the only approach that does not explicitly involve flow depth. Equations using the discharge or velocity approach have been criticized because sediment transport should depend on the velocity near the bed, rather than on the mean flow velocity.

Probabilistic: The probabilistic approach relates bed-load transport to the turbulent-flow fluctuations acting on the sediment particle, which vary in time and space. The movement of each particle depends on the probability that, for a particular time and location, the applied forces are greater than the resisting forces applied to the particle.

[1]This classification is not the only one possible. For example, some authors classify the equations into the following four categories: empirical equations (based almost exclusively on fitting equations to large amounts of data); semitheoretical equations (based on physical concepts and reasoning); probability-based equations; and dimensional analysis equations (using dimensional analysis and some physical reasoning, also using large amounts of data for calibration of parameters). In some respects, this type of classification may be more useful to the practicing engineer.

Although listing and describing all bed-load and bed-material-load equations is beyond the scope of this chapter, some of the more common equations found in the literature are presented in Table D-2. It is of concern that there appear to be more bed-load equations than there are reliable data sets by which to test them. Consequently, few of the equations have been universally accepted or generally recognized as especially appropriate for practical application.

Fuller descriptions of these and many other equations can be found in Shulits and Hill, Jr. (1968), Garde and Ranga Raju (1977), Stelczer (1981), Graf (1984), Bathurst et al. (1987), Yang (1996), and Yang and Huang (2001), among others. Computer programs are available that implement some of these equations. A computer program developed by Stevens (1985), based on the computational sequence of Hubbell and Matejka (1959), facilitates computations by the Modified Einstein Procedure (Colby and Hembree 1955; USGS 2000a). The Bureau of Reclamation Automated Modified Einstein Procedure (BORAMEP) is described by Holmquist-Johnson (2004). O'Brien and McCorquodale (2001) describe a technique for applying the Modified Einstein Procedure in multiple subsections of a river cross section. Stevens and Yang (1989) provide a computer program for computing bed-load discharge using any of five equations and bed-material discharge with any of eight equations (USGS 2000b). All of these equations are included in Table D-2.

Williams and Rosgen (1989) provide a compilation of measured suspended-sediment loads and approximately concurrently measured bed-load transport rates with associated hydraulic variables for 93 U.S. streams, which the authors consider to be the first comprehensive collection of field-measured total sediment load—bed loads plus suspended loads—in a variety of streams. These data sets might be useful to those who wish to test selected equations with data collected by the best sampling techniques available before 1987.

Because of the number of available equations, the ultimate question is which equation(s) should be selected for a given application. There is no simple answer to this question. Because of the semiempirical character of most equations and the extensive use of data calibration in deriving the transport-equation coefficients, each equation has a range of validity determined by the range of experimental data used in those calibrations (see Table D-2). Therefore, application of an equation for a range of hydraulic and sedimentary parameters, such as water depth, channel width, and sediment particle size, should be similar to those for which the equation was validated. Unfortunately, authors of transport equations do not always indicate the range of validity for their equations. Additionally, application of equations beyond their verified range is all too common, often resulting in substantial discrepancies between observed and estimated transport rates, or in production of unverified transport estimates.

Various comparative analyses of sediment-transport equations have been formulated with the purpose of assessing their quality. This is a subjective task that depends on the data and methods of comparison. Some of the most complete and/or useful assessments can be found in White et al. (1975); Alonso (1980); Alonso et al. (1982); ASCE (1982); Vetter (1987; 1988); Gomez and Church (1989); Yang and Wan (1991); Lopes et al. (2001); and Yang and Huang (2001). Some of these analyses rank the equations by reliability and applicability. Not surprisingly, the rankings are quite different. A summary of the results obtained by ASCE (1982) is shown in Table D-3.

Yang and Huang (2001) performed a comprehensive and systematic analysis of 3,391 sets of laboratory and river sediment-transport data to aid in selecting from 13 sediment-transport formulas under different flow and sediment conditions. Among their conclusions are the following:

- Sediment-transport formulas based on energy dissipation rates or power concepts are superior to those based on other concepts.
- Yang's 1973, 1979, and 1984 formulas are the most robust and least sensitive to the variation of relative depth, Froude number, dimensionless shear velocity, dimensionless unit stream power, and sediment concentration.
- All but the formulas of Engelund and Hansen (1967) and Yang (1973; 1979; 1984) should be limited to subcritical flows.
- The Einstein bed-material-load and bed-load (1950) formulas and those by Meyer-Peter and Müller (1948) and Toffaleti (1968) are not as accurate as those formulas based on the power approach.

Lopes et al. (2001) categorized stream reaches into three bed-load-transport categories based on supply: those without bed-load supply limits (transport limited); those with supply limits for some particle sizes; and those supply-limited for all particle sizes. The applicability of seven bed-load equations—those of Kalinske (1947), Meyer-Peter and Müller (1948), Einstein (1950), Schoklitsch (1962), Yalin (1963), Bagnold (1980), and Parker et al. (1982)—in 22 stream reaches for which comparative bed-load data were available was tested. They found that equations of Parker et al. (1982) and Meyer-Peter and Müller (1948) adequately estimated bed-load transport in transport-limited reaches. The equations of Bagnold (1980) and Schoklisch (1962) performed well in supply-limited channels, including those limited in some particle-size classes. The equations considered most robust were the Schoklitsch (1962) equation, which is capable of estimating the trend of measured bed load for 8 of the 22 streams; and the Bagnold equation (1980), which duplicated the trend of measured data in 7 streams.

Yang (1996) presented the following steps for the selection of a sediment-transport-rate equation:

1. Use as many field data as permissible within the resource limits of the study.
2. Examine as many equations as possible, based on assumptions used in their derivation and the range of data used to determine their coefficients, and select

Table D-2 Some Common Bed-Load and Bed-Material-Load Equations and Associated Information Presented in Chronological Order of Development

Formula	Foundation	Type[a]	Range of validity[b]	Comments
Du Buoys (1879)	Theoretical, based on excess of shear stress	B	—	First known model of sediment transport, it is based on the concept that the bed load moves in sliding layers. Includes parameters that can be determined only by experimentation and that have limited range of validity; has to be calibrated for each application.
Schoklitsch (1934)[c]	Theoretical, based on excess of shear stress	B	$0.305 \leq d \leq 7.02$	Can be applied to sediment mixtures divided into size fractions. Bed load is a function of water discharge.
Shields (1936)	Semiempirical, based on excess of shear stress	B	$1.56 < d < 2.47$ $1.06 < s < 4.25$	Derived to show the many factors influencing sediment transport, rather than to establish a universal equation.
Einstein (1942, 1950)[c]	Theoretical, probabilistic	B, BM	$0.785 \leq d \leq 28.65$	Originally derived for single-size sediments, it was later extended to sediment mixtures by the introduction of hiding factors. Hiding factors account for the sheltering of the smaller particles by the larger particles present in the mixture. Bed-material-load formula is the sum of bed load and suspended load formulae. Einstein's formula has been corrected and expanded by many authors, such as Brown (1950), Colby (1964), Pemberton (1972), and Yalin (1972).
Kalinske (1947)[c]	Theoretical, probabilistic	B	—	This equation is based on a discharge relation. It can be applied to sediment mixtures.
Meyer-Peter and Müller (1948)[c]	Theoretical, based on shear stress	B	$0.15 \leq W \leq 2$ $0.01 \leq D \leq 1.2$ $0.04 \leq S_f \leq 2$ $1.25 \leq \rho \leq 4$ $0.40 \leq d \leq 30$	Expansion of earlier work by Meyer-Peter et al. (1934). It is widely used in mountain streams with gravel beds. Should not be used for grain sizes d smaller than ~1 mm.
Frijlink (1952)	Empirical, based on shear stress	B	—	This method is simply an approximation to the formula of Meyer-Peter and Müller (1948) and Einstein (1950).
Velikanov (1954)	Theoretical, based on energy concepts	BM	—	Equation derived from gravitational power theory. Led to a number of other similarly derived sediment-transport equations by Chinese engineers, such as those by Zhang (1959) and Dou (1974).
Bagnold (1956,1966)	Theoretical, based on energy concepts	B, BM	$d > 0.015$	Bagnold's bed-material-load formula is the sum of his bed-load and suspended-load formulae.
Laursen (1958)[c]	Empirical	BM	—	Can be applied to sediment mixtures divided in size fractions. It is based on a graphical relation representing experimental data collected in sand-bed flumes, without direct physical interpretation. Originally based on laboratory data, it has been modified and expanded by others to increase its scope of validity (e.g., Madden 1993).
Rottner (1959)[c]	Empirical, based on dimensional considerations	B	—	Related bed-load transport per unit width to dimensionless depth, velocity, and slope parameters. A regression analysis was performed to determine the effect of a relative roughness parameter d_{50}/d. The equation may not be applicable at low bed-load-transport rates.

(*Continued*)

Table D-2 Some Common Bed-Load and Bed-Material-Load Equations and Associated Information Presented in Chronological Order of Development (*Continued*)

Formula	Foundation	Type[a]	Range of validity[b]	Comments
WIHEE (1961)[d]	Empirical	BM	—	Originally a suspended-load equation, it applies to rivers flowing over alluvial plains, where bed load is generally negligible and suspended load predominates. It is one of the equations most widely used in China.
Yalin (1963, 1972)	Theoretical, based on probabilistic concepts	B	$0.315 \leq d \leq 28.65$	This equation incorporates both probabilistic and energy concepts, such as Bagnold's rate-of-work approach. It considers particle saltation to be the mode of sediment transport.
Colby (1964)[c]	Empirical	BM	—	Formula is presented in graphical relations. It includes a correction factor for flows with high concentrations of fine silt and clay. Applicable to rivers with medium to fine sand beds. Available on line at http://water.usgs.gov/cgi-bin/man_wrdapp?modein.
Engelund and Hansen (1967)[c]	Semiempirical, based on energy concepts	BM	—	Derived for sand-dune beds; has been widely used for sandy streams. Not accurate close to the initiation of sediment motion. Yang (2005) provide a step-by-step deviation of this transport fuction.
Graf and Acaroglu (1968)	Semiempirical, based on shear stress	BM	—	This equation was developed for open channels and closed conduits. Somewhat similar to Einstein's (1950) equation for open channels.
Toffaleti (1968, 1969)[c]	Theoretical, probabilistic	BM	—	Makes the following departures from Einstein's method: collapses several correction factors into one; sediment transport is related to stream properties using more parameters; and a vertical velocity distribution is used.
Paintal (1971)	Empirical, based on shear stress	B	$\theta < 0.06$ $1 < d \leq 25$	For bed-load transport at low shear stress.
Shen and Hung (1972)	Empirical	BM	—	A regression equation based on laboratory data with sand bed.
Ackers and White (1973)[c]	Semiempirical, based on energy concepts	BM	$0.04 \leq d \leq 4.94$	Updated by Ackers (1993) to correct transport rates for fine and coarse material. The 1973 equation was expanded by White and Day (1982) to allow the computation of the transport rate by particle size fraction. Yang (2005) provide a step-by-step deviation of this transport fuction.
Yang (1973, 1979)	Theoretical, based on energy concepts	BM	$0.063 \leq d \leq 2.0$	Unit stream power formula. Coefficients found by computer calibration. Has been used successfully for sediments with particle sizes in the silt range. The 1979 equation should be used for concentrations higher than 100 mg/L.

Engelund and Fredsoe (1976)	Theoretical, probabilistic	B	—	—
Bagnold (1980)	Theoretical, based on energy concepts	BM	—	Stream power formula. Included bimodal gravel-bed rivers in the analysis.
Brownlie (1981)	Semiempirical, based on energy concepts	BM	—	Based on regression analysis of laboratory and field data with mainly sand beds.
Parker et al. (1982)	Semiempirical, probabilistic	B	$0.60 \leq d \leq 102.0$	Uses the concept of equal mobility. It has been corrected and expanded by others, such as Diplas (1987) and Bakke et al. (1999). Applies to gravel-bed rivers with pavement and subpavement layers, and is used by particle size fraction.
Smart (1984)	Empirical, based on shear stress	B	Plane bed $d \geq 0.4$ $0.4 \leq S \leq 20$	Equation for steep slopes. Based on the old data of Meyer-Peter and Müller (1948) and on new data collected on a steep flume. Not applicable to negative slopes.
van Rijn (1984a, 1984b)	Semiempirical, based on energy concepts	B, BM	$0.2 \leq d \leq 2.0$	Different semiempirical methods were used to derive bed-load transport rate equations. Experimental data and other simplifications were used to fine-tune the equations. The bed-material-load formula is the sum of the bed-load and suspended-load equations.
Yang (1984)[c]	Theoretical, based on energy concepts	BM	$2.0 \leq d \leq 10$	Unit stream power formula for gravel.
van Rijn (1987)	Empirical, probabilistic	B	—	—
Karim and Kennedy (1990)	Empirical	BM	—	This is a set of equations based upon nonlinear multiple regression analysis, 339 sets of river data, and 608 sets of laboratory data. They have no physical meaning. Equations require iterative solution schemes.
Suszka (1991)	Empirical, probabilistic	B	$3.3 \leq d \leq 43.5$ $0.9 \leq D/d \leq 73.3$ $0.17 \leq S \leq 9$ $147 \leq R_e \leq 14000$	Modification of an earlier formula by Graf and Suszka (1987). Developed for stream mountains, with high slopes and low submergence (i.e., low values of *D/d*).
Yang et al. (1996)	Theoretical, based on energy concepts	BM	—	Unit stream power formula for sediment-laden flows. Has been applied with success to the Yellow River in China.
Damgaard et al. (1997)	Empirical, based on shear stress	BM	$2 \leq \theta/\theta_{cr} \leq 6$	Valid for horizontal, mild, and steep slopes. Authors also present a method for including the effects of steep beds in the equation of Meyer-Peter and Müller (1948). Equation is based on limited laboratory data with well-sorted sand with mean size $d = 0.208$ mm.

(*Continued*)

Table D-2 Some Common Bed-Load and Bed-Material-Load Equations and Associated Information Presented in Chronological Order of Development (*Continued*)

Formula	Foundation	Type[a]	Range of validity[b]	Comments
Karim (1998)	Empirical	BM	$0.137 \le d \le 28.65$ $20 \le C \le 49{,}300$ $0.03 \le D \le 5.29$ $0.32 \le U \le 2.88$ $0.015 \le S \le 2.4$ $0.09 \le \mathsf{F}_r \le 2.08$	The transport relation results from fitting a power-form relationship to experimental data from natural rivers and laboratory flumes. It takes into account sediment mixtures, including particle sheltering and exposure. Not accurate for partially armored beds.

Nomenclature:
C = sediment concentration, ppm;
d = particle diameter, mm;
d_{50} = particle size for which 50% of the material by weight is finer;
D = water depth, m;
F_r = Froude number;
g = acceleration due to gravity;
R_e = Reynolds number, = $u^* d/\nu$;
s = specific gravity of sediment;
S = bed slope, %;
S_f = energy slope, %;
U = flow velocity, m/s;
u^* = shear velocity;
W = width, m;
θ = bed shear stress parameter, = $u^{*2}/[(s{=}1)gd]$;
θ_{cr} = critical bed shear stress parameter;
ρ = density, g/cm^3;
ν = kinematic viscosity of water.

[a] B, bed load; BM, bed-material load.
[b] Representative of the range of the data that were used in the derivation of the equations.
[c] Described by Stevens and Yang (1989) and available from the U.S. Geological Survey on the World Wide Web at http://water.usgs.gov/software/seddisch.html.
[d] WIHEE: Wuhan Institute of Hydraulic and Electric Engineering, China.

Table D-3 Summary of the Sediment-Transport Equations Ranking by ASCE (1982), Based on 40 Sets of Field Data and 165 Sets of Flume Data

Rank	Equation	Type
1	Yang (1973)	Bed-material load
2	Laursen (1958)	Bed-material load
3	Ackers and White (1973)	Bed-material load
4	Engelund and Hansen (1967)	Bed-material load
5	Bagnold (1956)	Bed load
6	Meyer-Peter and Müller (1948) and Einstein (1950)	Bed-material load
7	Meyer-Peter and Müller (1948)	Bed load
8	Yalin (1963)	Bed load

those consistent with the data and field conditions from step 1.

3. If more than one equation is acceptable after step 2, compute sediment-transport rates with these equations and select those that best agree with any field measurements taken in step 1.
4. In the absence of measured sediment loads for comparison, the following guidelines could be considered:

   a. Use Meyer-Peter and Müller's (1948) equation when the bed material is coarser than 5 mm.
   b. Use Einstein's (1950) method if the bed load constitutes a substantial part of the total load.
   c. Use Toffaleti's (1968; 1969) equation for large sand-bed rivers.
   d. Use Colby's (1964) equation for rivers with a depth of less than 10 ft.
   e. Use Shen and Hung's (1972) regression equation for laboratory flumes and small streams.
   f. Use Karim and Kennedy's (1990) equation for natural rivers with a wide range of variation in the flow and sediment conditions.
   g. Use Yang's (1973) equation for sand transport in laboratory flumes and natural rivers; use Yang's (1979) equation for sand transport when the critical unit stream power at incipient motion can be neglected.
   h. Use Parker's (1990) or Yang's (1984) gravel equation for bed-load or gravel transport.
   i. Use Yang's (1996) modified equation for high-concentration flows when the wash load or concentration of fine material is high.
   j. Use Ackers and White's (1973) or Engelund and Hansen's (1967) equation for subcritical flow in the lower flow regime.
   k. Use Laursen's (1958) equation for laboratory flumes and shallow rivers with fine sand or coarse silt.
   l. Use Meyer-Peter and Müller's (1948) equation for bed load and the Modified Einstein equation (Colby 1964) for suspended load to obtain total bed-material load.
   m. Apply a regime or regression equation only if the flow and sediment conditions of interest are similar to those used in the equation's derivation.
   n. Select an equation according to the ranking in Table D-3.
   o. Select an equation based on the analysis of Yang and Wan (1991).

5. If none of the available sediment-transport equations is adequate, use available data and plot them against water discharge, velocity, slope, depth, shear stress, stream power, unit stream power (or dimensionless unit stream power), and Velikanov's parameter.[2] Select the curve with the least scatter in the data.

D.5 TOWARD COLLECTION OF CONSISTENT, RELIABLE FLUVIAL-SEDIMENT DATA

The preceding sections presented a synopsis of the methods commonly used to calculate sediment transport loads in rivers and streams, and the problems associated with them. Those problems—which range from data collection procedures, interpretation, and manipulation to the principles (or absence thereof) behind the equations employed—burden these methods with uncertainty, inconsistency, and inaccuracies of unknown magnitudes. They also contribute to considerable difficulty in the error analysis of the methods' results, therefore severely compromising their reliability.

[2]The Velikanov parameter is defined as $U^3/(gR\omega)$, where U is the mean velocity, g is the acceleration due to gravity, R is the hydraulic radius, and ω is the sediment particle's fall velocity.

In an attempt to overcome some of the limiting difficulties described above, Gray (2002) presents a vision of a national sediment monitoring and research network that would provide a national sediment dataset collected with uniform protocols and methods. It is predicated on development and adoption of surrogate technologies (Bogen et al. 2003; Wren and Kuhnle 2003; Gray 2005) providing fluvial-sediment data characteristics at a site continuously with only periodic calibration. The components of a national sediment monitoring and research network are

- A core streamgauging station network that is equipped to continuously monitor a basic set of flow, sediment, and ancillary characteristics based on a consistent set of protocols and equipment at perhaps hundreds of sites representing a broad range of drainage basins in terms of geography, areal extent, hydrology, and geomorphology. The focus of these sites would be measurement of fluvial-sediment yields.
- A subset of the core streamgauging station network at which testing on emerging sediment-surrogate technologies and new methodologies can take place at a minimum of additional expense. A major focus of this effort would be to identify technologies that provide a reliable sediment-concentration time series that can be used as the basis for computing daily suspended-sediment discharges with known accuracies (Bogen et al. 2003; Gray and Glysson 2003; Gray 2005; Kuhnle and Wren 2005). A secondary focus would be to identify surrogate technologies for measuring characteristics of bed load (Bogen et al. 2003; Gray 2005; Ryan et al. 2005), bed material, and bed topography (Gray 2005; Young and Tidwell 2005).
- An equipment and techniques research component that addresses development of new, less expensive, safer, and quantifiably accurate means for collection, processing, and laboratory analysis of sediment samples (Bogen et al. 2003; Gray 2005).
- A data-synthesis component that focuses on identifying or developing more efficient methods of measuring and estimating selected fluvial-sediment characteristics; developing a means to estimate the uncertainty associated with these measurements and estimates; and performing syntheses on historical and new sediment and ancillary data to learn more about the sedimentary characteristics of the nation's rivers (Gray 2005; Landers and Freeman 2005).
- A common database that can accept all types of instantaneous and time series sediment and ancillary data collected by approved protocols (see Chapter 5 in this volume), including specific information on the instruments and methods used to acquire the data, available online via a map interface (Gray 2005; USGS 2005).

The principal benefits of a national sediment monitoring and research network would be production of quality-assured data that in some cases would preclude the need for the sediment-discharge estimating tools described in this section.

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