May 29, 2009

Transmittal to Basin and Bay Expert Science Teams (BBESTs)

Report # SAC-2009-04

Title: Fluvial Sediment Transport as an Overlay to Instream Flow Recommendations for the Environmental Flows Allocation Process.

The attached document constitutes another deliverable from the Senate Bill 3 Science Advisory Committee (SAC) to assist the BBESTs in carrying out their responsibilities to develop instream environmental flow regime recommendations. This document deals with the issue of sediment transport, and presents information for the BBESTs to consider as a possible overlay to HEFR-based results, in particular to assess impacts on sediment loads resulting from HEFR-based hydrologic evaluations.

The document reviews various methods for assessing suspended-load and bedload transport, and recommends that the BBESTs consider application of the SAM Hydraulic Design Package for estimating effective discharge. A detailed example is presented, cautioning that it presents a worst-case scenario in which annual flow volumes are strictly limited to the HEFR-prescribed results in all respects.

While the SAC does not believe that sufficient data exists to directly prescribe a "sediment load regime" that would maintain instream ecology, we do suggest that the information contained in this report, in particular the SAM model, can be used to validate HEFR-based flow regimes from the perspective of sediment transport impacts.

The SAC is hopeful that the BBESTs will find this information useful in their deliberations, and we invite feedback as we all move forward with our respective responsibilities under SB3.

Robert J. Huston, Chairman, SB3 Science Advisory Committee

WORKING DRAFT

Fluvial Sediment Transport as an Overlay to Instream Flow Recommendations for the Environmental Flows Allocation Process

Senate Bill 3 Science Advisory Committee for Environmental Flows

SAC Members

Robert Brandes, Ph.D., P.E., Vice-Chair
Franklin Heitmuller, Ph.D.
Robert Huston, Chair
Paul Jensen, Ph.D., P.E.
Mary Kelly
Fred Manhart
Paul Montagna, Ph.D.
George Ward, Ph.D.
James Wiersema

Document Version Date: May 29, 2009

Report # SAC-2009-04

TABLE OF CONTENTS

LIST OF TABLES

LIST OF FIGURES

SECTION 1
FLUVIAL SEDIMENT TRANSPORT

The fluvial system commonly is conceptualized on the basis of three dominant processes that operate at various spatial and temporal scales: (1) erosion in the upper source zone, (2) transport in the middle transfer zone, and (3) deposition in the lower accumulation zone (Schumm, 1977) (Figure 1). This macroscopic conceptual model is applicable to many coastal-draining river systems, and all three of the 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 from hillslopes or channel margins and terminate when the material either is deposited or dissolved. Fluvial deposits, including instream bars and benches, floodplains, and deltas, can be either temporary and remobilized or permanent and converted to sedimentary rock over geologic timescales.

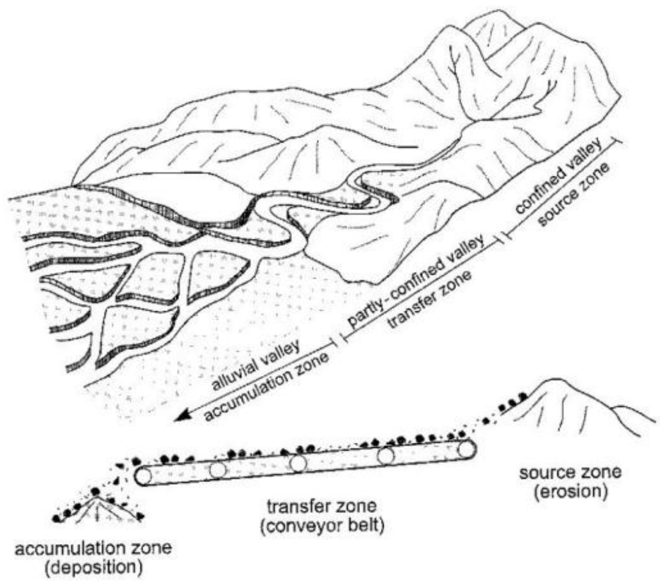

Figure 1. Conceptual diagram of a large fluvial system, with an emphasis on sediment erosion transport, and deposition (from Kondolf, 1994; scanned from Brierley and Fryirs, 2005).

The transport of material in fluvial systems is segregated into three general modes: (1) dissolved load, (2) suspended load, and (3) bedload (Figure 2). Dissolved load includes chemical constituents moving through the system, and suspended load and bedload are mechanisms of sediment transport. Suspended load refers to particles that are continuously entrained in the water column, and mostly consists of clay and silt, with varying amounts of sand derived from the channel bed during turbulent flows. Sand-sized particulates can either be transported along the bed during low- or moderate-flow conditions or in suspension during turbulent flows, thus a sub-category termed wash load is defined by only those particles continuously entrained in the water column (e.g., clay, silt, and organic matter) at all times. 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 (Figure 2). Some references segregate bed-material load from bedload (e.g., Stevens and Yang, 1989), where the former 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 assists in forming its channel geometry and its ability to recover from natural or anthropogenic disturbances, including floods and upstream impoundments.

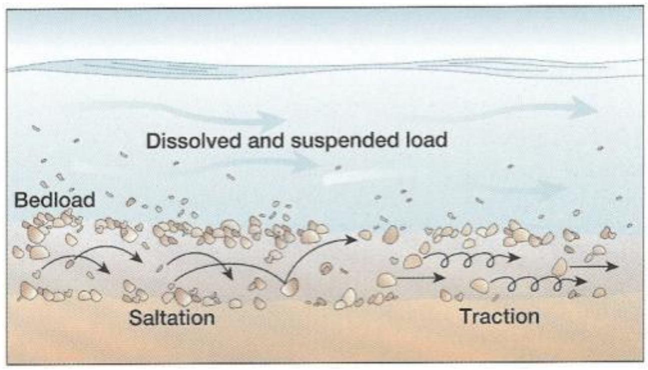

Figure 2. Generalized mechanisms of fluvial transport (from McKnight and Hess, 2000).

SECTION 2
PURPOSE AND SCOPE

This report provides guidance for the inclusion of fluvial sediment transport as a possible overlay to the HEFR approach for determination of an environmental flow regime required by Texas Senate Bill 3 (Senate Bill 3 Science Advisory Committee for Environmental Flows, 2009). Although numerous sources associate the majority of fluvial sediment transport with high-pulse flows, the discussion and guidance provided below are not contingent on an exclusive association of sediment transport with HEFR-based high-pulse flows. In many cases, a healthy sediment regime could be associated either with overbank, high-pulse, or even base flows. Further, it should be recognized that sediment transport processes do not encompass the full breadth of fluvial geomorphic investigation, but can be readily associated with an environmental flow regime.

Section 3 of this report provides a rationale and context to justify inclusion of a sediment transport overlay to the environmental flows allocation process mandated by Texas Senate Bill 3. Section 4 discusses various methods of assessment, including the use of historical data, model equations, and computation of effective discharge. Strengths and weaknesses of various methods are presented. Section 5 recommends the effective discharge approach to assess sediment transport at gaging stations and discusses some limitations of this approach. Further, a step-by-step example of the effective discharge approach at a long-term USGS streamflow-gaging station is provided and the use of the SAM hydraulic design model for estimation of effective discharge is advocated. Section 6 identifies several decision points that a practitioner tasked with a sediment-transport analysis will encounter. Section 7 provides a step-by-step example of SAM sediment-transport analyses of historically observed flows and HEFR-adjusted flows for the Sabine River near Bon Wier, Texas. Importantly, the HEFR-based SAM analysis assumes a “worst-case scenario” where the annual flow volume in excess of the HEFR-prescribed flow regime is removed (e.g., a new reservoir is constructed and flows are regulated to not exceed the HEFR-prescribed flows). Section 8 draws some general conclusions and reinforces various limitations of an effective discharge analysis.

This report originally was prepared by the Science Advisory Committee, with contributions and comments from the Texas Water Development Board (TWDB). Members of the Science Advisory Committee have reviewed, edited, and expanded the document and have provided recommendations regarding the application of the information and procedures presented in the document pursuant to the requirements of SB 3.

SECTION 3
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 erosion, transport, and deposition of sediment are 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 habitat degradation.

3.1 TEXAS SENATE BILL 2

The importance of sediment 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 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 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 programmatic goals.

3.2 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 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 might consider sediment data as they become available.

Measurable objectives that link sediment 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 units such as pool-riffle sequences, bars, and benches, among others (see Brierley and Fryirs, 2005); (3) turbidity; and (4) floodplain accretion rates. Measureable objectives that link sediment 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 by supporting the abiotic conditions to which native species have successfully adapted over time.

Although some objectives associated with sediment transport can be measured, little can be done using readily available desktop methods to prescribe a "sediment-load regime" that would adequately maintain instream ecology. The chief reason for this is the paucity of historically-observed geomorphic and sediment-transport data for rivers in Texas, contrasting with the availability of streamflow data for HEFR-based flow-regime analyses. Further, various fluvial processes (e.g., channel bar deposition and modification, channel migration, floodplain sedimentation) initiate and/or occur over a range of flows and, therefore, are dependent on sufficient rates of sediment transport during those flows. The unavailability of data for Texas rivers obfuscates the determination of optimized sediment concentrations or loads for these physically-relevant flows.

As an alternative to determining a "sediment-transport regime" to maintain instream ecology, methodological approaches are outlined below that would facilitate quantification of sediment loads for observed flows or HEFR-adjusted flow prescriptions. Using these methods, "what if" hydrologic scenarios could be analyzed to infer changes in sediment loads. Further, these methods can be applied using historical data, including sediment-load measurements (e.g., suspended load) or river channel dimensions (e.g., cross sections), thereby providing a context for contemporary conditions. Evaluations of sediment load in Texas eventually need to be related to habitat structure, function, and change, which would require interdisciplinary research among specialists in biology, geomorphology, and hydrology. Many of these efforts fall under the auspices of the Texas Instream Flow Program mandated by Senate Bill 2.

SECTION 4
METHODS OF ASSESSMENT

Suspended load and bedload are measured or estimated separately because the physical processes that govern their rates of transport are contingent 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.

4.1 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 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.

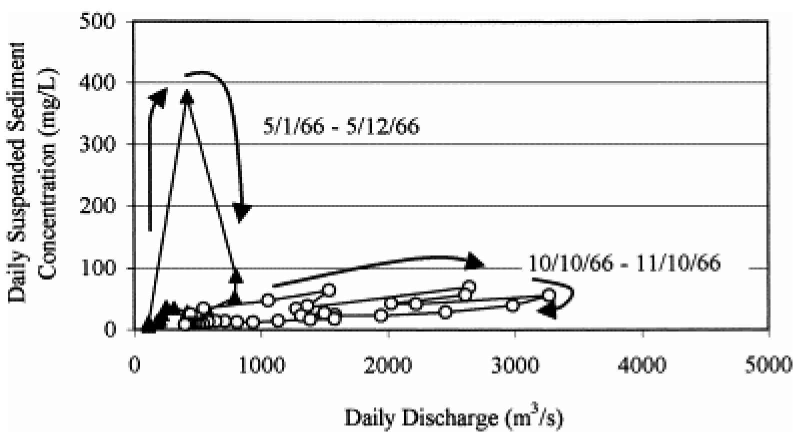

Figure 3. Type-I hysteresis loop of suspended-sediment concentrations for two stormflow events, showing (1) concentrations higher on the rising limb than the falling limb and (2) sediment exhaustion effects for the second, larger flood (from Hudson, 2003).

A series of reports by the TWDB and predecessor agencies (Stout et al., 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. The data were collected by the "Texas-sampler method". Historic suspended sediment samples were obtained in an 8-oz narrow-neck bottle held in a 10-lb torpedo-shaped frame, positioned no more than one foot below the water surface. Samples were obtained daily at one-sixth, one-half, and five-sixths of the water-surface width (Stout et al., 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 data summarized in these reports were collected to estimate reservoir siltation and should be used with caution for determining an environmental flow regime.

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 "Texas-sampler method" 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 because of highly-variable ratios of the two estimates along different rivers. However, for rivers with mixed or gravel beds, it was found that suspended-sediment load (in tons/year) computed by the former method closely matches loads computed by the USGS method.

Strengths: representative of historical conditions; measured data; easily coupled with streamflow measurements

Weaknesses: USGS data not available since mid-1990s; TWDB data not available since mid-1980s; Texas-sampler method not as accurate as USGS depth-integrated method; restricted to selected streamflow-gaging stations; restricted to the measurement period of record

4.2 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 found. 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.

Strengths: representative of historical conditions; measured data

Weaknesses: mostly unavailable, unless embedded within published or unpublished project-specific reports; restricted to measurement stations; restricted to the measurement period of record

4.3 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 et al. (1982), and Gomez (2006), among others. The choice of bedload equations should be based on: (1) the composition of the bed material, (2) channel geometry, and (3) the hydraulic conditions under consideration. If changes in channel-bed and bank positions over time are known, another approach is Exner's equation used in a morphodynamic model. 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).

A very useful application to estimate bedload and suspended-load transport is SAM – Hydraulic Design Package for Channels, which includes 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, and 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 by coupling the 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 or SAM should have considerable background or training, and caution should be given to computed estimates. 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.

Strengths: not contingent on sediment-load measurements; flexibility over space and time (e.g., model parameters could be from any station along a river, or could be historical)

Weaknesses: result accuracy; requires accurate model parameters (e.g., cross-sectional data, channel slope, bed-material size distribution)

4.4 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, usually bed-material load, at a channel cross section 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. Although effective discharge is informative with respect to sediment transport, it is less predictive for assessments of channel form or adjustment over time.

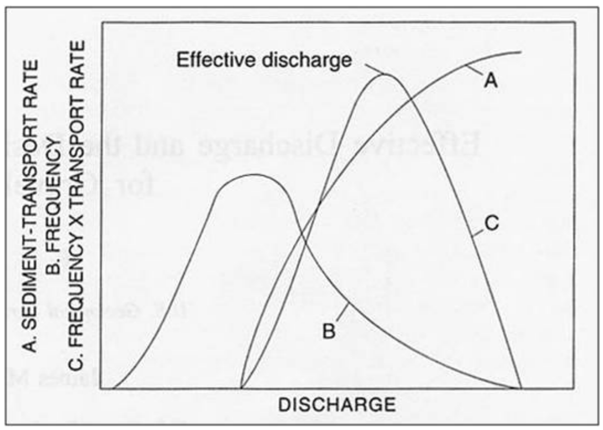

Figure 4. Effective discharge, in its graphical form, is the largest product of the sediment transport rate and the frequency of transport (from Wolman and Miller, 1960; scanned from Andrews and Nankervis, 1998).

Although a number of investigations confirm that relatively frequent, moderate flows (Hudson and Mossa, 1997) or bankfull flows (Andrews and Nankervis, 1995; Biedenharn et al., 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. Instead, an emphasis on flow variability and the range of flows necessary to transport sediment over time should be embraced. For example, average flow conditions are known to transport appreciable quantities of sediment in sand-bed river systems.

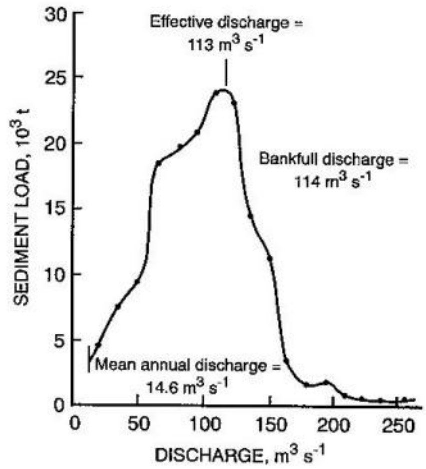

Figure 5. Effective discharge in this example approximately is equal to the bankfull discharge (from Andrews, 1980; scanned from Knighton, 1998).

A process to compute effective discharge at gaged or ungaged stations is provided in Biedenharn et al. (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 various 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.

Strengths: adaptable to both measured and model-estimated data; adaptable to bedload, suspended-load, or total load

Weaknesses: assumes steady-state equilibrium; restricted to streamflow-measurement stations; restricted to the streamflow-measurement period of record

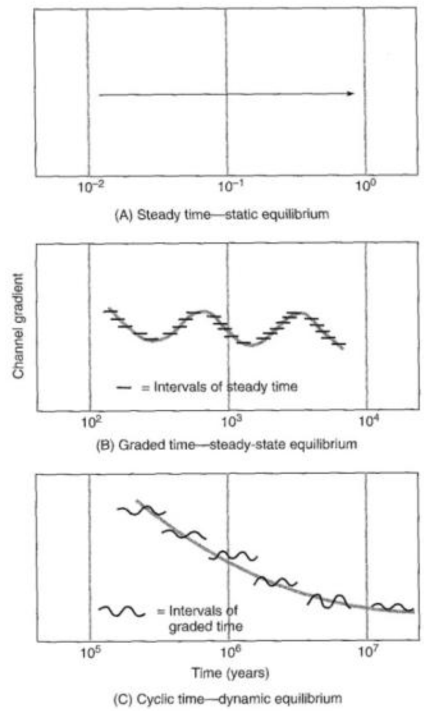

Figure 6. Concepts of equilibrium in fluvial geomorphology (from Schumm, 1977; scanned from Ritter et al., 2002). Channel rehabilitation or engineering applications focus on graded time scales, and efforts are usually made to promote a steady-state channel condition that is resilient to disturbances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

SECTION 5
RECOMMENDATIONS AND EXAMPLE COMPUTATION OF EFFECTIVE DISCHARGE

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 HEFR-based flow prescriptions (mostly high-pulse flows or overbank flows). For gaging stations with accurate suspended-load data, effective discharge can be computed using the methodology described in Biedenharn et al. (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.

It should be recognized that an analysis of effective discharge does not encompass nor entirely explain the breadth of fluvial geomorphic processes. Sediment transport, however, is a fairly straightforward process to relate with streamflow, and collection of sediment-transport data commonly occurs simultaneous with streamflow at a gaging station. Furthermore, computation of effective discharge based on bed-material load is the widely accepted method (Biedenharn et al. 2000) for evaluating changes in channel morphology. Effective discharge of suspended load offers comparatively less insight toward assessments of instream habitat conditions and dynamics.

5.1 EXAMPLE OF EFFECTIVE DISCHARGE ANALYSIS

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). Further, a procedural flowchart of effective discharge analysis is shown in Figure 7.

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

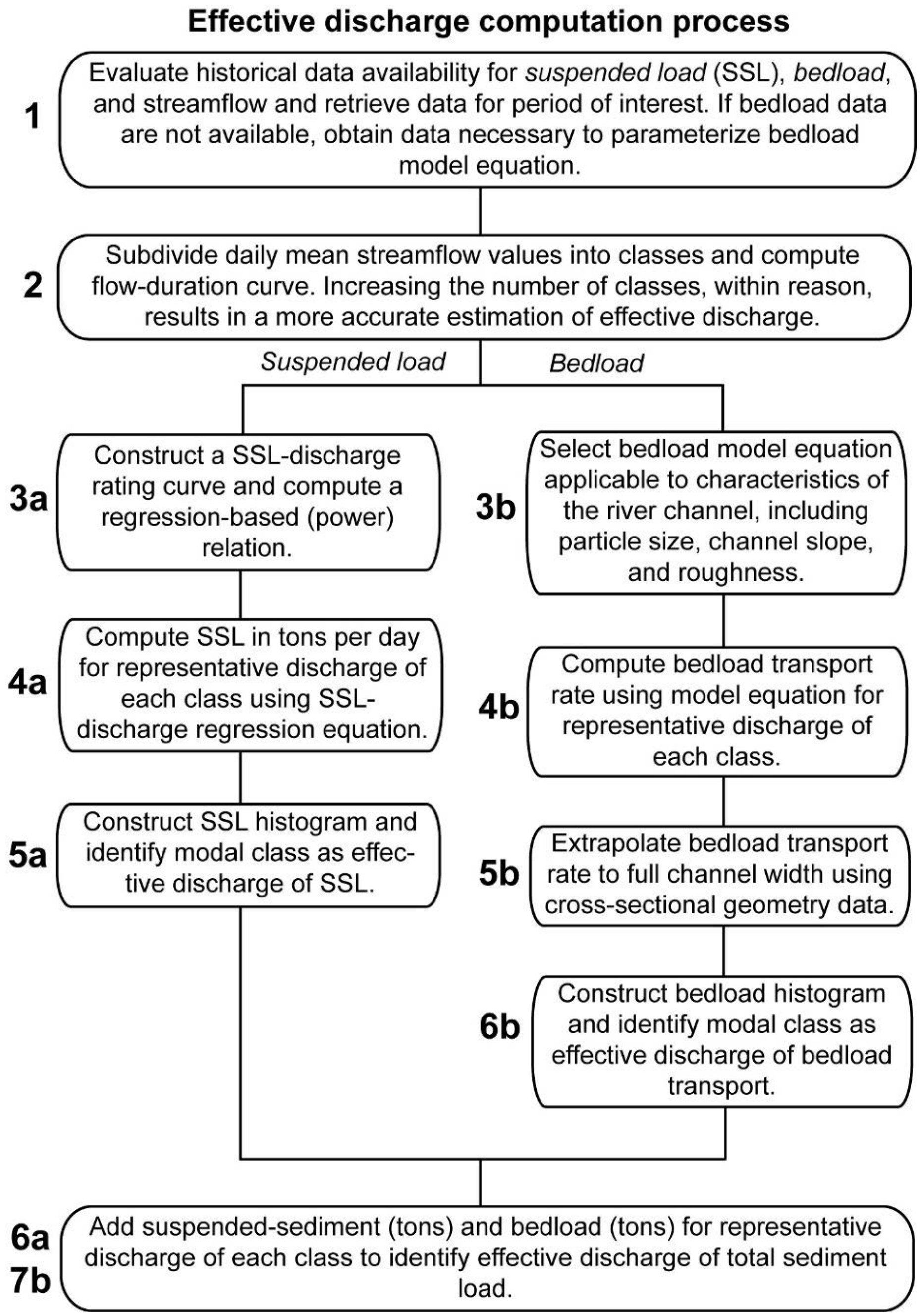

Figure 7. Procedural flowchart for computation of effective discharge for suspended-sediment load, bedload, and total load.

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

	Data	Source
1.	Daily mean streamflow (ft^3/s)	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)

5.1.1 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 et al. (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 8.

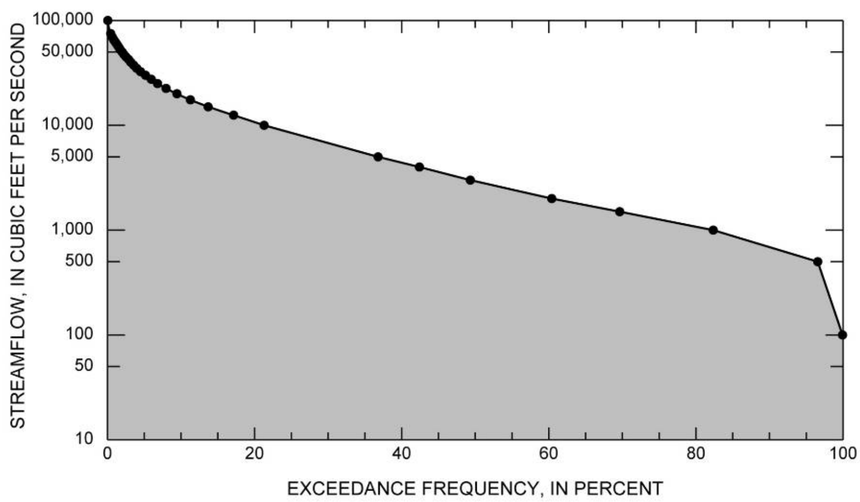

Figure 8. Flow-duration curve for 08114000 Brazos River at Richmond, Texas, for the full period of record using daily mean values. The high density of points at the upper tail is for a more accurate determination of effective discharge.

5.1.2 Suspended-Sediment Load

2. Suspended-sediment-load (SSL) data (period of record: February 1966 to September 1995) (tons/day) 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 9). The power function fitted to predict SSL from streamflow (Q) (ft^3/s) is:

    - $\boldsymbol{SSL = (0.0000527)Q^{2.1463}}$, where *SSL* is suspended-sediment load (tons/day) and Q is discharge (ft^3/s).

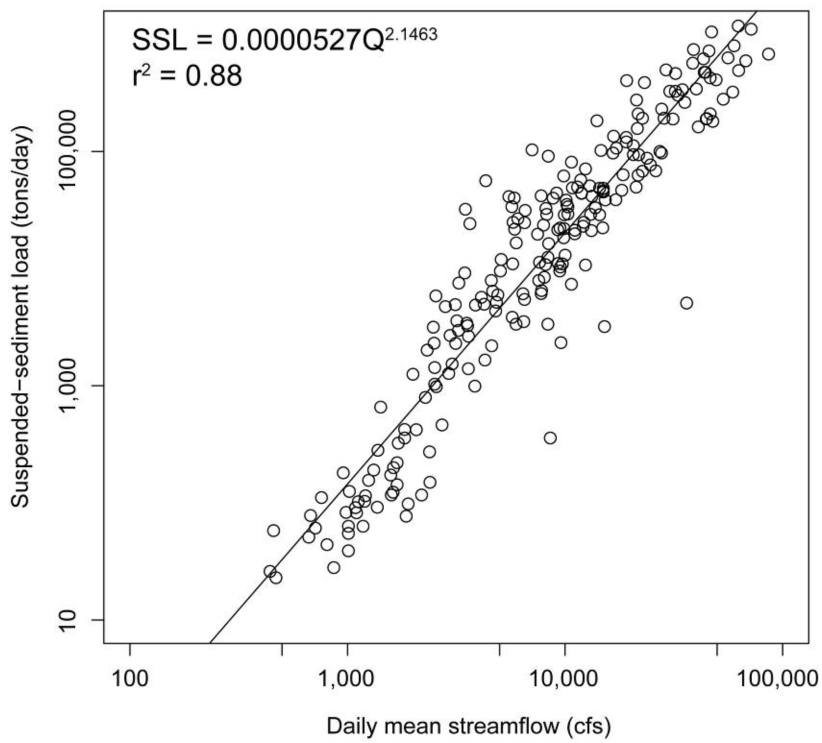

Figure 9. Suspended-sediment-load and streamflow rating curve for 08114000 Brazos River at Richmond, Texas. Scatter about the power trendline is attributed to sediment availability and hysteretic behavior of suspended-sediment concentrations over time.

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 10). 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. However, 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 expanded stage-discharge rating table. Therefore, effective discharge of SSL is substantially less than flood stage.

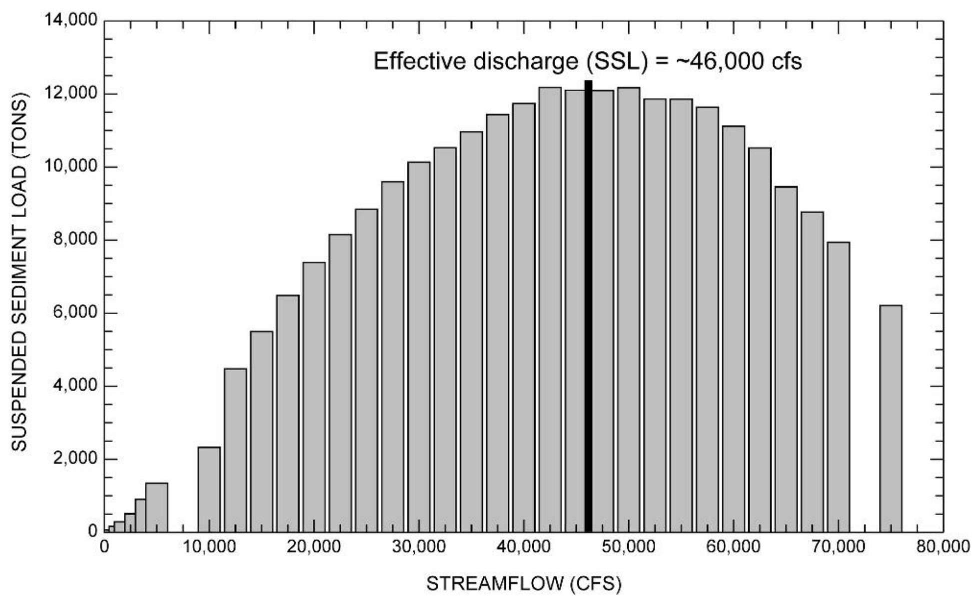

Figure 10. Suspended-sediment load (SSL) histogram showing effective discharge for SSL at 08114000 Brazos River at Richmond, Texas, approximately is 46,000 ft^3/s.

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.

(ft^3/s; cubic feet per second; %, percent; SSL, suspended-sediment load)

Streamflow (ft^3/s)	Days exceeded	Exceedance frequency	Representative streamflow (ft^3/s)	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

5.1.3 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 11) 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.

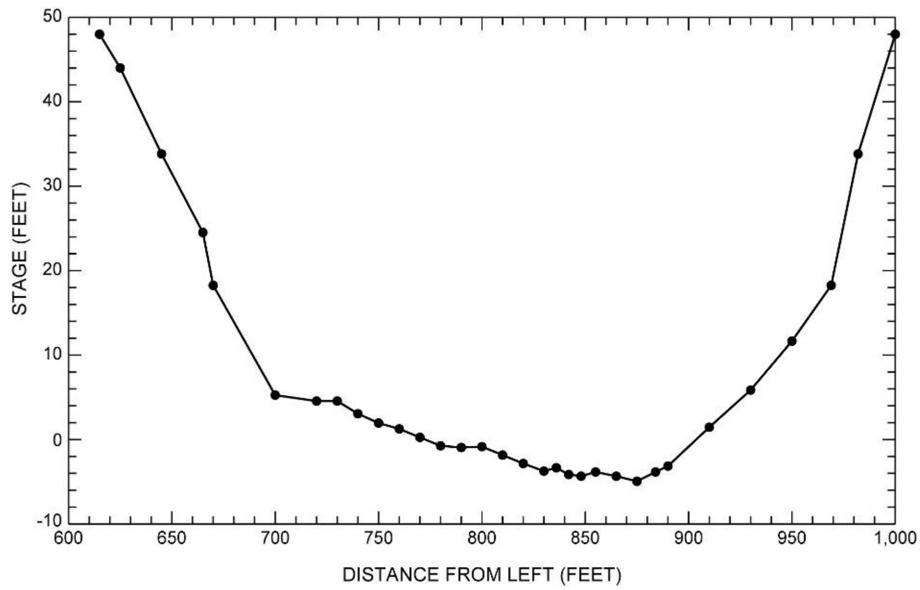

Figure 11. Cross section of 08114000 Brazos River at Richmond, Texas, based on USGS streamflow measurements in February 1998 and November 2004, and extended to NWS flood stage of 48 feet. The moderate flow of 1998 was used to construct geometry up to about 18 feet and the high flow of 2004 further extended geometry to about 34 feet.

6. The cross section was imported into WinXSPRO, a free software package available online from the U.S. Department of Agriculture Forest Service (2009). 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-ft 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

5.1.4 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) (ft/s) and hydraulic radius (R) (ft) for each discharge were entered from the WinXSPRO results. Stream power per unit area (ω) (lb/s^3) for each discharge class interval was computed from the following equation:

    - $\boldsymbol{\omega = \rho g d S U}$, 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 (ft/s).

    Using the median particle size (D_{50}) (ft) 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) (lb/ft^2) for entrainment was computed from the following equation:

    - $\boldsymbol{\tau_c = \tau^*(\rho_s - \rho)D_{50}}$, 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 (ft) required to entrain the median particle size (D_{50}) (ft) was computed from the following equation:

    - $\boldsymbol{d = \tau_c/(\rho S)}$

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

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

    Next, the critical stream power (ω_c) (lb/s^3) required to entrain the median particle size (D_{50}) (ft) was computed from the following equation:

    - $\boldsymbol{\omega_c = U_c \tau_c}$

    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:

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

Finally, the bedload transport rate (I_b) (lb/ft/s) 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/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 lb/s^3 for this example. Gray columns were used to generate a bedload histogram.

(ft^3/s; cubic feet per second; %, percent; ft, feet; ft/s, feet per second; ω, stream power per unit bed area; lb/s^3, pounds per cubic second; lb/ft/s, pounds per foot per second; yr, year)

Streamflow (ft^3/s)	Exceedance frequency	Stage (ft)	Mean velocity (ft/s)	Mean depth (ft)	Stream power (ω) (lb/s^3)	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 12), 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, for instance 100 ft^3/s, filled up the cross section to a mean depth of 7.6 feet at a mean velocity of 2.1 ft/s 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. Furthermore, it is very unusual for bedload to exceed suspended-load transport, thereby providing additional evidence for the problematic data used to compute 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.

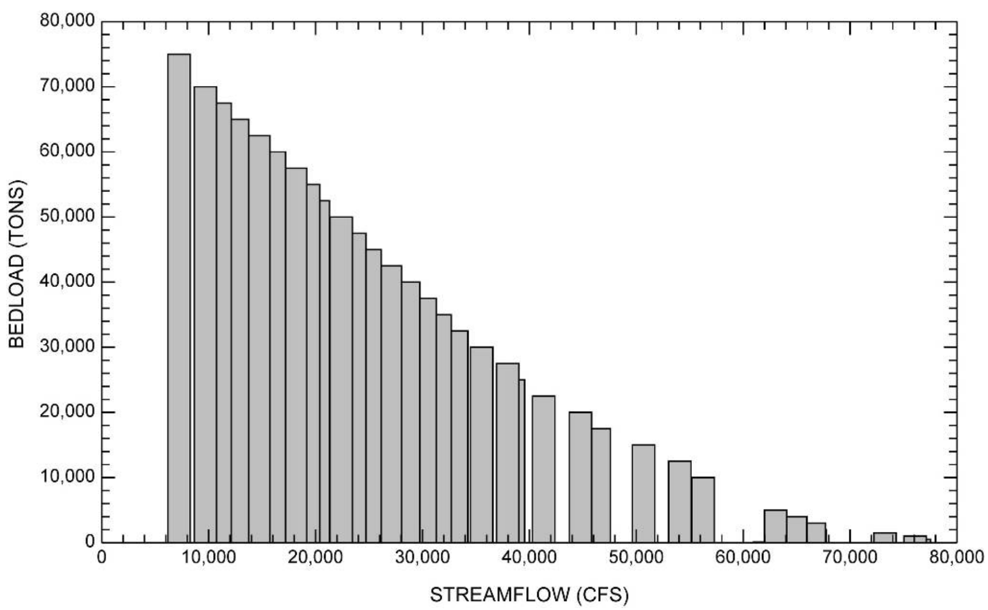

Figure 12. Bedload histogram showing an inaccurately low estimate of effective discharge for bedload at 08114000 Brazos River at Richmond, Texas.

9. Finally, the practitioner can combine suspended load (tons) and bedload (tons) for a given flow to evaluate the effective discharge for total sediment load.

5.2 ADVOCACY OF THE 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 hydraulic design model is a tool that can be used to establish effective discharge at gaging stations, but should be done by an expert in the field of fluvial geomorphology or sediment transport dynamics.

As discussed above, effective discharge 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 a SAM analysis of steady-state conditions. Another serious concern related to the practicality of effective discharge for environmental flow programs is the stasis of its approach. If an existing flow regime is modified to satisfy a prescription, then it is likely that the magnitude and frequency of the effective discharge changes as well. Iterations of effective discharge overlays and subsequent modification of the flow regime becomes impractical at some level.

SECTION 6
DECISION POINTS

Similar to the HEFR-based approach to determine an environmental flow regime for Texas rivers, a variety of decisions are required to compute the effective discharges of sediment transport processes. One decision point not specifically discussed below regards computation of effective discharges for ungaged locations, which is beyond the scope of this report. The decision points include:

1. **Bedload, bed-material load, suspended load, <u>or</u> total sediment load:** The practitioner must decide if effective discharge will be required for bedload only, bed-material load only, suspended load only, or the combination of bedload and suspended load (total load). For objectives associated with instream-habitat structure, channel morphology, deltaic lateral accretion, and beach or shoreline maintenance, bed-material load is the most important sedimentary variable. For objectives associated with floodplain sedimentation, turbidity, or deltaic vertical accretion, suspended-load is the most important sedimentary variable. Finally, total load constitutes the most complete picture of sediment transport.

2. **Historically collected sediment-load data <u>or</u> model application:** The practitioner must decide whether to use previously collected sediment-load data or to apply a sediment-transport model equation to estimate load. In Texas, the USGS and TWDB have historically collected suspended-load data at a number of USGS streamflow-gaging stations. Bedload, however, has not historically been collected, unless done so on a project-specific basis. It is highly likely, therefore, that a model equation would have to be used for computation of effective discharge for bedload transport.

3. **USGS <u>or</u> Texas-sampler method for historical suspended-load data:** The USGS has historically collected depth-integrated suspended-load data at a number of streamflow-gaging stations in Texas prior to the mid-1990s. The TWDB has various published reports of historical suspended-load data obtained by the Texas-sampler method at selected streamflow-gaging stations prior to the mid-1980s. In general, USGS depth-integrated data are more accurate than the Texas-sampler method.

4. **Period of record:** The period of record is a twofold decision: (a) hydrologic data and (b) sediment-load data. The period of record for sediment-load data is not applicable if a sediment-transport model equation is used.
   a. Historical streamflow data are required to generate a flow-duration curve for computation of effective discharge. The choice of an appropriate period of record of streamflow data could reflect pre- or post-regulation conditions, among other historical changes to the river's flow regime.
   b. Sediment load is highly sensitive variable over space and time. Sediment concentrations in the water column are dependent on season, antecedent rainfall,

land-use, characteristics of the storm hydrograph, and upstream impoundments, among other variables. The period of record for measured sediment-load data could reflect pre- or post-regulation conditions, among other historical changes to the river's sediment-transport regime.

5. **Flow-duration class intervals:** A flow-duration curve requires the practitioner to establish "class intervals" which are related to exceedance frequency of that interval's representative flow. Although various published sources offer guidance on establishing class intervals, the choice is relegated to the practitioner. Accuracy of effective discharge increases if class intervals are shorter and more numerous (e.g., class intervals of 1,000 ft^3/s are more accurate than 5,000 ft^3/s).

6. **Sediment-transport model:** This decision is only required if the practitioner does not have or chooses not to use measured sediment-load data to determine effective discharge. A variety of model equations exist that estimate bedload or bed-material load transport rates for various flow conditions, and are based on measured or estimated parameters. Bedload and bed-material load equations commonly are suited to particular conditions, such as a low-gradient sand-bed channel, for example. Other model equations exist that estimate suspended-load transport rates using either measured or estimated parameters. The choice of an appropriate model equation is relegated to the practitioner, possibly with guidance from the SAM hydraulic design model.

7. **Channel cross-section dimensions:** This decision is only required if using a model equation to estimate sediment load. Cross-sectional data are needed to compute channel hydraulics (e.g., width, mean depth, mean velocity) based on a given slope and flow-resistance coefficient. Further, most model equations render sediment-load estimates for a given channel length, and require a wetted perimeter for extrapolation to channel-wide transport rates. As shown from the Brazos River at Richmond, Texas, example above, an unrepresentative cross section can lead to erroneous results. Cross-sectional dimensions could be chosen to represent pre- or post-regulation conditions, pre- or post-disturbance conditions, straight-reach or meander-bend conditions, among other complex arrangements of channel shape over space and time.

8. **Model parameters:** This decision is only required if using a model equation to estimate sediment load. Various parameters, including channel slope, particle size, mean depth, and water temperature, among others, are needed to parameterize sediment-transport model equations and compute selected hydraulics at a channel cross section. Various published and unpublished sources exist that provide this information. For certain applications, the practitioner could elect to estimate required parameters.

9. **Extrapolation of effective discharge to a channel reach:** As outlined above, computation of effective discharge is restricted to one channel cross section. Given this

restriction, environmental flow objectives associated with sediment transport are valid for one station. If desired, extrapolation to a channel reach should consider variability in sediment sources and sinks upstream and downstream of the station, including tributary inputs, distributary outputs, active bank erosion, channel incision or aggradation, overbank deposition, among other complex watershed and channel characteristics and processes.

SECTION 7
USING SAM TO DETERMINE THE EFFECTIVE DISCHARGE FOR ALLUVIAL STREAMS

The purpose of this example is show how the SAM[1] software can be used to compute the effective discharge for the existing hydrology and the adjusted hydrology resulting from an implementation of an environmental flow regime (e.g., HEFR-based analysis). Effective discharge is defined as the mean of the discharge increment that transports the largest fraction of the annual sediment load over a period of years (Andrews, 1980). It is computed by integrating the flow-duration curve and a bed-material load rating curve (Biedenharn et al., 2000). When using SAM to compute effective discharge, the sediment load is the total bed-material load (i.e., material that is found in the channel bed). Wash load (i.e., material finer than the bed-material load) is not included in the SAM computational procedures. For this example, the HEFR procedure (Senate Bill 3 Science Advisory Committee for Environmental Flows, 2009), as developed by the Texas Parks and Wildlife Department (TPWD), is used. Importantly, the HEFR-based SAM analysis assumes a "worst-case scenario" where the annual flow volume in excess of the HEFR-prescribed flow regime is removed (e.g., a new reservoir is constructed and flows are regulated to not exceed the HEFR-prescribed flows).

The SAM package was chosen for this example because of its ability to transition from computations of flow hydraulics to sediment transport capacity and sediment yield. Effective discharge is determined using SAM results for sediment yield. More information on the SAM software can be found in the users' manual (Copeland et al., 1997) and Thomas et al. (2002).

The computation of effective discharge requires the development of a bed-material load histogram. The histogram is generated by using representative discharge bins, obtained by dividing the discharge range into equal size arithmetic bins (discharge classes). The mean discharge of the flow bin is integrated with the bed-material load rating curve to find the bed-material load for each discharge class. The sediment load transported by each bin is computed by multiplying the bed-material load by the percentage of time represented by each discharge class. The results are plotted as a histogram representing the annual bed-material load transported by each discharge class. This computation is performed by the Sediment Yield Module in the SAM hydraulic design package. The bed-material load histogram should display a continuous distribution with a single mode (peak). If this is the case, the effective discharge corresponds to the mean discharge for the modal class (the peak of the histogram). If the modal class cannot be readily identified, the effective discharge can be estimated by drawing a smooth curve through the tops of the histogram bars and interpolating the effective discharge from the peak of the curve. If the modal class of the bed-material-load histogram is the lowest discharge class, it is likely that the indicated effective discharge is erroneous. In this case it may be necessary to modify the procedure by either increasing the number of discharge classes or modifying the bed-

[1] Two versions of this system currently exist, SAM and SAMwin. SAMwin is the Windows version of the older DOS-based SAM. The SAM Hydraulic Design Package for Channels is a result of research conducted through the Flood Damage Reduction and Stream Restoration Research Program, starting in the late 1980s, at the Coastal and Hydraulics Laboratory (CHL) of the Engineer Research and Development Center (ERDC), Vicksburg, Miss. Recently, under Cooperative Research and Development Agreement (CRDA) number CRDA-01-CHL-04, Owen Ayres & Associates, Inc., Ft. Collins, Colo., developed a modern, user-friendly, graphical user interface. In this report, SAM refers to the Windows version known as SAMwin. The software is available from Owen Ayres & Associates, Inc., Ft. Collins, Colo.

material rating curve, noting that caution should be exercised in each case (Biedenharn et al., 2000).

The Sabine River at Bon Wier, Texas was selected to show how SAM can be used to determine effective discharge for pre- and post-implementation of a HEFR-based environmental flow prescription. Determination of the effective discharge also produces two additional outputs that are important in assessing geomorphic stability of streams: (1) average annual water yield and (2) average annual sediment yield.

The steps required to do an effective discharge computation are as follows:

1. Development of the hydraulic parameters needed to compute a bed-material load rating curve, which include effective width, effective depth, discharge or velocity, and channel slope.
2. Development of the bed-material load rating curve, which requires knowledge of the bed-material gradation.
3. Computation of the existing sediment yield and the bed-material load histogram, which requires the integration of the bed-material-load rating curve with the existing flow-duration curve.
4. Development of a flow-duration curve that reflects the hydrologic conditions expected to exist following the implementation of HEFR-based flow prescriptions.
5. Computation of the sediment yield and bed-material load histogram for post-HEFR implementation conditions, which requires the integration of the bed-material-load rating curve with the post-HEFR flow-duration curve.
6. Comparison of pre- and post-HEFR water yield, sediment yield, and effective discharge computations.

For this example, it is assumed that data developed in steps 1 and 2 above will be the same and that only the flow-duration curves will be different between the existing conditions and a fully implemented HEFR-based environmental flow regime. This constitutes the condition that would exist in year 1 of the implemented flow regime, assuming there is sufficient infrastructure and water demand to remove flows above those protected by HEFR. The conclusions reached by analyzing pre- and post-HEFR conditions are the same whether the flow changes occur all at once or if the transition to a fully implemented flow regime occurs over a period of years. A slower transition to a fully implemented flow regime could make for a more manageable change in channel character. Detailed modeling of the system could provide beneficial insights into channel behavior as the flow reduction from existing conditions to an implemented HEFR-based flow regime occurs.

7.1 STEP 1

Step 1-A: The application of SAM to determine the effective discharge requires hydraulic parameters needed to compute a bed-material load rating curve, including effective width, effective depth, discharge or velocity, and channel slope. These data can be obtained for the

USGS streamflow-monitoring network and by using the computational capabilities of SAM. Figure 13 shows a cross section for the Sabine River near Bon Wier, Texas (USGS streamflow-gaging station 08028500). The cross section is from a discharge measurement on April 1, 2004. The original cross-section is simplified for input into the SAM Hydraulic Module.

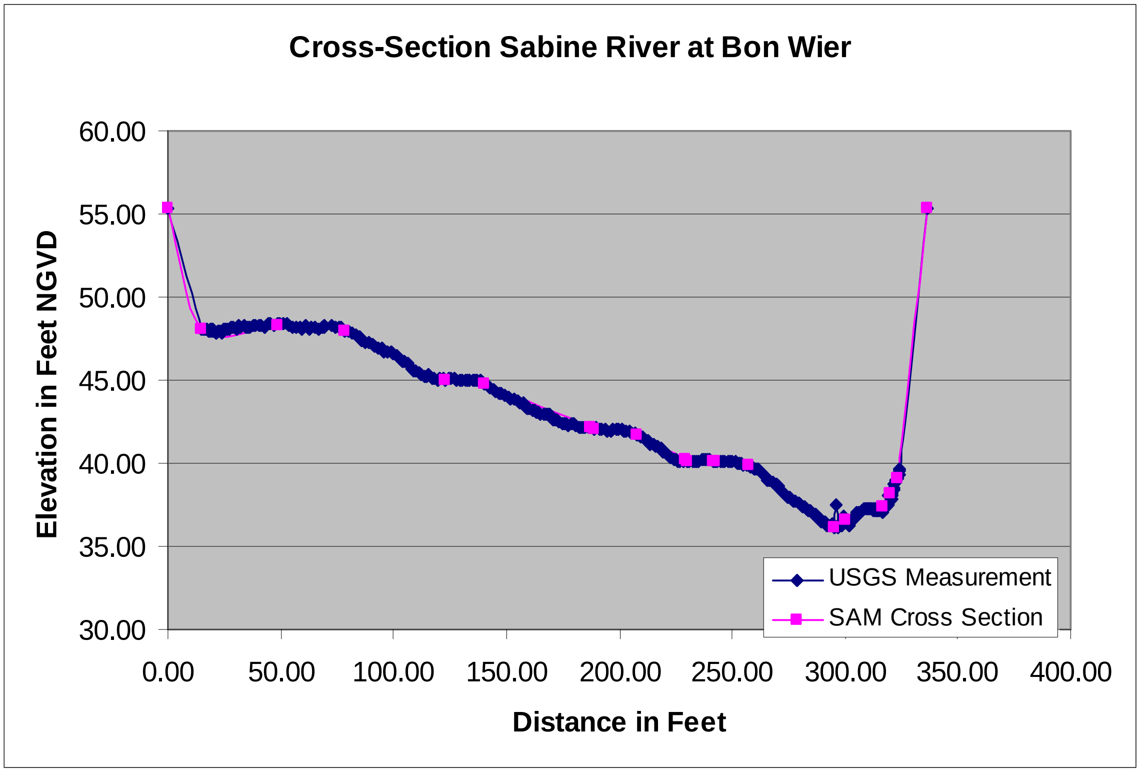

Figure 13. Cross section of the Sabine River near Bon Wier, Texas on April 1, 2004 (USGS streamflow-gaging station 08028500).

The SAM Hydraulic Module can solve for any one of the variables in the uniform flow equation (shown below). Water discharge is usually the dependent variable. However, SAM allows any of the variables on the right side of the equation to become the dependent variable, except side slope (*z*). The SAM Hydraulic Module inspects each input record type in a data set and determines which variables have been prescribed. The omitted variable becomes the dependent variable (Thomas et al. 2002).

- $Q = f(D, n, W, z, S)$, where Q is water discharge (ft^3/s), D is depth (ft), n is Manning's roughness coefficient, W is bottom width (ft), z is side slope of the channel, and S is energy slope.

For this example, normal depth was computed by SAM. The input required for the normal depth computations include the cross section as shown in Figure 13, discharges, channel slope, and Manning's *n* values. The input data used for the normal depth computation is shown below:

```
T1 T1 Sabine River Demonstration Run
T1 T2 Using USGS data to create cross sections
T1
TR     1
X1  97.7      21       0  336.46
GR 55.36    0.00   48.02   15.00   48.27   48.27   47.98   78.69   44.95  123.14
GR 44.80  140.49   42.11  187.45   42.07  188.65   41.67  208.18   40.17  229.17
GR 40.16  230.30   40.17  241.61   40.16  242.69   39.83  257.09   36.11  295.01
GR 36.60  300.46   37.39  316.36   38.16  320.18   39.07  323.06   55.36  336.46
GR  67.2     485
NE     0       0       0       0       0       0       0       0       0       0
NE     0       0       0               0       0       0       0       0       0
KN  .030                           .030
KN                                                                  .030    .125
ES.00014  .00014  .00014  .00014  .00014  .00014  .00014  .00014  .00014  .00014
QW   300    1520    4135   10200   16500   19300   27600   38400   52400   98100
WT    60
$$END
```

Step 1-B: The results of the normal depth computations are compared to the current USGS rating curve for the Sabine River near Bon Wier, Texas. The comparison of the computed vs. observed rating curves (Figure 14) shows sufficient agreement between the measurements, thereby enabling us to move forward with this example. The practitioner performing these computations will need to determine when the agreement of the computed and observed measurements is satisfactory to move forward with the study.

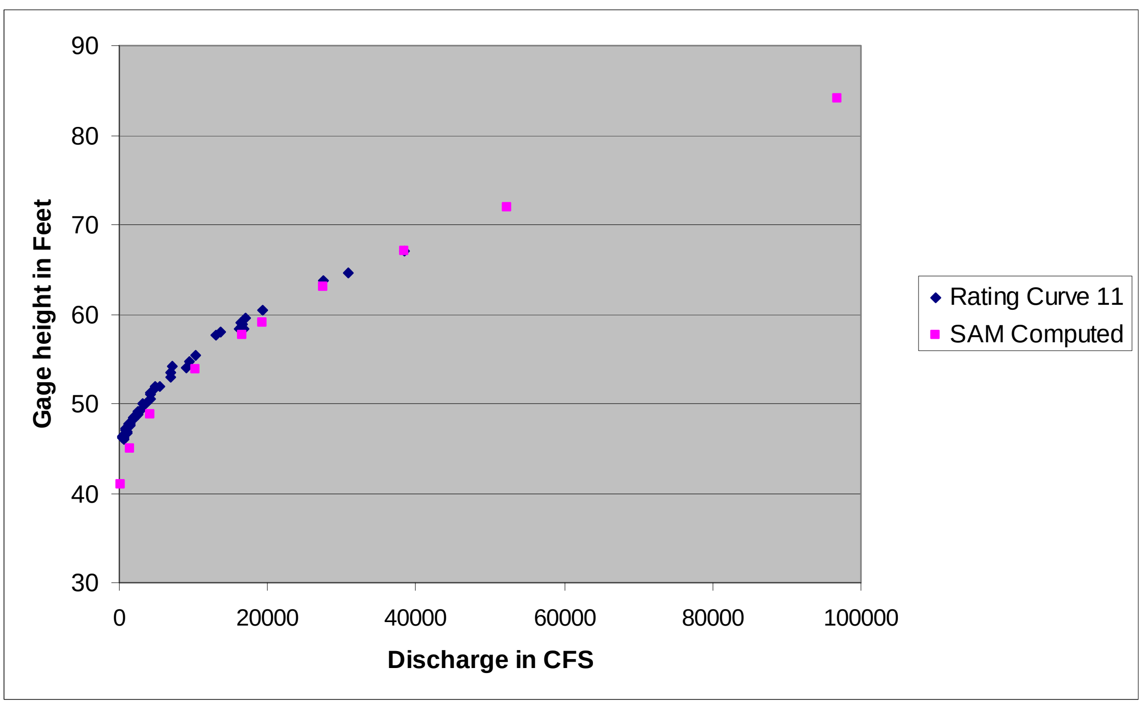

Figure 14. Comparison of current (2009) and SAM-computed stage-discharge curves for USGS streamflow-gaging station 08028500, Sabine River near Bon Wier, Texas.

7.2 STEP 2

The results of the SAM hydraulics computations are used with a bed-material gradation curve to compute the bed-material load rating curve.

SAM.HYD writes the following information into a file that used by SAM.SED to compute the Bed-Material Load Rating Curve:

```
T1      FILE WRITTEN BY SAM.hyd
T1
TF ACKERS-WHITE.        YES
TF COLBY                YES
TF ENGELUND-HANSEN      YES
TF VAN.RIJN             YES
TR
QW   300    1520    4135   10200   16500   19300   27600   38400   52400   98100
VE  1.31    1.97    2.53    3.18    3.69    3.89    4.39    4.92    5.50    6.92
DE  3.35    6.23    9.05   12.68   15.80   17.07   20.53   24.53   29.08   41.36
WI   69.   123.6   180.8   252.6   282.8   290.7   305.1   314.6   321.0   328.9
ES.00014  .00014  .00014  .00014  .00014  .00014  .00014  .00014  .00014  .00014
WT    60
```

The bed-material gradation for the Sabine River near Bon Wier, Texas is input into the SAM Sediment Module. The input data are found in the PF records (see below). For the Bon Wier gage, the data included a D_{16} (i.e., 16 percent of the material is finer than) of 0.0625mm, a D_{50} (i.e., median particle size) of 0.14 mm, and a D_{84} (i.e., 84 percent of the material is finer than) of 0.50 mm. For the Bon Wier gage, the bed-material data came from Soar and Thorne (2001).

```
PF                  1.0     .50      .5     100      .3      84     .14      50
PFC.0625      16   .0625      0
SP  2.65
$$END
```

The SAM Sediment Module allows the user to chose up to 20 sediment transport functions to compute the total bed-material load rating curve. These functions include equations developed for bed material from cobble and gravel to very fine sands. Some of the functions compute by grain-size class while others use only D_{50} for a single grain-size computation. A tool called SAM-AID is available in SAM to help the user pick out one or more appropriate sediment functions for the initial computations. The practitioner usually selects 3 or 4 sediment transport functions and then chooses one that falls in the middle of pack. If the practitioner has enough data to develop a total bed-material load rating curve from observed measurements, then the curve can be directly input into the sediment yield module and steps 1 and 2 are not required. The important thing to remember here is if you want to compare pre- and post-implementation conditions, you should use the same sediment transport function or use the same observed total bed-material load rating curve for both conditions. Figure 15 shows bed-material load rating curves developed for 4 sediment transport functions: (1) Ackers-White, (2) Engelund-Hansen, (3) Colby, and (4) Van Rijn. Based on input conditions of the Sabine River near Bon Wier, Texas, the SAM-AID tool recommended that the Engelund-Hansen function would most accurately compute bed-material discharge. Therefore, the Engelund-Hansen function was used to compute sediment yield (bed-material yield) and effective discharge.

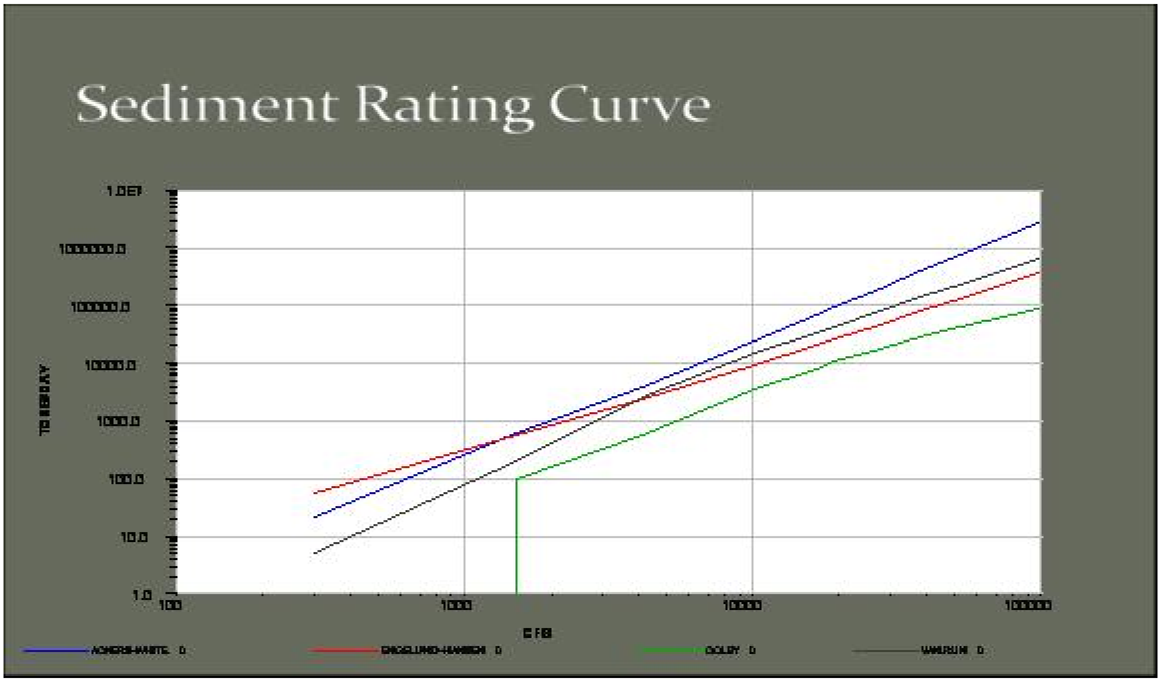

Figure 15. Sediment-load rating curves computed by SAM-AID using input parameters for USGS streamflow-gaging station 08028500, Sabine River near Bon Wier, Texas.

7.3 STEP 3

Step 3-A: The Sediment Transport Module develops an input file for the Sediment Yield Module. This file contains the total bed-material load rating curve, also known as QW and SC cards (see sediment yield input file 1 below). A second file is needed for the Sediment Yield Module that contains the flow-duration curve, the number of output class intervals, and the specific weight of sediment. This file can be developed using input boxes produced by the SAM program (see sediment yield input file 2 below). The flow-duration curve for existing conditions on the Sabine River near Bon Wier is shown in Figure 16. For the number of output class intervals, the default value is 20 but in some cases as many as 50 or more might be necessary to describe the flow regime. The default specific weight of sediment is 93 lbs/ft^3, which can be changed as required by the SAM practitioner.

The Sediment Yield Module input files are:

Sediment yield input file 1:

```
1      FILE WRITTEN BY SAM.hyd
T1
TI      FILE WRITTEN BY SAM.sed
TF     ENGELUND-HANSEN
QW   300    1520    4135   10200   16500   19300   27600   38400   52400   98100
SC74.100    150.    233.    346.    449.    492.    607.    738.    890.   1308.
$$END
```

Sediment yield input file 2:

```
T1 Sabine River at Bon Wier
T1 observed Flows
T1 After Toledo Bend 1972-2007
T1
JP    50             365             365              93
QQ   307     575     738     917    1270    1970    3180    4570    6150    8280
QQ 14300   17520   19016   21400   24400   29700   35604   98000
QD   100      98      95      90      80      70      60      50      40      30
QD    20      10       8       6       4       2       1       0
$$END
```

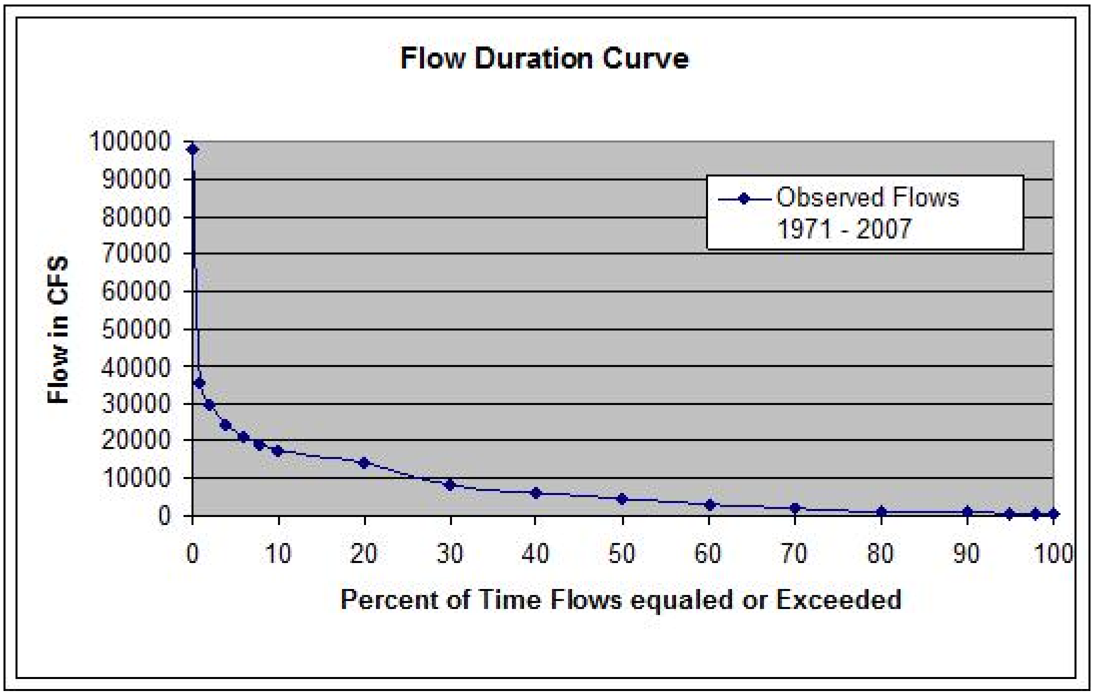

Figure 16. Flow-duration curve for USGS streamflow-gaging station 08028500, Sabine River near Bon Wier, Texas.

Step 3-B: Execution of the Sediment Yield Module for the existing hydraulic and hydrologic conditions shows:

Average annual water yield is: 5,465,145 acre feet
Average annual sediment yield is: 3,342,038 tons

Figures 17 and 18 show the bed-material load histogram generated by the SAM Sediment Yield Module. The bed-material load histogram shows the bin containing flows from 13,984 to 15,938 ft^3/s carries the largest percentage of the annual bed-material load. This bin has a midpoint of 14,961 ft^3/s and conveys about 412,000 tons of bed material annually. For existing conditions, the effective discharge would reference as 14,961 ft^3/s, but more importantly the practitioner should consider the effective discharge range for this computation to be between 14,000 and 16,000 ft^3/s.

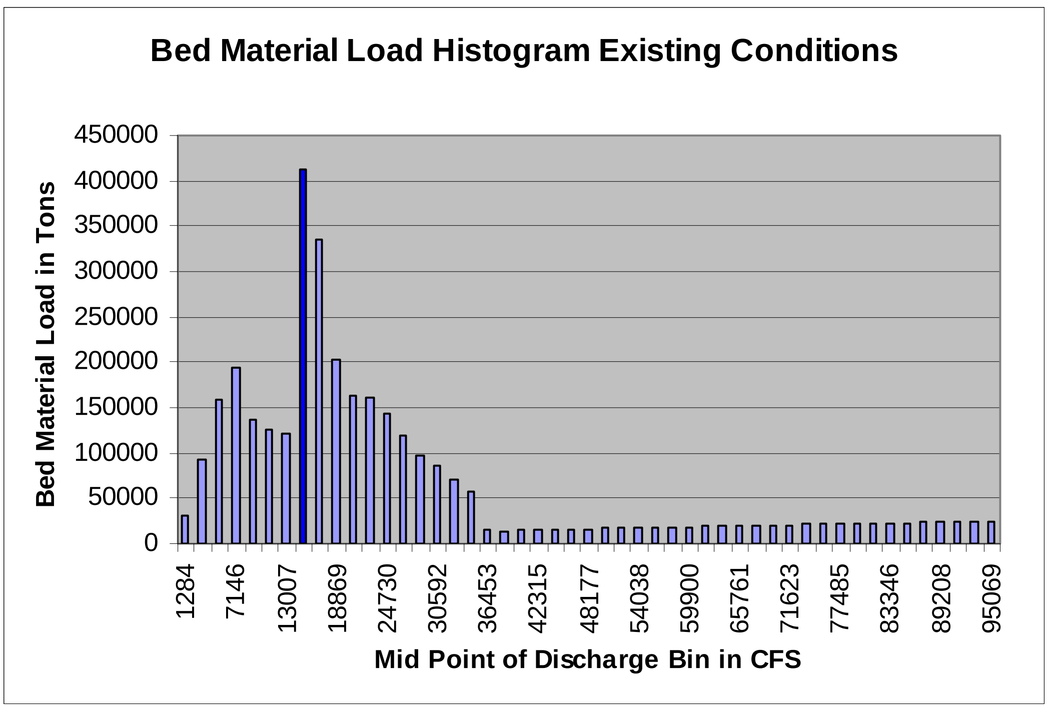

Figure 17. Bed-material load histogram for existing hydrologic conditions at USGS streamflow-gaging station 08028500, Sabine River near Bon Wier, Texas.

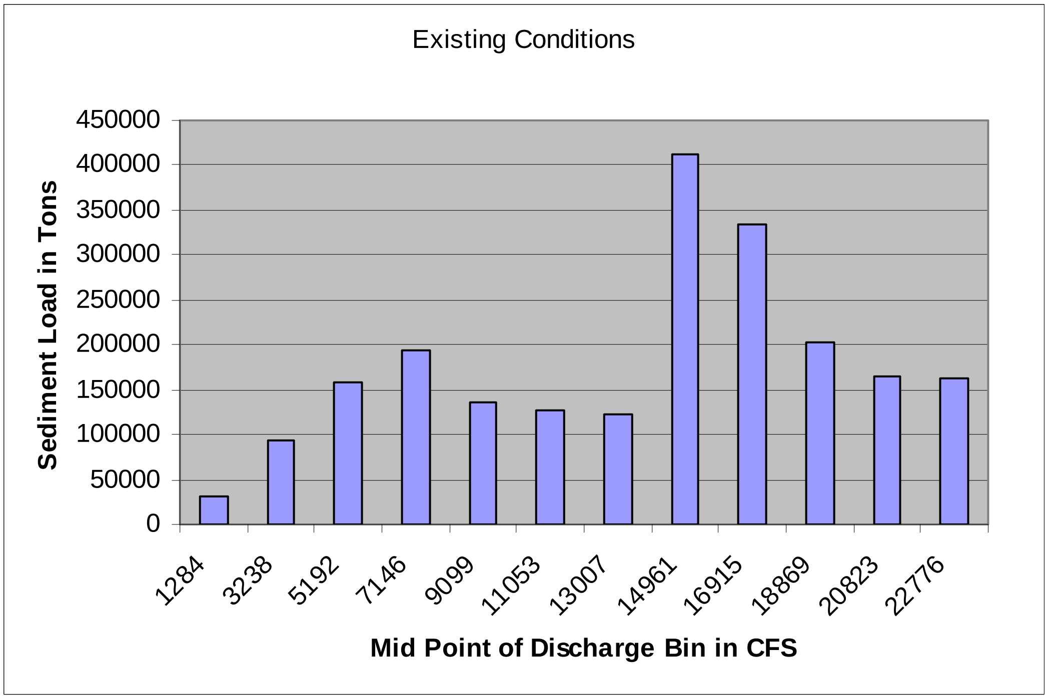

Figure 18. Bed-material load histogram for existing conditions less than 25,000 ft^3/s at USGS streamflow-gaging station 08028500, Sabine River near Bon Wier, Texas.

7.4 STEP 4

Step 4-A: Step 4-A is the development of the flow duration that will exist after the HEFR-based implementation. For this example, the HEFR-based flow regime was developed using the observed discharge measurements for the Sabine River near Bon Wier, Texas for water years 1924 to 1960. The water years 1924 to 1960 represent flow conditions that existed before the construction of any major reservoirs in Sabine River Basin. The HEFR-based flow regime is shown in Table 4.

Table 4. Results of HEFR-based flow regime analysis using water years 1924 to 1960 at USGS streamflow-gaging station 08028500, Sabine River near Bon Wier, Texas.

Overbank Flows	Return Period (R) : 0.8 (years)		Duration (D) : 32 (days)	
	Volume (V) : 1353987 (ac-ft)		Peak Flow (Q) : 31800 (cfs)	
High Flow Pulses	F: 1 D: 18 Q: 19000 V: 416351	F: 1 D: 16 Q: 17400 V: 384814	F: 0 D: 12 Q: 11900 V: 120397	F: 0 D: 10 Q: 7135 V: 82354
	F: 1 D: 12 Q: 13400 V: 207868	F: 1 D: 11 Q: 12900 V: 191207	F: 0 D: 9 Q: 5690 V: 67716	F: 1 D: 6 Q: 3705 V: 37964
	F: 1 D: 6 Q: 8690 V: 87610	F: 1 D: 6 Q: 10700 V: 98500	F: 0 D: 4 Q: 2995 V: 24258	F: 1 D: 4 Q: 2350 V: 17009
Base Flows (cfs)	6110	6640	2190	1430
	2800	4000	1220	870
	1540	2340	770	703
Subsistence Flows (cfs)	703	703	703	703
	Dec Jan Feb	Mar Apr May	Jun Jul Aug	Sep Oct Nov
	Winter	Spring	Summer	Fall

Hydrologic Conditions	Wet
	Average
	Dry
	Subsistence

High Flow Pulse Characteristics	F = Frequency (per season)
	D = Duration (days)
	Q = Peak Flows (cfs)
	V = Volume (ac-ft)

Step 4-B: After the HEFR-based flow regime is computed (shown in Table 4), the next step is to adjust the observed flows for the analysis period 1971 to 2007 to reflect implementation of the prescribed flow regime. The adjustment to the observed hydrograph was accomplished as follows:

1. The total annual flow volume from December 1st to November 30th was computed. The lower 25% of the years were considered dry (lowest 9 of the 36 years). The upper 25% of the years were considered wet (highest 9 of the 36 years). Flows between 25% and 75% were considered average flow years.
2. Based on the hydrologic classification (dry, average, wet), the years were analyzed for the amount of water available to be removed from the system. This constitutes a "worst-case scenario" where flows in excess of the HEFR-based flow prescription are removed.
3. Flows above overbank (31,800 ft^3/s) were removed by the following procedure. The hydrograph was analyzed for a full year from December 1^{st} to November 30^{th}, a 5-day window was set, and when a flow 5 days from the current day exceeded 31,800 ft^3/s, an

overbank flow event was started. Flows above 31,800 ft^3/s were removed until the desired flow volume and duration were reached. Until the flow volume and duration criteria were met, no flow was removed from system, even for flows less than 31,800 ft^3/s.

4. The hydrograph was analyzed for high-pulse flows in a matter similar to the overbank flow analysis. Seasonal high-pulse flow discharge values are based on dry, wet, and average hydrologic conditions. The hydrologic condition for each year was determined as discussed above. If the flows exceeded a high-pulse flow value for the season, they were removed from the system until pulse duration and volume were equaled or exceeded. One pulse per season was allowed; after one high pulse had passed, all flows above baseflow were removed from the system. See Figure 19 for how this was done in 1994 (December 1, 1993 to November 30, 1994).
5. Flows above baseflow and not part of an overbank or high-pulse flow event were removed from system. See Figure 19 for how this was done in 1994 (December 1, 1993 to November 30, 1994).
6. Flows less than baseflow were left untouched. Figure 19 shows an example for flows below the seasonal baseflow during an average flow year for few days in January and February of 1994.

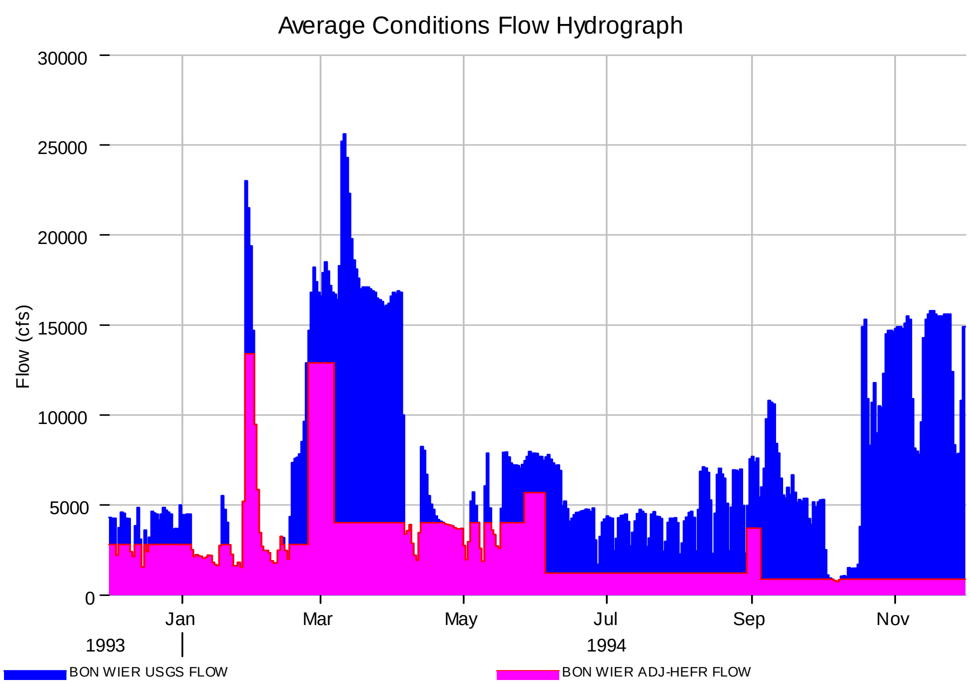

Figure 19. Daily flow hydrograph showing observed and HEFR-adjusted flows for December 1, 1993 to November 30, 1994, at USGS streamflow-gaging station 08028500, Sabine River near Bon Wier, Texas.

The daily flow records for all 36 hydrographs were adjusted, and a new flow-duration curve was computed (Figure 20).

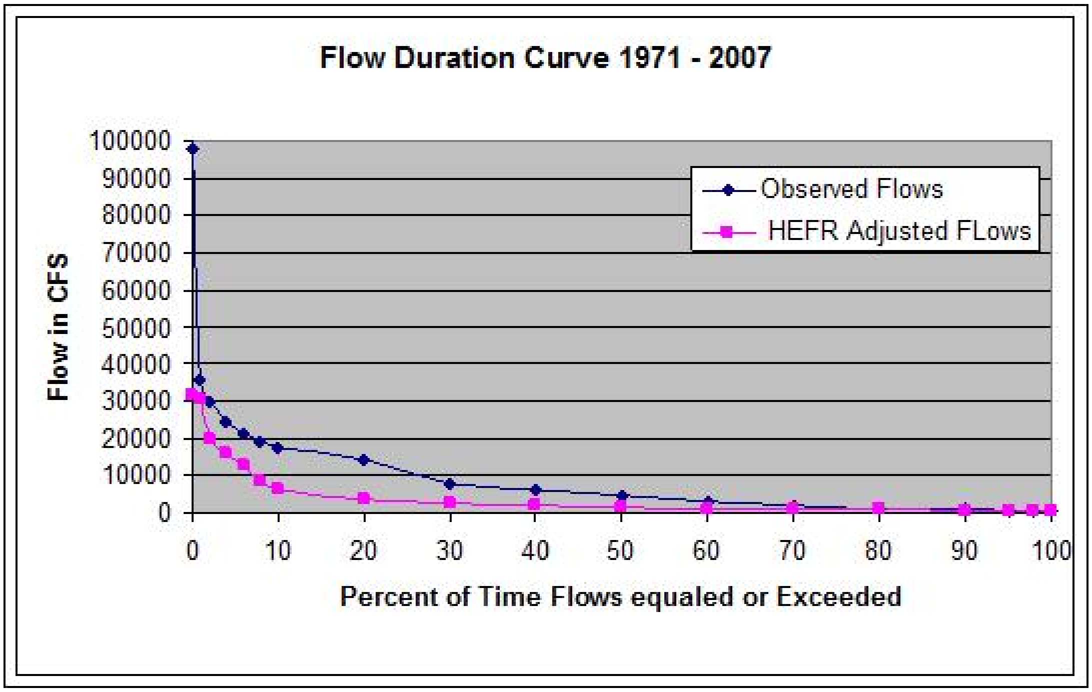

Figure 20. Flow-duration curves based on non-adjusted and HEFR-adjusted daily discharge values, at USGS streamflow-gaging station 08028500, Sabine River near Bon Wier, Texas.

7.5 STEP 5

The computation of sediment yield and the bed-material load histogram for HEFR-adjusted flow conditions requires the integration of the bed-material load rating curve with the flow-duration curve. The SAM Sediment Yield Module for the HEFR-adjusted hydraulic and hydrologic conditions shows that:

Average annual water yield is: 2,397,320 acre-feet
Average annual sediment yield is: 1,068,724 tons

Figure 21 shows the bed-material load histogram generated by the SAM Sediment Yield Module for the HEFR-adjusted hydrology. The histogram does not show a normal distribution, and the high-flow bins carry the greatest percentage of the bed-material load. This is because flows greater than 31,800 ft^3/s have been reduced to 31,800 ft^3/s, therefore compressing the flow-duration curve and increasing the percentage of time flows in this bin occur. Other observations from reviewing Figure 21 are that flows less than about 3,000 ft^3/s are carrying a high percentage of bed-material load, and a second peak in the bed-material histogram occurs at about 17,000 ft^3/s.

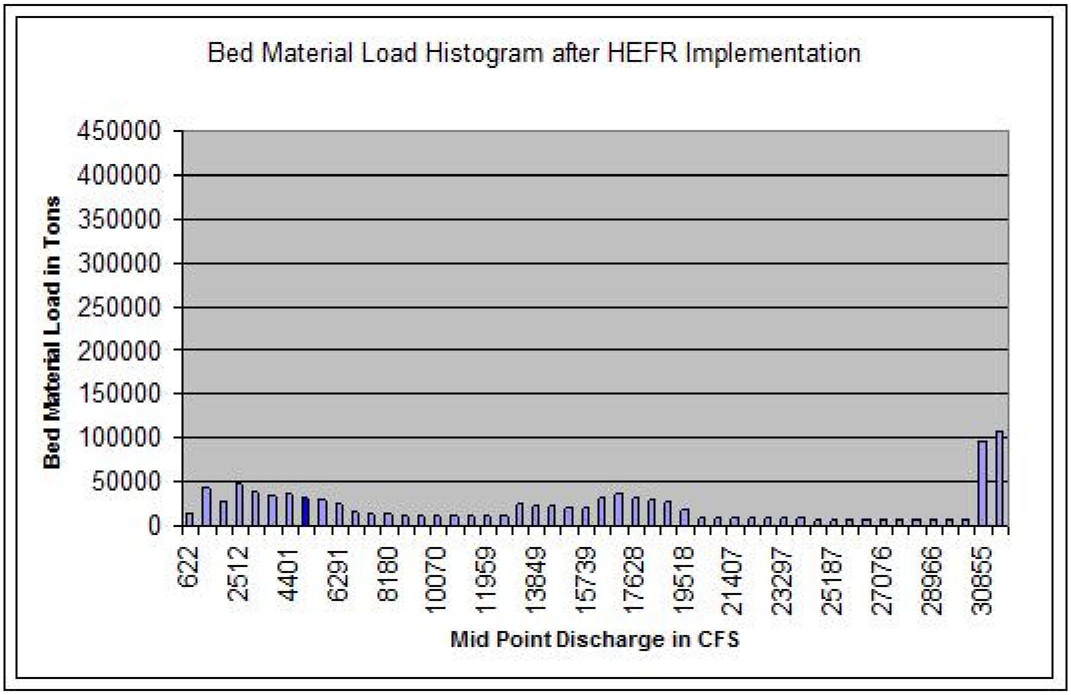

Figure 21. Bed-material load histogram for HEFR-adjusted conditions at USGS streamflow-gaging station 08028500, Sabine River near Bon Wier, Texas.

7.6 STEP 6

The SAM analysis of pre- and post-HEFR conditions at the Sabine River near Bon Wier, Texas shows a substantial difference for hydrologic and sediment-transport dynamics. Average annual water yield and average annual bed-material load are significantly reduced for the HEFR-adjusted flow regime (Table 5).

Table 5. Comparison of average annual water yield and average annual bed-material yield for observed and HEFR-adjusted flow regimes at USGS streamflow-gaging station 08028500, Sabine River near Bon Wier, Texas.

Condition	Average annual water yield (millions of acre feet)	Average annual bed-material yield (millions of tons)
Observed hydrology	5.5	3.3
HEFR-adjusted hydrology	2.4	1.1

The effective discharge computations for a pre- and post-HEFR hydrologic regime indicate a high probability for channel change and instability until steady-state equilibrium is achieved. The amount of channel instability could be determined by a long-term sediment-load monitoring program, which could be used to analyze how the timing of water and sediment withdrawals from the system affects channel adjustments. From the work of Schumm (1969), reducing both the flow and sediment of a river channel can lead to a reduction in width, depth changes, a decrease in width-depth ratio, and an increase in sinuosity.

Despite the dramatic differences between observed and HEFR-adjusted water and sediment yields for the Sabine River near Bon Wier, Texas, it should be noted that (1) practitioners have alternatives in their assignment of HEFR results to create prescribed flow regimes, and (2) HEFR is an evolving software tool with updates that give practitioners more flexibility to statistically model hydrologic conditions at a given site. To summarize, the HEFR results could have been assigned differently, which would result to a change in annual sediment yield, or the HEFR model could have been parameterized differently, resulting in changes to annual water and sediment yield. Further, this example represents a “worst-case scenario” where the volume of water more than that protected by this particular HEFR-based flow prescription was removed to assess sediment transport. Such a scenario is only possible if a reservoir fully regulates flow, including floods, or if water diversions are sufficiently developed to withdraw all flows more than the HEFR-based prescription.

SECTION 8
CONCLUSIONS

An analysis of effective discharge of suspended-sediment load (SSL), bedload, bed-material load, and/or total load at streamflow-gaging stations could be used to modify HEFR-based flow prescriptions for establishing environmental flows. Specifically, a SAM (Hydraulic Design Package) analysis of effective discharge of bed-material load would be most informative for assessments of instream habitat conditions and dynamics. For the majority of locations, the high-pulse flow or overbank-flow categories are associated with the cumulative majority of sediment transport over time. Computations for suspended load should utilize historical measurements, if available, and bed-material load likely requires application of a model equation. Sediment transport, although relatively straightforward in its association with discharge, does not encompass the breadth of fluvial geomorphic processes. Furthermore, concepts of steady-state equilibrium challenge assumptions that a constant discharge value is responsible for the cumulative majority of sediment transport over time. Finally, practitioners utilizing effective discharge for rivers in Texas should be cognizant of the contemporary sediment-transport regime and historical channel adjustments at each location considered. Assignment of an effective discharge to altered or regulated rivers is problematic and implementation efforts could be harmful if a holistic perspective (e.g., sediment trapped behind reservoirs, non-representative cross section to estimate bedload transport, etc.) is not considered.

The SAM Hydraulic Design Package is a very useful desktop tool to assist practitioners in modeling sediment transport and determining effective discharge at streamflow-gaging stations. It conveniently facilitates the choice of a sediment-transport model equation based on user input, and can be used to compare annual sediment loads for existing and HEFR-based hydrologic conditions.

Although SAM is a useful tool to compare observed sediment-transport loads and effective discharge with HEFR-based conditions, little can be done using readily available desktop methods to prescribe a “sediment-load regime” that would adequately maintain instream ecology. The chief reason for this is the paucity of historically-observed geomorphic and sediment-transport data for rivers in Texas, contrasting with the availability of streamflow data for HEFR-based flow-regime analyses. Further, various fluvial processes (e.g., channel bar deposition and modification, channel migration, floodplain sedimentation) initiate and/or occur over a range of flows and, therefore, are dependent on sufficient rates of sediment transport during those flows. The unavailability of data for Texas rivers obfuscates the determination of optimized sediment concentrations or loads for these physically- and ecologically-relevant flows. At minimum, the practitioners responsible for environmental-flow prescriptions at a given site should be cautious if bed-material load is shown to be considerably reduced as a result of an implementable schedule of flows.

SECTION 9
REFERENCES

Ackers, P., and White, W.R., 1973, Sediment transport—New approach and analysis: ASCE Journal of the Hydraulics Division, v. 99(HY11), p. 2,041–2,060.

Adey, E.A., and Cook, H.M., 1964, Suspended-sediment load of Texas streams—Compilation report—October 1959–September 1961: Texas Water Commission Bulletin 6410, 50 p.

Andrews, E.D., 1980, Effective and bankfull discharges of streams in the Yampa River Basin, Colorado and Wyoming: Journal of Hydrology, v. 46, p. 311–330.

Andrews, E.D., and Nankervis, J.M.,1995, Effective discharge and the design of channel maintenance flows for gravel-bed rivers, *in* Costa, J.E., Miller, A.J., Potter, K.W., and Wilcock, P.R., eds., Natural and anthropogenic influences in fluvial geomorphology: Washington, D.C., American Geophysical Union, p. 151–164.

Bagnold, R.A., 1977, Bed load transport by natural rivers: Water Resources Research, v. 13, p. 303–312.

Bagnold, R.A., 1980, An empirical correlation of bedload transport rates in flumes and natural rivers: Proceedings of the Royal Society of London, v. 372A, p. 453–473.

Biedenharn, D.S., Copeland, R.R., Thorne, C.R., Soar, P.J., Hey, R.D., and Watson, C.C., 2000, Effective discharge calculation—A practical guide: United States Army Corps of Engineers ERDC/CHL TR-00-15, 63 p.

Biedenharn, D.S., Little, C.D., and Thorne, C.R., 1999, Magnitude-frequency analysis of sediment transport in the Lower Mississippi River: Vicksburg, Miss., U.S. Army Corps of Engineers, Miscellaneous Paper CHL–99–2.

Bourke, M.C., and Pickup, G., 1999, Fluvial form variability in arid central Australia, *in* Miller, A.J., and Gupta, A., eds., Varieties of fluvial form: Chichester, UK, Wiley, p. 249–271.

Brierley, G.J., and Fryirs, K.A., 2005, Geomorphology and river management—Applications of the River Styles Framework: Malden, Mass., Blackwell, 398 p.

Cook, H.M., 1967, Suspended-sediment load of Texas streams—Compilation report—October 1961–September 1963: Texas Water Development Board Report 45, 62 p.

Cook, H.M., 1970, Suspended-sediment load of Texas streams—Compilation report—October 1963–September 1965: Texas Water Development Board Report 106, 63 p.

Copeland, R.R., McComas, D.N., Raphelt, N.K., and Thomas, W.A., 1997, Users' manual for the Hydraulic Design Package for Channels (SAM): Vicksburg, Miss., U.S. Army Engineering Waterways Experiment Station.

Dougherty, J.P., 1979, Suspended-sediment load of Texas streams—Compilation report—October 1971–September 1975: Texas Water Development Board Report 233, 83 p.

Edwards, T.K., and Glysson, G.D., 1999, Field methods for measurement of fluvial sediment: U.S. Geological Survey Techniques of Water-Resources Investigations, Book 3, Chapter C2, 89 p.

Einstein, H.A., 1950, The bedload function for sediment transportation in open channel flows: U.S. Department of Agriculture Technical Bulletin 1026.

Gomez, B., 2006, The potential rate of bed-load transport: Proceedings of the National Academy of Sciences, v. 103, p. 17,170–17,173.

Gomez, B., and Church, M., 1989, An assessment of bed load sediment transport formulae for gravel bed rivers: Water Resources Research, v. 25, p. 1,161–1,186.

Gomez, B., and Phillips, J.D., 1999, Deterministic uncertainty in bed load transport: Journal of Hydraulic Engineering, v. 125, p. 305–308.

Gupta, A., 1988, Large floods as geomorphic events in the humid tropics, *in* Baker, V.R., Kochel, R.C., and Patton, P.C., eds., Flood geomorphology: Chichester, UK, Wiley, p. 301–315.

Hudson, P.F., 2003, Event sequence and sediment exhaustion in the lower Pánuco basin, Mexico: Catena, v. 52, p. 57–76.

Hudson, P.F., and Mossa, J., 1997, Suspended sediment transport effectiveness of three, large impounded rivers, U.S. Gulf Coastal Plain: Environmental Geology, v. 32, p. 263–273.

Knighton, D., 1998, Fluvial forms and processes—A new perspective: London, Arnold, 383 p.

Kondolf, G.M., 1994, Geomorphic and environmental effects of instream gravel mining: Landscape and Urban Planning, v. 28, p. 225–243.

McKnight, T.L., and Hess, D., 2000, Physical geography—A landscape appreciation, 6th ed.: Upper Saddle River, N.J., Prentice Hall, 604 p.

Meyer-Peter, R., and Müller, R., 1948, Formulas for bedload transport, *in* Proceedings 2nd Meeting International Association of Hydraulic Research: Stockholm, p. 39–64.

Mirabal, J., 1974, Suspended-sediment load of Texas streams—Compilation report—October 1965–September 1971: Texas Water Development Board Report 184, 121 p.

National Cooperative Highway Research Program, 2004, Archived river meander bend database: Washington, D.C., Transportation Research Board of the National Academies, 4 CD-set.

National Research Council of the National Academies, 2005, The science of instream flows—A review of the Texas Instream Flow Program: Washington, The National Academies Press, 149 p.

Parker, G., Klingeman, P.C., and McLean, D.G., 1982, Bedload and size distribution in paved gravel-bed streams: ASCE Journal of the Hydraulics Division, v. 108(HY4), p. 544–571.

Quincy, R.M., 1988, Suspended sediment load of Texas streams—Compilation report, October 1975–September 1982: Texas Water Development Board Report 306, 153 p.

Ritter, D.F., Kochel, R.C., and Miller, J.R., 2002, Process geomorphology, 4th ed.: New York, McGraw-Hill, 560 p.

Robert, A., 2003, River processes—An introduction to fluvial dynamics: London, Arnold, 214 p.

Schumm, S.A., 1969, River metamorphosis: ASCE Journal of the Hydraulics Division, v. 95(HY1), p. 255–273.

Schumm, S.A., 1977, The fluvial system: New York, John Wiley, 338 p.

Senate Bill 3 Science Advisory Committee for Environmental Flows, 2009, WORKING DRAFT—Use of hydrologic data in the development of instream flow recommendations for the environmental flows allocation process and the hydrology-based environmental flow regime (HEFR) methodology: SAC-2009-01, 46 p.

Soar, P.J., and Thorne, C.R., 2001, Channel restoration design for meandering rivers: Vicksburg, Miss., U.S. Army Engineer Research and Development Center.

Stout, I.M., Bentz, L.C., and Ingram, H.W., 1961, Silt load of Texas streams—A compilation report—June 1889–September 1959: Texas Board of Water Engineers Bulletin 6108, 237 p.

Texas Commission on Environmental Quality, Texas Parks and Wildlife Department, and Texas Water Development Board, 2008, Texas Instream Flow Studies—Technical Overview: Texas Water Development Board Report 369, 137 p.

Thomas, W.A., Copeland, R.R., and McComas, D.N., 2002, SAM Hydraulic Design Package for Channels: Vicksburg, Miss., U.S. Army Engineer Research and Development Center.

Torizzo, M., and Pitlick, J., 2004, Magnitude-frequency of bed load transport in mountain streams in Colorado: Journal of Hydrology, v. 290, p. 137–151.

U.S. Department of Agriculture Forest Service, 2009, WinXSPRO version 3.0: at *http://www.stream.fs.fed.us/publications/winxspro.html*

U.S. Geological Survey, 2009, National Water Information System (NWIS), accessed January 2009, at *http://waterdata.usgs.gov/nwis*

Welborn, C.T., 1967, Comparative results of sediment transport sampling with the Texas sampler and the depth-integrated samplers and specific weight of fluvial sediment deposits in Texas: Texas Water Development Board Report 36.

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

SECTION 10
GLOSSARY

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

Bed-material load: a measure of the transport of fluvial sediment as bedload or sand grains in suspension during turbulent flows; only comprised of particles derived from the channel bed; does not include silt or clay particles; 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 flow 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 whereby particles skip along the channel bed

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

Steady-state equilibrium: concept that a river channel adjusts over graded time (decades to hundreds of years) 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 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: a measure of the transport of fluvial sediment continuously entrained in the water column; mostly clay and silt, with varying amounts of sand derived from the channel bed during turbulent 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 whereby particles roll or slide along the channel bed

Wash load: a measure of the transport of fluvial sediment and other material continuously entrained in the water column (e.g., clay, silt, and organic matter); does not include the sand-sized fraction; expressed as mass over time

SECTION 11
CONTRIBUTORS

Contributors and Contact Information

Franklin Heitmuller, ftheitmu@usgs.gov
Nolan Raphelt, nolan.raphelt@twdb.state.tx.us

Commenter and Contact Information

TWDB:
Greg Malstaff, greg.malstaff@twdb.state.tx.us