Fluvial Sediment Transport

The fluvial system commonly is conceptualized into three process-dominated zones: (1) the upper source zone, (2) the middle transfer zone, and (3) the lower accumulation zone (Schumm, 1977) (Figure 1). This macroscopic conceptual model generally is applicable for large, coastal-draining river systems, and all three of the general processes; erosion, transport, and deposition; occur to varying degrees in each zone. Sediment transport processes associated with flowing water begin when earth material is entrained and terminate when the material either is deposited or dissolved. Fluvial deposits, including instream bars and benches, floodplains, and deltas, are either temporary and remobilized or permanent and converted to sedimentary rock over geologic timescales.

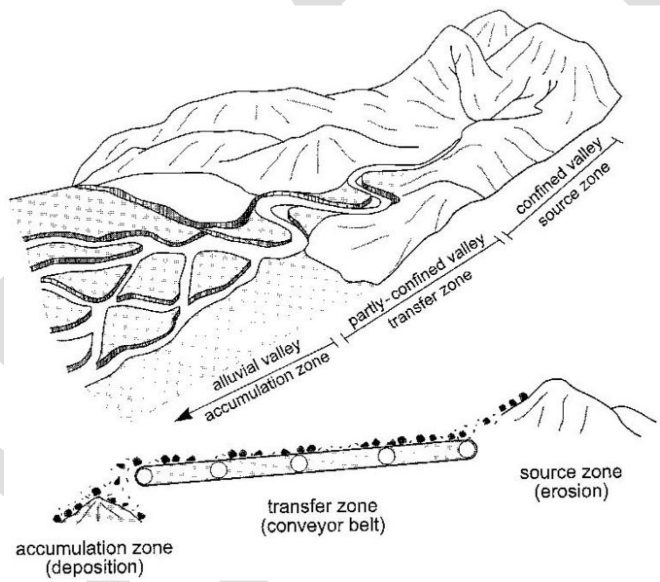

Figure 1. Conceptual diagram of the fluvial system, with an emphasis on sediment erosion, transport, and deposition (from Kondolf, 1994; scanned from Brierley and Fryirs, 2005).

Fluvial sediment transportation is segregated into two distinct modes (Figure 2): (1) suspended load and (2) bedload. Suspended load refers to particles that are continuously entrained in the water column, and mostly consist of clay and silt, with varying amounts of sand during high-energy flows. Suspended load is important for natural floodplain deposition processes and maintenance of deltaic and estuarine wetland environments. Bedload refers to sand grains, gravels, or larger particles that move along or near the channel bed by various mechanisms, including (1) traction and (2) saltation. Traction describes the condition where particles are in constant contact with the channel bed while moving, and includes sliding and rolling. Saltation describes the condition where particles skip along the channel bed, which is common in sand-bed channels. It is also noted that some references segregate bedload from bed-material load (Stevens and Yang, 1989), where the latter is defined as all particles originating from and exchanging with the channel bed irrespective of the transport mode. Bedload transport is responsible for instream habitat complexity and maintenance, as well as deltaic accretion (formation). The amount of bedload transported by a river also determines its channel geometry and ability to recover from natural or anthropogenic disturbances, including floods and upstream impoundments.

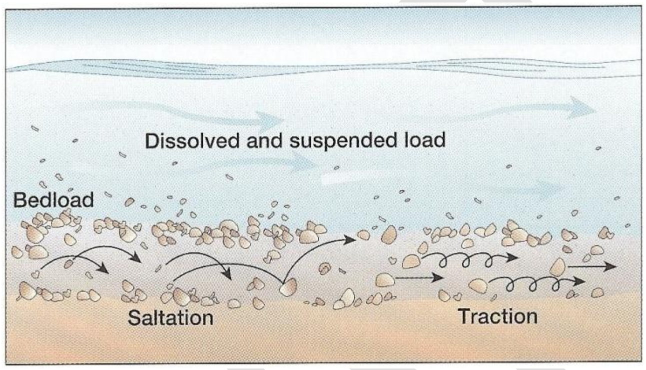

Figure 2. Mechanisms of sediment transport (from McKnight and Hess, 2000).

Rationale and Context

As flows increase from base flow to high-pulse flows to overbank floods, rates of sediment transport in the water column and at the channel bed greatly increase. The transport of sediment is as important to the complexity and structural diversity of rivers, riparian zones, deltas, and estuaries as the conveyance of water itself. The balance between the force of water and the resistance of sediment sculpts the many fluvial patterns and shapes that provide habitats and conditions to which aquatic and riparian species uniquely adapt over time. If only flows are considered, without the associated sediment, then an incomplete assessment of the state's rivers and bays reduces the likelihood of conservation or rehabilitation. A worst-case scenario might involve high-pulse flow releases that increase rates of river-channel degradation.

Texas Senate Bill 2

The importance of sediment transport and river channel morphology has been highlighted by instream flow activities associated with Texas Senate Bill 2. Also, in a National Research Council review of the Texas Instream Flow Program (TIFP) (2005), it was stated that the section considering physical processes and sediment transport required "significant augmentation" to relate them to the hydrologic regime, and that a "thin, single set of analytical approaches" would be insufficient to "address the range or complexity of physical processes." In response to these comments, the state agencies responsible for the TIFP further addressed physical processes and sediment transport in the revised technical overview document (TOD) of the TIFP (2008), which contains the following statements:

"Geomorphic studies will assess the active channel processes responsible for developing physical habitats."

"Agencies will develop sediment budgets…"

"…geomorphic studies need to be tailored to the specific sub-basin being investigated"

"…the lack of geomorphic data for Texas' rivers is problematic."

"…a monitoring program that collects geomorphic data for major rivers will be required."

The TOD goes on to recommend specific lines of inquiry to address these problems and achieve program goals.

Texas Senate Bill 3

Texas Senate Bill 3 mandates that locally based basin and bay expert science teams (BBESTs), with consultations and support from the Environmental Flows Science Advisory Committee (SAC) and basin and bay area stakeholder committees, "develop environmental flow analyses and a recommended flow regime" that "maintain(s) the viability of the state's streams, rivers, and bay and estuary systems" using "reasonably available science." BBESTs are responsible for flow recommendations required by Senate Bill 3. It is thus within their purview to consider reasonably available scientific methods to account for instream sediment transport and its delivery to bay and estuary systems. The imminent deadlines for which the BBESTs must provide flow-regime recommendations exclude the possibility of making present-day sediment-load measurements and analyses for the short-term requirements. However, estimates or predictions of sediment transport for various flows would serve as a benchmark from which to assess programmatic goals, and adaptive management practices could include consideration of sediment transport data as they become available. Measurable objectives that link sediment transport to healthy rivers and floodplains include achieving optimized: (1) channel-bed elevations and rates of bank erosion, (2) instream geomorphic unit structure and function, including composition and adjustment frequency of pool-riffle sequences and other units (see Brierley and Fryirs, 2005), (3) turbidity, and (4) floodplain accretion rates. Measureable objectives that link sediment transport to healthy estuaries include achieving optimized: (1) rates of deltaic accretion, (2) rates of estuarine shoreline erosion, and (3) turbidity. Achieving these objectives would promote healthy aquatic and riparian habitats, thereby providing native species with the abiotic conditions to which they have successfully adapted.

Methods of Assessment

Suspended load and bedload are measured or estimated separately because the physical processes that govern their rates of transport are dependent on different factors. The sum of suspended load and bedload is the total sediment load. Methods to assess suspended load and bedload in Texas rivers and streams can be separated into two categories: (1) historical data analyses and (2) model estimates.

Historical Suspended-Sediment Data

Historical suspended-sediment load data are available until the early 1980s for various streamflow-gaging stations in Texas, and are derived from two general sources: (1) reports published by the Texas Water Development Board (TWDB) and predecessor agencies and (2) the U.S. Geological Survey (USGS). Suspended-sediment load measurements commonly are associated with discharge to generate a sediment-discharge rating curve. This, however, is problematic because suspended-sediment concentrations are known to be variable for a given discharge. Stormflow hydrographs usually, but not always, are characterized by higher suspended-sediment concentrations during the rising limb than the falling limb, referred to as a type-I hysteresis loop (Figure 3). Further, the timing between storm events also influences availability of fine-grained sediment from the watershed, such that an initial stormflow following relatively dry conditions usually has a greater suspended-sediment concentration than subsequent flows of similar magnitude. Aside from these complications, assessments of suspended-sediment load for various flows are encouraged.

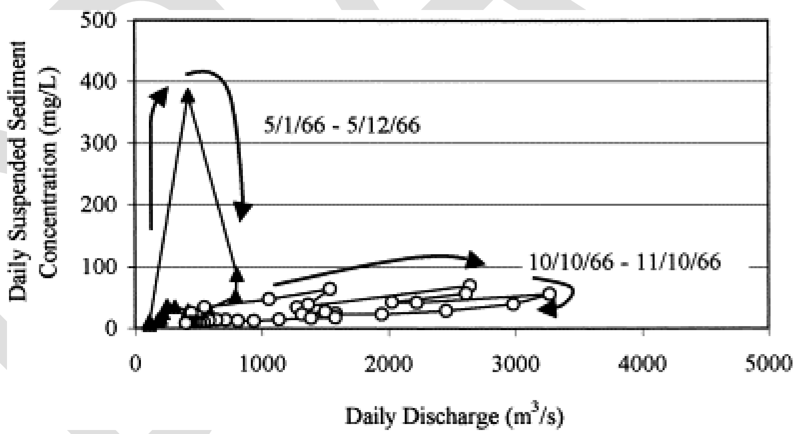

Figure 3. Type-I hysteresis loop of suspended-sediment concentrations for two stormflow events, showing (1) concentrations higher on the rising limb than the falling limb and (2) sediment exhaustion effects for the second, larger flood (from Hudson, 2003).

A series of reports by the Texas Water Development Board and predecessor agencies (Stout and others, 1961; Adey and Cook, 1964; Cook, 1967; Cook, 1970; Mirabal, 1974; Dougherty, 1979; Quincy, 1988) summarize daily suspended-sediment concentration and load measurements into monthly values at various stations in Texas over various periods of record. Historic suspended sediment samples were obtained in an 8-ounce narrow-neck bottle held in a

10-pound torpedo-shaped frame, positioned no more than one foot below the water surface. Samples were obtained daily or throughout the day if a considerable change in stage occurred. Samples were obtained at one-sixth, one-half, and five-sixths of the water-surface width (Stout and others, 1961). To account for increasing suspended sediment concentrations with depth, the measured percent of suspended sediment by weight was multiplied by 1.102 to obtain the mean percentage of suspended sediment in the vertical profile (Quincy, 1988).

The USGS also collected suspended-load data at various stations in Texas and for various periods of record. Data typically were collected 5 to 10 times per year for various flow magnitudes. The data can be accessed through the National Water Information System (NWIS) at *http://waterdata.usgs.gov/tx/nwis/qwdata*. USGS suspended-sediment data were collected by one of two methods: (1) equal-discharge-increment (EDI) or (2) equal-width-increment (EWI) (Edwards and Glysson, 1999). In simple terms, the EDI method obtains depth-integrated samples of suspended sediment from the centroids of equal-discharge increments across the channel. The EWI method obtains depth-integrated samples of suspended sediment at equally-spaced increments across the channel. Both methods provide similarly accurate results.

A comparison of the sampling method discussed for the TWDB (and predecessor agency) reports and the USGS method was made by Welborn (1967). For sand-bed rivers, including the Sabine, Neches, Trinity, and San Jacinto, correlations could not be formulated between the two methods and preference is given to the more accurate USGS method. However, for rivers with mixed or gravel beds, it was found that suspended-sediment load (in tons per year) computed by the former method closely matches loads computed by the USGS method.

Historical Bedload Data

Historical bedload data for Texas rivers are practically unavailable. Discrete measurements of bedload probably are available in isolated sources associated with one-time investigations. However, the great difficulties in accurately measuring bedload, especially in sand-bed channels, should be considered if data sources are located. If sufficient historical bedload data are identified and their quality deemed acceptable, then computations of effective discharge for bedload transport can be made with available streamflow data.

Sediment Transport Models

Bedload models, usually based on hydraulic principles, are notoriously inaccurate (Gomez and Church, 1989), uncertain (Gomez and Phillips, 1999), and applicable to rivers that exhibit steady-state equilibrium, but offer the most rapid approach to estimate transport. The various formulas for estimating bedload transport commonly require values for bed-material particle size, channel slope (energy gradient), flow depth, among other measureable or estimated factors. Common bedload transport equations include Meyer-Peter and Müller (1948), Einstein (1950), Ackers and White (1973), Bagnold (1980), Parker and others (1982), and Gomez (2006), among others. The choice of bedload equations should be based on: (1) the composition of the bed material and (2) the hydraulic conditions under consideration. One investigator has recently recommended the Einstein (1950) approach for low-gradient sand-bed channels (Dennis Evans, U.S. Geological Survey, personal communication, 2008) although others recommend excess stream power approaches (Gomez and Church, 1989) modeled after Bagnold (1980). If changes in channel-bed elevation over time are known, then another method to estimate bedload transport is Exner's equation (see equation 1 in Paola and Voller [2005]). The following sources provide useful bedload transport model equations and explanations: (1) Gomez and Church (1989), (2) Stevens and Yang (1989), and (3) Robert (2003). An excellent online resource with technical discussions of sediment transport and river channel dynamics, especially for gravel-bed rivers, is found on Gary Parker's (University of Illinois) website (2008), and various spreadsheets are available to compute sediment transport and associated channel-bed adjustments.

A very useful application to estimate bedload and suspended-load transport is SAM – Hydraulic Design Package for Channels, an assemblage of various sediment transport equations that accompany a one-dimensional hydraulic computation model. User input to SAM includes channel cross-sectional data, energy gradient (channel slope), bed-material particle size distributions, a roughness value, among other limited data. The SAM application assesses the user input to determine which sediment transport equations are most applicable, and then computes sediment transport loads using a combination of model output with the cross-sectional geometry data. Further, flow-duration curve data can be included to determine which flows cumulatively transport the most sediment over time, referred to as the effective discharge. A final comment should be made that personnel involved with application of sediment transport models should have considerable background or training in the field, and caution should be given to computed estimates, especially when extrapolating to ungaged reaches. For some rivers in Texas, a source of data to parameterize sediment transport models is provided in a 4-CD set of data published by the National Cooperative Highway Research Program (2004). Further, cross-sectional data from streamflow measurements can be requested from the U.S. Geological Survey (USGS) water-science centers in Texas.

Effective Discharge

Sediment load is a measure of mass transport over time and, with a reasonably extensive dataset, one could formulate sediment-flow prescriptions in the same manner as streamflow. However, the most commonly applied method to associate sediment load with streamflow is through an analysis of effective discharge. Effective discharge is the flow that cumulatively transports the majority of sediment in a river or stream over time (Figure 4). It is usually a flow of moderate magnitude and frequency. Although high-magnitude floods can transport substantial quantities of sediment, their relatively infrequent occurrence often is outpaced by the sediment transport of more frequent moderate flows.

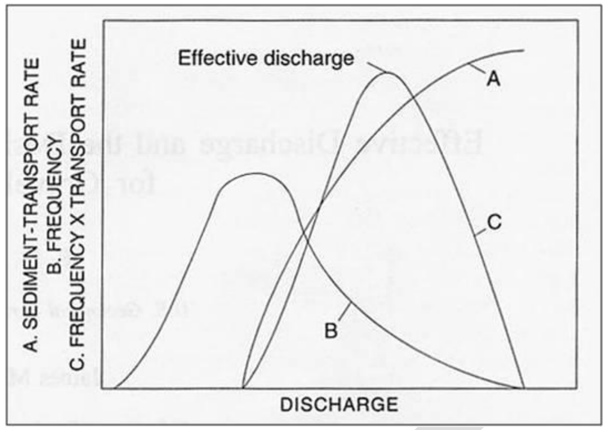

Figure 4. Effective discharge, in its most basic form, is the largest product of the sediment transport rate and the frequency of transport (from Wolman and Miller, 1960; scanned from Andrews and Nankervis, 1998).

Although a number of investigations confirm that relatively frequent, moderate flows (Hudson and Mossa, 1997) or bankfull flows (Andrews and Nankervis, 1995; Biedenharn and others, 1999; Torizzo and Pitlick, 2004) are responsible for the majority of cumulative sediment transport over time (Figure 5), others have shown that infrequent, high-magnitude floods equate to the effective discharge (Gupta, 1988; Bourke and Pickup, 1999), especially in fluvial systems with highly variable flow regimes. Generally, effective discharge is less frequent as the average annual precipitation and regularity of flooding decreases. A further complication associated with applications of effective discharge is the tendency to rely solely on one flow value to transport sediment over time. Similar to the major premise of environmental flows, an emphasis on flow variability, is that sediment is transported by a range of flows over time. For example, average flow conditions are known to transport appreciable quantities of sediment in sand-bed river systems.

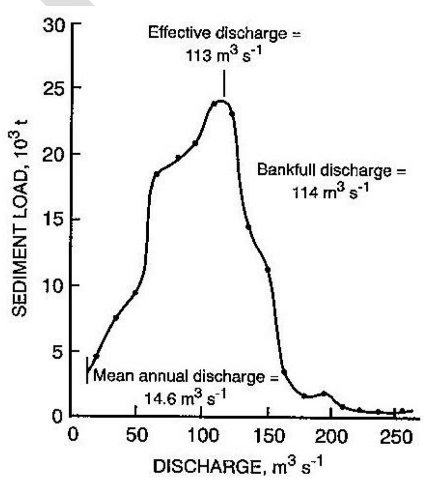

Figure 5. Effective discharge in this example approximately is equal to the bankfull discharge (from Andrews, 1980; scanned from Knighton, 1998).

A process to compute effective discharge at gaged or ungaged stations is provided in Biedenharn and others (2000). Effective discharge requires an annual flow-duration curve and a sediment-discharge rating curve. Discharges are divided into a range of equal arithmetic classes and the total sediment load is computed for each class. This is done by multiplying the frequency of each flow class by the median sediment load of that class. The average of the flow class with the highest load is the effective discharge. Further, the quantification of sediment load by flow classes enables an assessment of the relative importance of the effective discharge compared to lesser and greater flows. For purposes of instream channel maintenance, the method is suggested for bed-material load only. However, the method could independently be applied to determine effective flows for suspended load or bedload.

The actual concept of effective discharge should be taken into consideration when evaluating its potential to prescribe channel-maintenance flows. First, its application assumes steady-state equilibrium of the river channel, or the tendency to fluctuate around an average geometric condition (e.g., bankfull width-to-depth ratio) (Figure 6). If the channel does not display equilibrium, such as would be the case for an actively incising channel-bed, then a computation of effective discharge does not describe the condition acceptable for conservation or restoration efforts. Further, the effective discharge is a product of flow frequency; therefore a regulated adjustment of the flow regime would result in a different value.

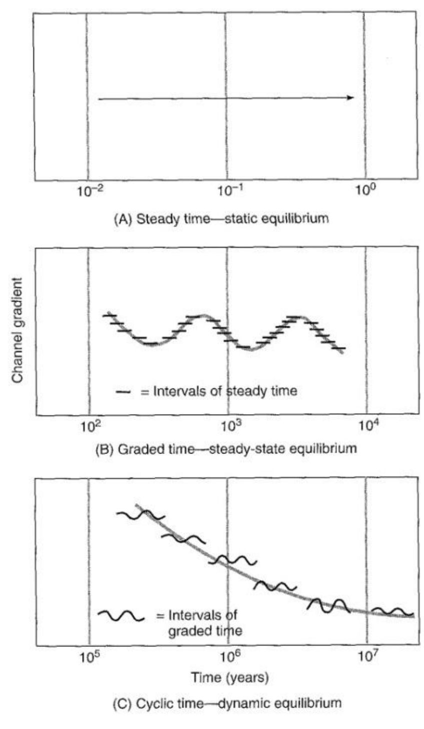

Figure 6. Concepts of equilibrium in fluvial geomorphology (from Schumm, 1977; scanned from Ritter and others, 2002). Channel rehabilitation or engineering applications focus on graded time scales, and efforts are usually made to promote a steady-state channel condition that is resilient to disturbances (e.g., floods).

Recommendations

An analysis of the effective discharge of sediment transport at gaging stations with a sufficient period of record (20 or more years) could serve as an overlay to modify high-pulse flows based on hydrology alone. For gaging stations with accurate suspended-load data, effective discharge can be computed using the methodology described in Biedenharn and others (2000). Bedload transport can be accounted for with a model equation, which requires inputs of bed-material size, channel slope, cross-sectional geometry, and flow depth, among other hydraulically relevant parameters. The caveat of using measured suspended-load data is that the values represent conditions during the period of measurement, which might have been degraded or not representative of desired conditions for many rivers in Texas, especially for stations downstream of reservoirs. An illustrative example is provided below for the Brazos River near Richmond, Texas, using streamflow and suspended-load data from the USGS National Water Information System (NWISWeb) (U.S. Geological Survey, 2009) and supporting data from the National Cooperative Highway Research Program (2004).

08114000 Brazos River at Richmond, Texas

Data required for an analysis of effective discharge at 08114000 Brazos River at Richmond, Texas, are summarized in Table 1.

Table 1. Data required for effective discharge analysis at 08114000 Brazos River at Richmond, Texas.

DATA	SOURCE
1. Daily mean streamflow (cfs)	USGS NWISWeb
2. Suspended sediment load (tons/day)	USGS NWISWeb water-quality data
3. Bed-material particle size (in)	National Cooperative Highway Research Program (2004)
4. Dimensionless channel slope	National Cooperative Highway Research Program (2004)
5. Manning's *n* coefficient	National Cooperative Highway Research Program (2004)
6. Cross-sectional channel geometry data	Hard-copy USGS streamflow measurement notes (available at USGS water science centers)

Flow-Duration Curve

1. Daily mean streamflow for the period of record were downloaded from USGS NWIS and exported to a spreadsheet. Days with missing values were deleted from the dataset, and streamflow values were sorted in descending order. Intervals of discharge were subdivided into 36 classes, the last class being 100,000 ft^3/s (Table 1). A simple quantitative method to determine class intervals is provided in Biedenharn and others (2000), but was not used for this analysis. Exceedance frequencies were computed using the number of days in the period of record, and plotted data are shown in Figure 7.

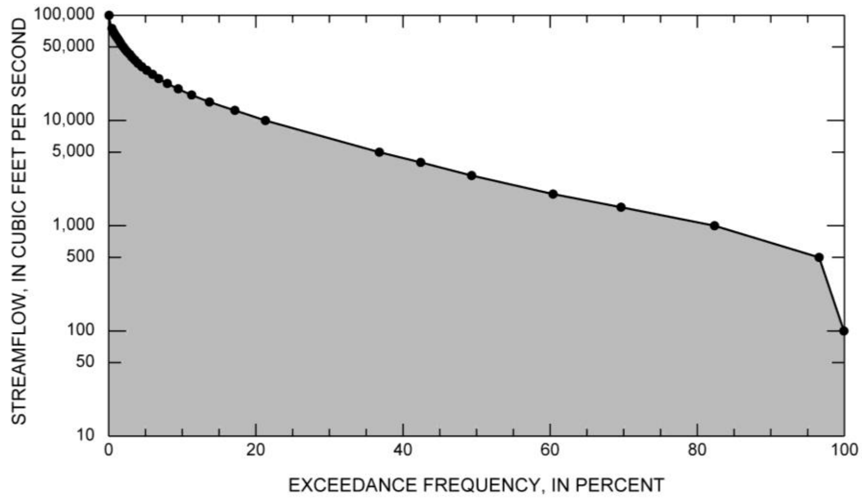

Figure 7. Flow-duration curve for 08114000 Brazos River at Richmond, Texas, for the full period of record using daily mean values. The high density of points at the upper tail is for a more accurate determination of effective discharge.

Suspended-Sediment Load

2. Suspended-sediment-load (SSL) data (period of record: February 1966 to September 1995) were downloaded by selecting the water quality / sediment measurements from USGS NWIS, and were exported to a spreadsheet. Records were sorted by the parameter code, and only data for suspended-sediment load were retained (USGS parameter code 80155). For days with multiple measurements of SSL, the mean value was used for that day. SSL (in log-10 space) for each day was plotted against its corresponding daily mean streamflow (in log-10 space), and a power function was fit to the data (Figure 8). The power function fitted to predict SSL from streamflow is:
    - $SSL = (0.0000527)^{2.1463}$ tons/day

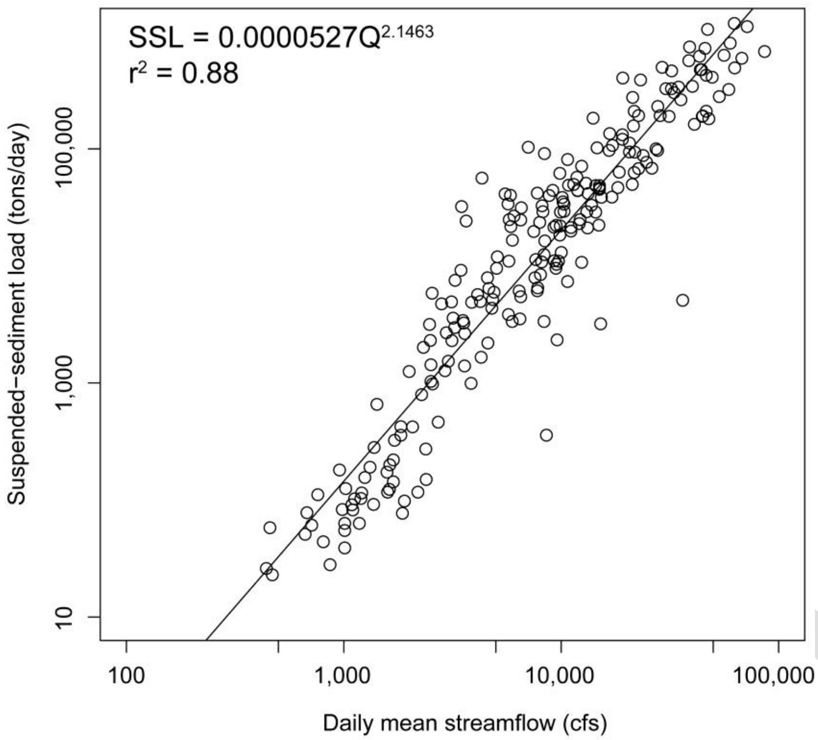

Figure 8. Suspended-sediment-load and streamflow rating curve for 08114000 Brazos River at Richmond, Texas. Scatter about the power trendline is attributed to sediment availability and hysteretic behavior of suspended-sediment concentrations over time.

3. A representative streamflow for each discharge class interval was computed as the mean discharge between two classes. The representative discharge was used in the power function determined in step #2 to compute SSL in tons/day for each discharge class. The result was multiplied by the discharge exceedance frequency to obtain the load transported by each discharge class. Finally, the load values were plotted as a histogram for each class, using the discharge value originally used in the flow-duration curve (Figure 9). Results of the entire analysis are also presented in Table 2. It takes some iterations of this step to ensure that discharge class intervals are appropriate to accurately determine the effective discharge.
4. The effective discharge is determined by evaluating the modal class of the histogram. In this case, four discharge classes exhibited the highest suspended-sediment loads, and the mean discharge representing their bounds was selected and approximates 46,000 ft^3/s, which is the effective discharge for suspended-sediment transport. Thus, for the period February 1966 to September 1995, the Brazos River at Richmond transported the cumulative majority of suspended sediment at about 46,000 ft^3/s. At this point, this does not include bedload transport. According to the National Weather Service (NWS)

West Gulf River Forecast Center (http://www.srh.noaa.gov/wgrfc/), flood stage occurs at a USGS stage of 48 feet, or 81,800 ft^3/s based on the current stage-discharge rating curve. Therefore, effective discharge of SSL is substantially less than bankfull conditions.

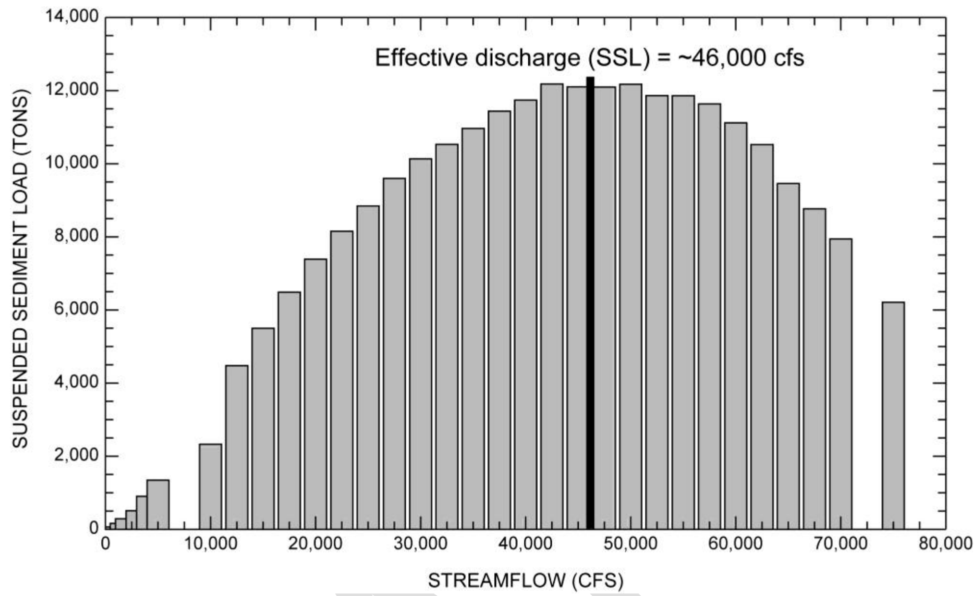

Figure 9. Suspended-sediment load (SSL) histogram showing effective discharge for SSL at 08114000 Brazos River at Richmond, Texas, approximately is 46,000 ft^3/s.

Table 2. Computations for the flow-duration curve and histogram for determination of effective discharge for suspended-sediment load (SSL). Gray columns were used to generate an SSL histogram.

(cfs; cubic feet per second; %, percent; SSL, suspended-sediment load)

Streamflow (cfs)	Days exceeded	Exceedance frequency	Representative streamflow (cfs)	SSL (tons per day) via power function	SSL (tons)
0	32,796	100.00%	0	0	0
100	32,774	99.93%	50	0	0
500	31,669	96.56%	300	11	11
1,000	27,009	82.35%	750	78	64
1,500	22,838	69.64%	1,250	234	163
2,000	19,809	60.40%	1,750	481	291
3,000	16,177	49.33%	2,500	1,035	510
4,000	13,908	42.41%	3,500	2,130	903
5,000	12,066	36.79%	4,500	3,653	1,344
10,000	6,987	21.30%	7,500	10,936	2,330
12,500	5,624	17.15%	11,250	26,110	4,477
15,000	4,489	13.69%	13,750	40,165	5,498
17,500	3,700	11.28%	16,250	57,486	6,486
20,000	3,100	9.45%	18,750	78,154	7,387
22,500	2,615	7.97%	21,250	102,240	8,152
25,000	2,234	6.81%	23,750	129,807	8,842
27,500	1,956	5.96%	26,250	160,912	9,597
30,000	1,699	5.18%	28,750	195,607	10,133
32,500	1,476	4.50%	31,250	233,941	10,529
35,000	1,303	3.97%	33,750	275,959	10,964
37,500	1,166	3.56%	36,250	321,702	11,437
40,000	1,037	3.16%	38,750	371,209	11,738
42,500	941	2.87%	41,250	424,517	12,180
45,000	824	2.51%	43,750	481,661	12,102
47,500	731	2.23%	46,250	542,675	12,096
50,000	657	2.00%	48,750	607,590	12,172
52,500	575	1.75%	51,250	676,436	11,860
55,000	519	1.58%	53,750	749,242	11,857
57,500	462	1.41%	56,250	826,035	11,636
60,000	402	1.23%	58,750	906,843	11,116
62,500	348	1.06%	61,250	991,691	10,523
65,000	287	0.88%	63,750	1,080,604	9,456
67,500	245	0.75%	66,250	1,173,605	8,767
70,000	205	0.63%	68,750	1,270,718	7,943
75,000	143	0.44%	72,500	1,424,145	6,210
100,000	18	0.05%	87,500	2,132,271	1,170

Cross-Sectional Data

5. In order to apply a bedload transport model, cross-sectional data are required to parameterize various steps in the model development. The choice of a cross section is very important because it represents the condition of the channel at a given time and place, such that the choice of an incised, degraded cross section downstream of a

reservoir would provide results inappropriate for assessment of naturalized conditions. For this exercise, hard-copy USGS streamflow measurement notes for two measurements in February 1998 (moderate flow) and November 2004 (high flow) were used to construct a cross-section on the upstream side of the bridge at Richmond. The moderate flow in 1998 was used to construct the channel bed and base of the bank, and the 2004 flow was used to vertically extend the banks to a maximum stage of 33.8 feet. Based on the observed bank angle, banks were artificially extended to the NWS flood stage of 48 feet (Figure 10) The reason for using a composite of two flows was to avoid excessive bed scour during the high flow but, nonetheless, capture as much of the bank morphology as possible.

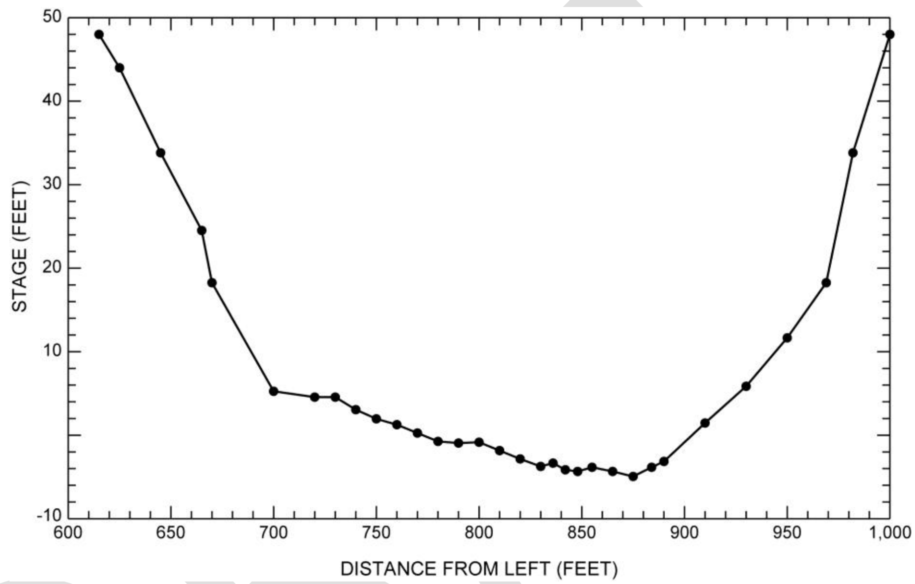

Figure 10. Cross section of 08114000 Brazos River at Richmond, Texas, based on USGS streamflow measurements in February 1998 and November 2004, and extended to NWS flood stage of 48 feet. The moderate flow of 1998 was used to construct geometry up to about 18 feet and the high flow of 2004 further extended geometry to about 34 feet.

6. The cross section was imported into WinXSPRO, a free software package available online from the U.S. Forest Service at http://www.stream.fs.fed.us/publications/winxspro.html. Care should be taken to correctly associate WinXSPRO results with the appropriate USGS stage because the software automatically sets the lowest point in the section to ‘0’. Hydraulic values, including hydraulic radius and mean velocity, for 0.25-foot stage increments were computed using the following hydraulic data for the Brazos River at Richmond, Texas, from the National Cooperative Highway Research Program (2004) CD set:

   Dimensionless channel slope: 0.00012

Manning's *n*: 0.03

Bagnold's (1977) Bedload Model

7. For all discharge class intervals used to compute suspended-sediment load above, a series of computations were made to estimate bedload transport (Table 3). English units were used. First, mean velocity (U) and hydraulic radius (R) for each discharge were entered from the WinXSPRO results. Stream power per unit area (ω) for each discharge class interval was computed from the following equation:

    - $\omega = \rho g d S U$, where ρ is the mass density of water (62.28 lb/ft^3), g is acceleration due to gravity (32.17 ft/s^2), d is mean flow depth (ft) which is considered analogous to R, S is dimensionless channel slope (0.00012), and U is mean velocity.

    Using the median particle size (D_{50}) of bed-material for the Brazos River at Richmond from the National Cooperative Highway Research Program (2004) CD set (see below), the critical shear stress (τ_c) for entrainment was computed from the following equation:

    - $\tau_c = \tau^*(\rho_s-\rho)D_{50}$, where $\tau^*$is the dimensionless Shields parameter (0.03 for sand-bed channels), ρ_s is the mass density of sediment (164.98 lb/ft^3 for quartz), and D_{50} is the median particle size (0.00075 ft).

    Average Bed Material D_{16}, D_{50}, D_{84} (in) (or the diameter at which 16, 50, and 84 percent of the sediment is finer than): 0.006, 0.009, 0.013

    Next, the mean flow depth required to entrain the median particle size (D_{50}) was computed from the following equation:

    - $d = \tau_c/(\rho S)$

    From this value, Manning's equation was used to compute the critical flow velocity (U_c) required to entrain the median particle size (D_{50}):

    - $U_c = (1.49 d^{2/3} S^{1/2})/n$, where n is Manning's coefficient (0.03).

    Next, the critical stream power required to entrain the median particle size (D_{50}) was computed from the following equation:

    - $\omega_c = U_c \tau_c$.

    The Bagnold (1977) formula to estimate the bedload transport rate (I_b) (lb/ft/s) for each discharge class interval was computed from the following equation:

    - $I_b = (\omega - \omega_c)^{3/2}(d/D_{50})^{-2/3}$.

Finally, the bedload transport rate (I_b) was multiplied by the wetted perimeter (from WinXSPRO) for each discharge class interval to estimate a channel-wide bedload transport rate (lb/s), and the value was converted to tons per year.

Table 3. Computations for bedload transport using the Bagnold (1977) model and effective discharge for bedload. Critical stream power (ω_c) was computed to be 0.00057 for this example. Gray columns were used to generate a bedload histogram.

(cfs; cubic feet per second; %, percent; ft, feet; ft/s, feet per second; ω, stream power per unit bed area; lb/ft/s, pounds per foot per second; yr, year)

Streamflow (cfs)	Exceedance frequency	Stage (ft)	Mean velocity (ft/s)	Mean depth (ft)	Stream power (ω)	Bedload transport (lb/ft/s)	Bedload transport (tons/yr)	Bedload (tons)
100	99.93%	7.8	2.1	7.6	3.837	0.01605	62,039	61,998
500	96.56%	8.87	2.3	8.4	4.645	0.02000	79,191	76,470
1,000	82.35%	9.75	2.4	9.1	5.251	0.02278	92,393	76,090
1,500	69.64%	10.45	2.5	9.7	5.830	0.02555	105,209	73,264
2,000	60.40%	11.06	2.5	10.1	6.071	0.02642	110,481	66,731
3,000	49.33%	12.11	2.7	10.9	7.076	0.03160	135,127	66,653
4,000	42.41%	13.02	2.8	11.6	7.809	0.03515	153,075	64,916
5,000	36.79%	13.89	2.9	12.2	8.506	0.03864	171,324	63,032
10,000	21.30%	17.66	3.3	14.9	11.822	0.05541	264,034	56,251
12,500	17.15%	19.24	3.5	16.2	13.632	0.06489	315,365	54,080
15,000	13.69%	20.78	3.7	17.5	15.568	0.07522	370,302	50,686
17,500	11.28%	22.26	3.8	18.7	17.085	0.08274	412,541	46,542
20,000	9.45%	23.68	4.0	19.9	19.138	0.09411	473,693	44,775
22,500	7.97%	25.01	4.1	20.9	20.602	0.10173	518,490	41,342
25,000	6.81%	26.31	4.2	21.8	22.013	0.10925	565,418	38,515
27,500	5.96%	27.56	4.4	22.7	24.014	0.12116	636,631	37,970
30,000	5.18%	28.76	4.5	23.5	25.425	0.12899	685,881	35,532
32,500	4.50%	29.94	4.6	24.4	26.985	0.13755	737,935	33,211
35,000	3.97%	31.08	4.7	25.2	28.476	0.14593	796,713	31,654
37,500	3.56%	32.2	4.8	25.9	29.890	0.15409	850,992	30,255
40,000	3.16%	33.28	4.9	26.6	31.337	0.16250	907,706	28,701
42,500	2.87%	34.35	4.9	27.4	32.280	0.16657	940,913	26,997
45,000	2.51%	35.38	5.0	28.0	33.660	0.17482	998,564	25,089
47,500	2.23%	36.4	5.1	28.7	35.191	0.18383	1,061,660	23,664
50,000	2.00%	37.42	5.2	29.3	36.631	0.19256	1,118,126	22,399
52,500	1.75%	38.4	5.2	30.0	37.506	0.19638	1,155,837	20,265
55,000	1.58%	39.36	5.3	30.6	38.992	0.20544	1,222,095	19,340
57,500	1.41%	40.28	5.4	31.2	40.507	0.21473	1,287,515	18,137
60,000	1.23%	41.12	5.4	31.7	41.156	0.21759	1,318,420	16,161
62,500	1.06%	41.95	5.5	32.2	42.579	0.22660	1,383,729	14,683
65,000	0.88%	42.78	5.6	32.7	44.027	0.23582	1,451,174	12,699
67,500	0.75%	43.58	5.6	33.2	44.700	0.23882	1,480,947	11,063
70,000	0.63%	44.38	5.7	33.7	46.183	0.24832	1,551,610	9,699

8. A bedload histogram was plotted in the exact same manner as the suspended-load exercise (Figure 11), multiplying the final bedload (tons/year) by the exceedance frequency of the discharge for which it was modeled. The results show that effective discharge for cumulative bedload transport occurs at relatively low flows. This, however, is an inaccurate assessment of bedload transport in reality. The Bagnold (1977) model is dependent on excess stream power, which is generated to a large measure by depth and velocity. The flaw in this example occurred because the stage for very low flows according to the USGS, say 100 ft^3/s, filled up the cross section to a mean depth of 7.6 feet at a mean velocity of 2.1 feet/second according to hydraulic computations modeled in WinXSPRO. These modeled hydraulic conditions are more than adequate at transporting sand-sized bedload, and their almost constant occurrence over time ensured low flows outpaced moderate to high flows with respect to cumulative transport. In reality, the hydraulic conditions at 100 ft^3/s at this cross section are sluggish and pond-like, not capable of transporting sand-sized bedload. This example underscores the importance of selecting an appropriate cross section to model bedload transport using any given equation. For appropriate cross sections with adequate data, however, the Bagnold (1977) equation has worked well for other investigations.

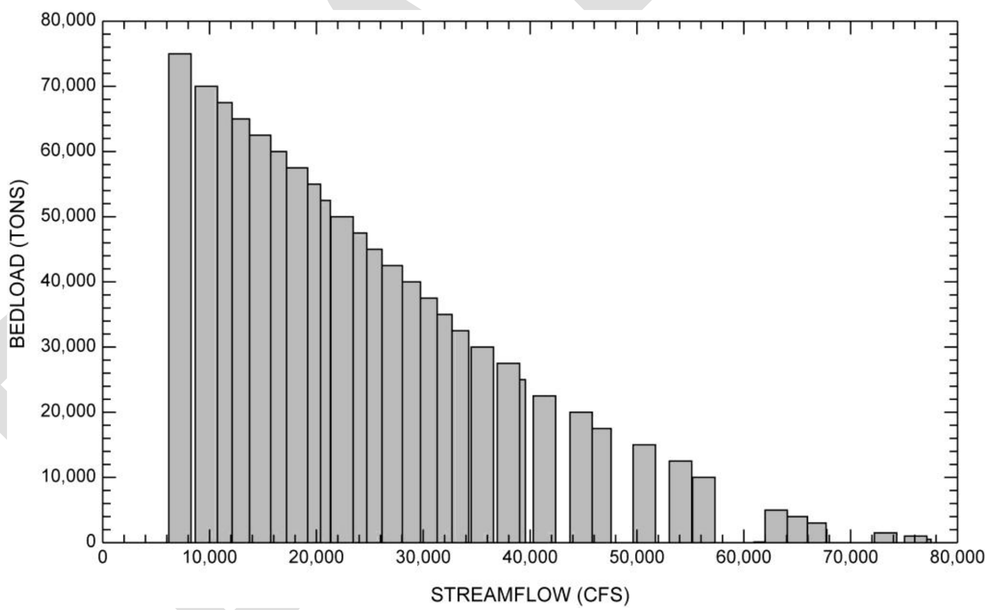

Figure 11. Histogram showing an inaccurately low estimate of effective discharge for bedload at 08114000 Brazos River at Richmond, Texas.

SAM Hydraulic Design Model

The SAM hydraulic design model efficiently computes the exercises shown above when parameterized with sufficient data. Furthermore, SAM can recommend appropriate sediment transport formulae for the given input, such as channel slope and bed-material particle size. The use of the SAM sediment-transport model is a tool that can be used to establish effective discharge at gaging stations. As discussed above, it should be applied with caution for rivers that do not exhibit steady-state equilibrium. The SAM model requires cross-sectional geometry data for the location of interest. For rivers that are degraded, such as those that have incised immediately below reservoirs, cross-sectional channel geometry probably is not representative of any natural condition. As a hypothetical example, cross-sectional area of a river channel immediately downstream of a reservoir is greatly enlarged as a result of channel incision and bank retreat, and SAM computes a sediment load much greater for the enlarged channel than would be expected naturally. Because the sediment transport models embedded within SAM are based on equilibrium-based theoretical constructs, however, the output of the model provides the analyst with a reference condition of sediment transport. As such, SAM output can be used in conjunction with field measurements of suspended load and bedload to determine if the river is over- or under-achieving with respect to sediment transport.

Regardless of the analysis employed, values of effective discharge should be considered with respect to desired conditions of particular river systems. For some rivers, it might be desirable to transport less sediment load than that computed by an effective discharge analysis. As a hypothetical example, a river reach 25 miles downstream of a reservoir receives much less sediment than it did during pre-impoundment conditions. In order to prevent channel incision and associated bank failure over time, it would be desirable for sediment transport to underperform that predicted by SAM analysis of steady-state conditions.

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Glossary

Bedload: fluvial sediment transported along or near the channel bed by traction or saltation; either sand, gravel, or larger size; expressed as mass over time

Bed-material load: the portion of the sediment load, whether suspended load or bedload, comprised of particles from the channel bed (e.g., could be bedload and sand grains in suspension during high-energy flows); expressed as mass over time

Effective discharge: the flow rate responsible for the majority of cumulative sediment transport over time; usually equated to a relatively frequent, moderate stormflow event; commonly accepted as bankfull discharge; association with bankfull discharge is less apparent for fluvial systems with a highly-variable flow regime

Saltation: a mechanism of bedload transport where particles skip along the channel bed

Sediment budget: a technique that accounts for sources (additions) and sinks (subtractions) of fluvial sediment in a defined area (e.g., watershed); accounts for sources from hillslopes, channel banks, tributaries, among others; and removals from impoundments, floodplain storage, distributaries, among others

Steady-state equilibrium: concept that a river channel adjusts over time to efficiently convey the amount of discharge and sediment load by maintaining a particular slope, pattern, and shape; suggests that the fluvial system will gradually recover from the effects of a large disturbance to the system (e.g., 100-year flood); a fundamental, but controversial, fluvial geomorphic concept

Stream power: the product of average shear stress and average velocity; commonly used to predict sediment transport; expressed in SI units as watts/square meter

Suspended-sediment load: fluvial sediment transported continuously in the water column; mostly clay and silt, with varying amounts of sand during high-energy flows; expressed as mass over time

Suspended-sediment concentration: the concentration of suspended sediment in the water column; computed as the ratio of suspended-sediment load to the streamflow; expressed as milligrams per liter

Traction: a mechanism of bedload transport where particles roll or slide along the channel bed