

THE APPLICATION AND VALIDATION OF DIMENSIONLESS SEDIMENT RATING CURVES

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Abstract: A model using Dimensionless Sediment Rating Curves (DSRCs) for both bedload and suspended sediment has been developed to predict dimensional Sediment Rating Curves (SRCs) for independent locations far removed from the river reaches used to develop the DSRCs. The model input requires measured or extrapolated bankfull stage bedload transport rate, suspended sediment concentration and stream discharge to convert the dimensionless relations to dimensional Sediment Rating Curve (SRC) values. This paper 1) tests the use of reference bedload and suspended DSRCs to predict bedload and suspended SRCs and compares them with observed sediment rating curves for a wide range of river types, scale and geographic locations; 2) compares the diversity and character of dimensional SRCs derived from their respective dimensionless equations for a wide range of stream types and geographic areas; and 3) establishes the feasibility of developing regional bankfull sediment curves by stability/stream type and geology in the absence of local bankfull data. Close agreement was found between the predicted SRCs using the DSRC model and the observed SRCs. Also, the predicted SRCs for a variety of river types do not appear to be the same when compared using the same model to generate each respective SRC. Last, DSRCs are a key component of the FLOWSED and POWERSED models to predict total annual sediment yield and riverbed stability and to evaluate restoration designs. The presented dimensionless model shows promise to aid in a relatively simple, yet accurate and reasonable sediment estimate to direct appropriate interpretations and future management recommendations.

INTRODUCTION

River studies, bridge designs, flood level computations, fish habitat assessments, cumulative watershed determinations and river restoration plans all require an understanding of sediment transport relations. Unfortunately, many of these efforts do not include detailed and accurate sediment predictions or measured data. The absence of sediment data and subsequent analysis is often attributed to the difficulty, expense, training requirements and the timely opportunity to obtain sediment measurements. Due to the availability of numerous sediment transport models and the advantage of various scenario simulations, sediment is often modeled rather than measured. However, without measured sediment data, the models cannot be calibrated. Although many sediment transport models exist, their performance to predict at less than an order of magnitude from observed data is disconcerting as shown by Parker *et al.* (1982), Gomez and Church (1989), Lopes *et al.* (2001), Yang and Huang (2001), Bravo-Espinosa *et al.* (2003) and Barry *et al.* (2004, 2007, 2008). The disparity between observed versus predicted values often discourages model use and limits their interpretation.

The prediction of bedload and suspended Sediment Rating Curves (SRCs) for use in calculating total sediment yield has been a long-term goal and application employed by most sediment transport models. For comparative purposes, many models have a valuable application in predicting various channel response scenarios. The extended applications beyond this use, however, often require detailed model calibration and comparisons of predicted to observed values for application as shown in Barry *et al.* (2004). The challenge is then to understand the limits of the empirical relation extrapolated to other stream types without measured sediment data. If the resultant predicted sediment yield is required for specific studies and simulations that influence channel designs, water quality issues, etc., then the model accuracy becomes of keen interest. In combination with flow-duration curves, bedload and suspended rating curves are used to predict annual sediment yields or loads; thus errors in the SRCs are directly transmitted into the computation and subsequent interpretations. It is especially critical when the sediment results are used to influence management decisions or designs that directly relate to environmental and ecological sensitivity, financial issues and human risk.

One of the problems of sediment transport capacity models is the ability to adequately ascertain sediment supply. A major assumption behind the development of bedload equations is that the channel has an unlimited sediment supply (Lopes *et al.*, 2001). Recent work by Barry *et al.* (2004), based on earlier work by Dietrich *et al.* (1989), developed a dimensionless bedload transport ratio based on supply-related channel armoring relative to the local transport capacity. The model proposed by Barry *et al.* (2004) also includes a power function coefficient of drainage area as a surrogate for the magnitude of basin-specific sediment supply, which subsequently improved the model prediction

accuracy. In addition, Barry *et al.* (2007, 2008) added a dimensionless discharge term in their predictive equation using bankfull discharge as the normalization parameter. This added a scaling adjustment to also improve the model accuracy. These recent efforts at development and calibration have improved model prediction accuracy.

This paper describes a method to accurately predict SRCs for a wide range of river sizes, types, geology and stability. Streams that are both sediment limited as well as unlimited are included in this test. The basis for this approach lies in the application of dimensionless relations for both discharge and sediment with the bankfull stage condition selected as the normalization parameter. A model using Dimensionless Sediment Rating Curves (DSRCs) for both bedload and suspended sediment has been developed separately for various river stability conditions that influence sediment supply. The model input requires a measured or extrapolated bankfull stage bedload transport rate, suspended sediment concentration and stream discharge to convert the dimensionless relations to dimensional Sediment Rating Curve (SRC) values.

The described approach using Dimensionless Sediment Rating Curve (DSRC) relations is designed to potentially reduce the known documented error term of many of the sediment prediction models. The use of DSRCs is a major departure from traditional sediment transport capacity models. To determine sediment supply, many traditional sediment transport models use some method of particle size entrainment or energy threshold to initiate particle movement for bedload transport computations. These particles represent a transport rate related to bed-material sizes and related sediment supply. The exception to this is the Einstein (1950) and Parker *et al.* (1982) models where a transport rate for various-sized material is predicted for all flow ranges. The best solution is to obtain measured sediment data; however, time, financial and physical constraints often limit extensive sediment data collection.

Dimensionless Sediment Relations Test The approach suggested here uses dimensionless functions for bedload and suspended sediment versus stream discharge at ungaged sites to provide a sediment supply function for a range of flows to predict dimensional SRCs and annual sediment yields. Semi-dimensionless SRCs were first introduced by Emmett (1975) where the streamflows in the SRCs were normalized and scaled by their bankfull discharge value; however, the sediment values were not normalized in the same manner. “Reference” dimensionless relations for both bedload and suspended sediment and their corresponding discharges were normalized using the bankfull conditions for both the dependent and independent variables in the SRC as presented in Troendle *et al.* (2001). In this study, a “reference” set of DSRCs for bedload and suspended sediment were established for *Good* or *Fair* stability (based on a modified Pfankuch stability rating (1975) by stream type (Rosgen 1994, 1996). Troendle *et al.* (2001) indicated that the use of a “reference” DSRC could be used to determine departure of river stability and to predict sediment supply as reflected in the SRC.

Following the work by Troendle *et al.* (2001), questions arose of repeatability when changing geologic type and the minimum number of rivers and range of data needed to establish a “reference” DSRC for a given stability condition. Subsequently, six rivers were selected in the San Juan River basin near Pagosa Springs in Southwestern Colorado, three of which were stream types that represented *Good* and *Fair* stability ratings and three additional stream types with *Poor* stability. Each river had extensive measured bedload, using a six-inch Helley-Smith bedload sampler as per Emmett (1980), and measured suspended sediment, as per Edwards and Glysson (1999), with values obtained up to twice the bankfull discharge for all rivers. The measured SRCs were made dimensionless and are shown in Rosgen (2006a, 2006b). The form of the DSRCs for the three *Good/Fair* stability rivers and the three *Poor* stability rivers for both bedload and suspended sediment is non-linear. Thus, four sets of equations were established for *Good/Fair* stability streams and *Poor* or unstable channels for both bedload and suspended sediment (Equation 1 through Equation 4, where the independent x variable is dimensionless discharge and the dependant y variable is dimensionless sediment). Different exponents (slopes) resulted comparing the *Good/Fair* stability relations with the *Poor* stability relations, which reflect the higher bedload sediment supply of the *Poor* stability stream types. The suspended sediment DSRC exponent for the *Good/Fair* stability is 2.41, whereas the exponent for the *Poor* stability rating is 3.66 (Rosgen, 2006b). The bedload DSRC exponent also increased from the *Good/Fair* stability stream types of 2.19 to 2.38 for the *Poor* stability condition. The increase in slope for bedload for the *Poor* stability was not as high as the *Poor* suspended sediment, as the coarser bedload is more hydraulically controlled, although supply is somewhat influenced as well. Although separate equations were established for the *Poor* stability, they were not used in this test to be compared with the *Good/Fair* stability ratings due to the stability of the test streams.

$$\text{Bedload DSRC (Good/Fair Stability): } y = -0.0113 + 1.0139x^{2.1929} \quad (1)$$

$$\text{Suspended DSRC (Good/Fair Stability): } y = 0.0636 + 0.9326x^{2.4085} \quad (2)$$

$$\text{Bedload DSRC (Poor Stability): } y = 0.07176 + 1.02176x^{2.3772} \quad (3)$$

$$\text{Suspended DSRC (Poor Stability): } y = 0.0989 + 0.9213x^{3.659} \quad (4)$$

The resultant DSRCs are used to develop dimensional SRCs using one “averaged” data point for bankfull bedload sediment, bankfull suspended sediment and bankfull discharge. The general procedure is as follows: 1) determine the stability of a given stream type; 2) measure the bankfull discharge; 3) collect a range and calculate an average value of both suspended and bedload sediment measurements close to the bankfull stage; 4) multiply the ratios of discharge by the bankfull discharge, 5) multiply the ratios of suspended sediment by the average concentration of the bankfull value; and 6) multiply the ratios of bedload by the average bedload transport values at the bankfull stage.

If bankfull values for discharge, bedload and suspended sediment are not available, an alternative method is to utilize regional bankfull discharge curves by hydro-physiographic province (Dunne and Leopold, 1978; Rosgen, 2006b) and regional sediment curves stratified by geologic type and river stability/stream type (Rosgen, 2006b). Further explanations of these procedures are described in the FLOWSED and POWERSED models in Rosgen (2006a, 2006b). The procedures are simplified by computer-assisted computations to develop DSRCs and flow-duration curves as well as running the models as programmed in RIVERMorph™.

Objectives: 1) Test the use of reference bedload and suspended DSRCs to predict bedload and suspended SRCs and compare them with observed SRCs for a wide range of river types, scale and geographic locations using the smaller dataset of dimensionless relations from the Southern San Juan River basin near Pagosa Springs, Colorado; 2) Compare the diversity and character of dimensional SRCs derived from their respective dimensionless equations for a wide range of stream types and geographic areas (i.e., do they all appear similar using the same dimensionless equation or do they differ?); and 3) Establish the feasibility of developing regional bankfull sediment curves by stability/stream type and geology in the absence of available local data.

Validation of the Dimensionless Bedload and Suspended Sediment Rating Curve Model: A variety of 16 rivers with measured bedload and/or suspended sediment data were selected to be tested as an independent dataset. Because the majority of the sediment data was from USGS and measured streamflow gaged stations, an assumption of *Good/Fair* stability was applied as most sites selected are relatively stable sites to prevent large and frequent shifts in the stage or discharge rating curve. Thus these tests use the *Good/Fair* stability relations of the DSRC model for both bedload and suspended sediment where available. The sites selected represent a wide range of bankfull discharge values, diverse stream types from boulder-dominated to silt/clay streams, and are in a variety of physiographic settings. Data was selected from highly urbanized streams in Southern Ontario, Canada (sediment-limited urban streams); sand-bed streams to cobble-bed stream types; high sediment supply braided channels in Alaska; and river data from Montana, Colorado, North Carolina, South Carolina, Indiana, Kentucky, Mississippi and Nebraska. Figure 1 depicts a few of the comparisons for this wide range of rivers for both bedload and suspended sediment. The predicted SRCs are based on the average bankfull values for both bedload and suspended sediment versus bankfull discharge to convert the dimensionless relation to dimensional. No other measured data were used to generate the predicted SRCs.

Figure 2 shows the close agreement between the DSRC model for suspended sediment and the observed SRC of the Bell River (Frenette and Julien, 1987), a supply-limited stream. Figure 2 also compares predicted SRCs to observed values for numerous rivers indicating the close agreement between the predicted and observed values. The overlays in Figure 3 of the DSRC model prediction for sand-bed rivers, including the Niobrara River in Nebraska, Colorado River at Taylor’s Ferry, West Goose Creek in Mississippi, and Mountain Creek in South Carolina, illustrate the DSRC model prediction to observed data compared with other prediction models previously evaluated (Vanoni *et al.*, 1960; Julien, 1998). The apparent closeness of the predicted to observed relations over this very wide range of river sizes, types and geographic locations gives considerable encouragement as to the applicability of the model. Additional predicted versus observed comparisons are shown in Rosgen (2006b) with similar results.

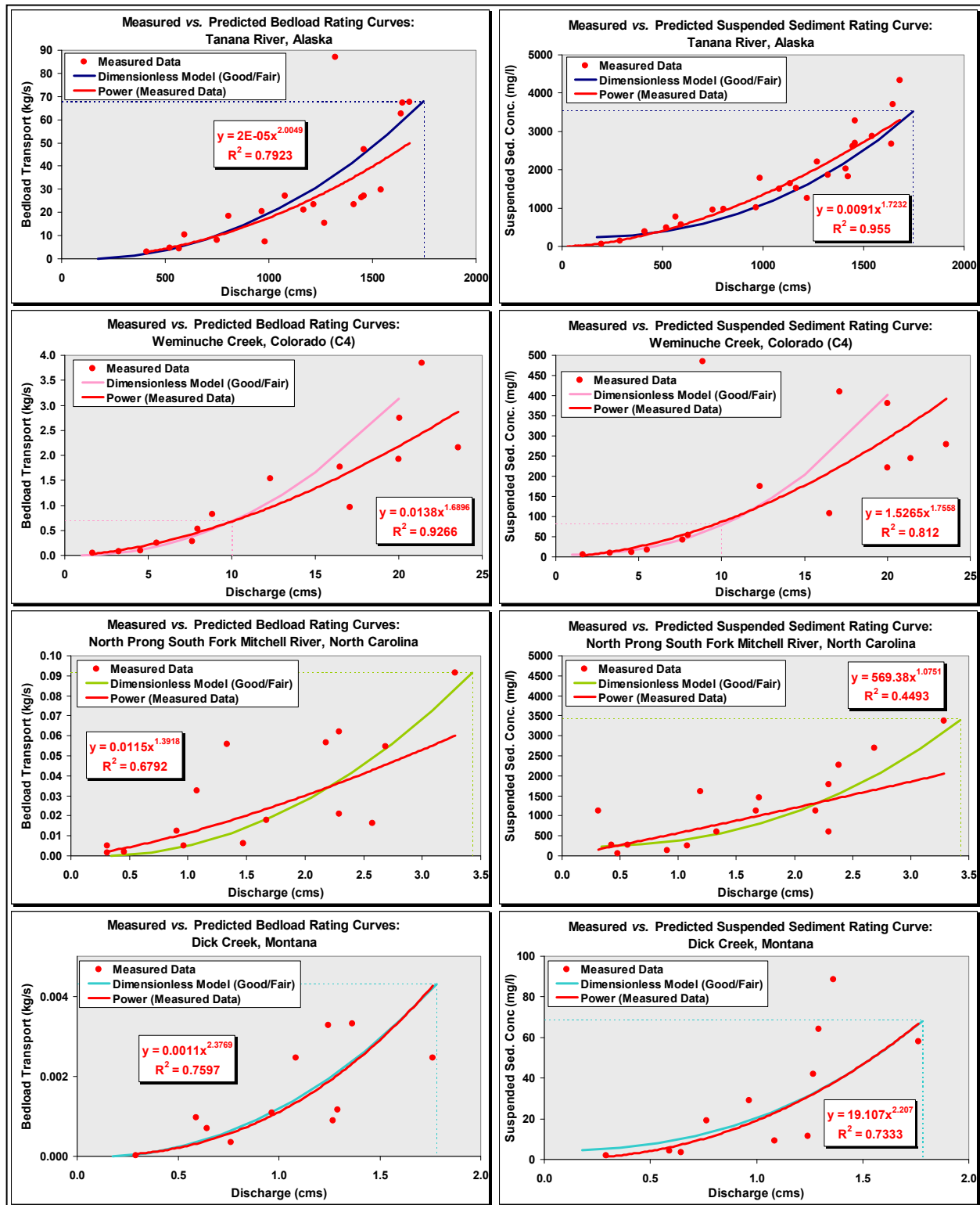


Figure 1 Predicted bedload and suspended SRCs derived from the dimensionless model compared to observed values for four diverse river systems: 1) Tanana River, Alaska (D4 stream type; 1747 cms bankfull discharge); 2) Weminuche Creek, Colorado (C4 stream type), 3) North Prong South Fork Mitchell River, North Carolina (C4 stream type); and 4) Dick Creek, Montana (C4 stream type; 1.8 cms bankfull discharge).

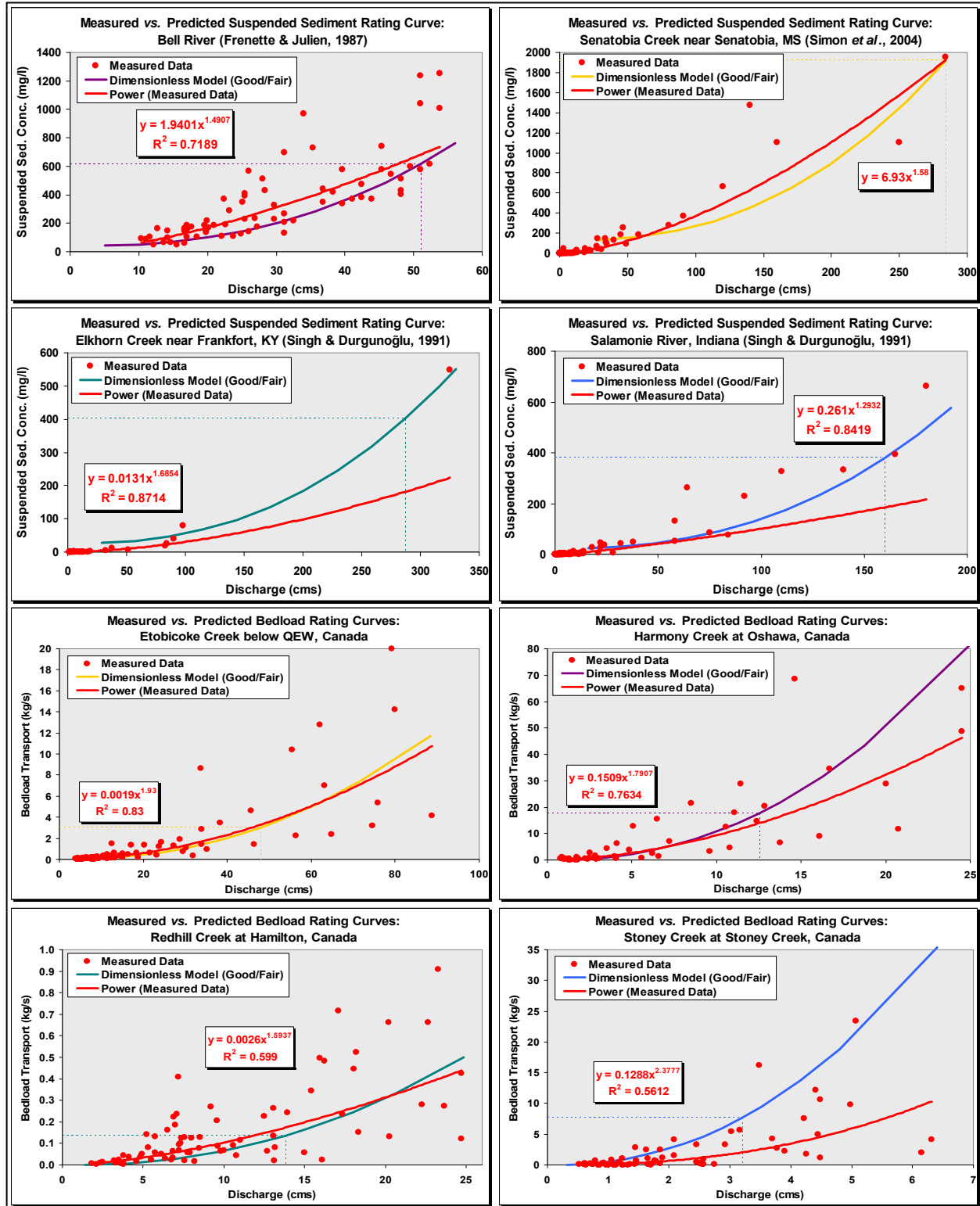


Figure 2 Predicted bedload and suspended sediment rating curves derived from the dimensionless model compared to observed values for eight diverse river systems: 1) Bell River (Frenette & Julien, 1987); 2) Senatobia Creek, MS (Simon *et al.*, 2004); 3) Elkhorn Creek, KY (Singh & Durgunoğlu, 1991); 4) Salamonie River, IN (Singh & Durgunoğlu, 1991); 5) Etobicoke Creek, Canada; 6) Harmony Creek, Canada; 7) Redhill Creek, Canada; and 8) Stoney Creek, Canada.

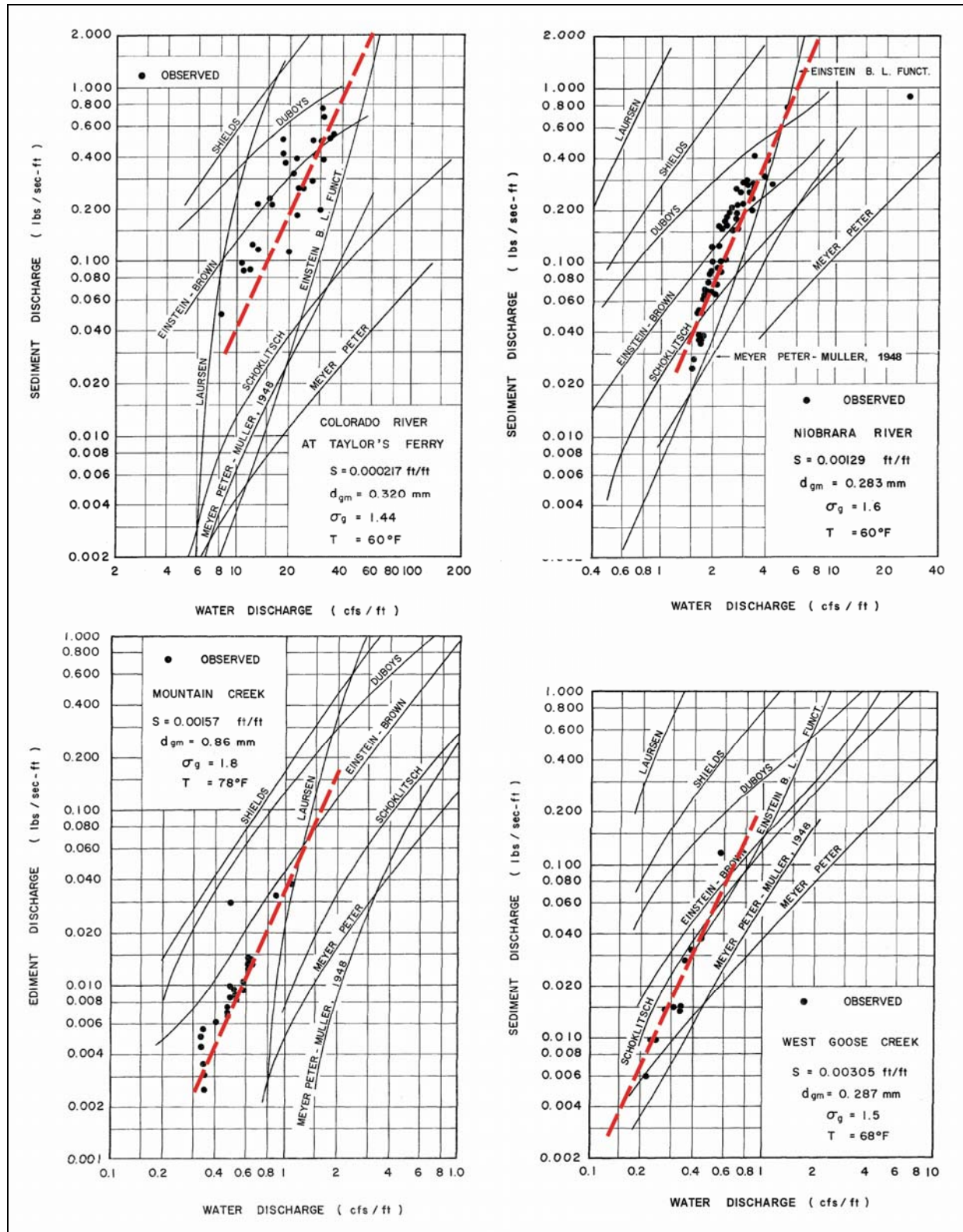


Figure 3 Bedload sediment rating curves derived from the dimensionless model for Good/Fair stability (represented by the red dashed lines) overlaid on observed data and numerous predicted curves from Vanoni *et al.*, 1960: 1) Colorado River at Taylor's Ferry, 2) Niobrara River near Cody, Nebraska, 3) Mountain Creek near Greenville, South Carolina, and 4) West Goose Creek near Oxford, Mississippi.

The Diversity and Character of Predicted Sediment Rating Curves: A common misconception amongst critics of this approach relates to the use of the same DSRC (same slope of the regression) for a variety of river types, which “will lead to large errors in predicted transport rate” (Wilcock *et al.*, 2009, p. 20). The prediction results as shown in Figures 1–3 indicate that this statement is not well-founded as each predicted SRC using the same regression constants of the respective reference DSRC relation is close to observed values. For example, the predicted bedload sediment rating curve of the Niobrara River using the bedload *Good/Fair* DSRC with a slope of 2.19 was compared with a power fit curve slope of 2.5; however, the prediction fit the data points well and did not produce large errors (Figure 3). Even with flood data, the predicted SRC went through the measured data point at a flow 1.4 times the bankfull value (Figure 3). The greatest departure for other rivers, however, will most likely be associated with the rare flood, not the more frequent flow and sediment values up to the bankfull stage, which are responsible for the majority of sediment transport over time (effective discharge).

The linear plots of the predicted suspended SRCs for many of the same streams from Figure 1 and Figure 2, using the same exponent of 2.4 from the DSRC model for *Good/Fair* stability, are shown in Figure 4. The predicted bedload rating curves for these streams using the bedload DSRC for *Good/Fair* stability with an exponent value of 2.19 are also plotted on the linear format in Figure 4. It is apparent that not only does the dimensionless model predict closely to observed SRCs, but the individual character or sediment signature of each river system is retained when compared to various rivers using the same model coefficients that generated each respective SRC. In other words, the predicted SRCs from the same dimensionless model for a variety of river types *do not* appear to be the same for all rivers when made dimensional. This variation in each river is due to the measured sediment supply as reflected in the bankfull values for a given bankfull discharge. There exists a major separation of the predicted SRC for each individual river as depicted in Figure 4 even though they share the same exponent value of the SRC as predicted.

If streams in a particular region have exponent slopes much less or much larger than those presented in the Pagosa Springs, Colorado dimensionless model tests, then a localized DSRC can be established and tested following the same approach as in the development of the discussed DSRC model. In this manner one does not have to be corralled into a “fixed” relation that may not represent observed values. The FLOWSED/POWERSED model allows for this variation in the procedure as programmed in RIVERMorph™ by providing the option to use the Pagosa Springs DSRCs or to insert differing regression constants for the dimensionless relations for both bedload and suspended sediment. Thus the concern expressed by Wilcock *et al.* (2009) can be offset by this approach if the error term exceeds an acceptable level. However, the results in Troendle *et al.* (2001) and these subsequent tests indicate that it is unlikely to require the development of localized DSRC relations to predict dimensional SRCs once bankfull values are obtained as the DSRCs are more universal than initially perceived.

Development of Regional Bankfull Sediment Curves: A limitation of this model lies in the difficulty, cost and timing to obtain bankfull sediment and discharge data. Bedload sampling can be quite labor intensive, hazardous on medium to large rivers, expensive to purchase samplers and support equipment, and difficult in stormflow-dominated regions to capture the bankfull stage measurements. Streamflow measurements must also be obtained concurrently. The protocols for streamflow, bedload and suspended sediment measurements follow USGS standards; thus training is necessary if personnel are not familiar with such methods. To help offset these problems to use the dimensionless model, existing bankfull sediment data can be used to potentially establish regional relations by drainage area and bankfull discharge (Rosgen, 2006b). The regional sediment curves should additionally be stratified by stability ratings to reflect sediment supply by various stream types within a broad geologic type associated with channel materials and hillslope processes. For example, streams in the batholith geology will have a higher ratio of bedload to suspended sediment for the same drainage area compared to streams in shale-derived geology, which will often have the opposite ratio. Stream types with corresponding *Good/Fair* stability ratings generally have a lower bankfull sediment concentration and bedload transport for the same drainage area in the same geologic setting compared to *Poor* stability stream types.

Differences in sediment supply as reflected in the regional bankfull bedload and suspended sediment curves by stability ratings for the North-Central Colorado basin in alpine glaciation and volcanism-dominated geology are shown in Figure 5. Regional sediment curves were also developed for Northwestern Montana (Blackfoot and Clark Fork River basins) as influenced by both continental and alpine glaciation and metamorphic geology (Figure 5). These relations span a range of drainage areas from 15 km² to over 9,000 km². In the interim of available sediment data, these regional bankfull bedload and suspended sediment curves are useful to initially apply the dimensionless

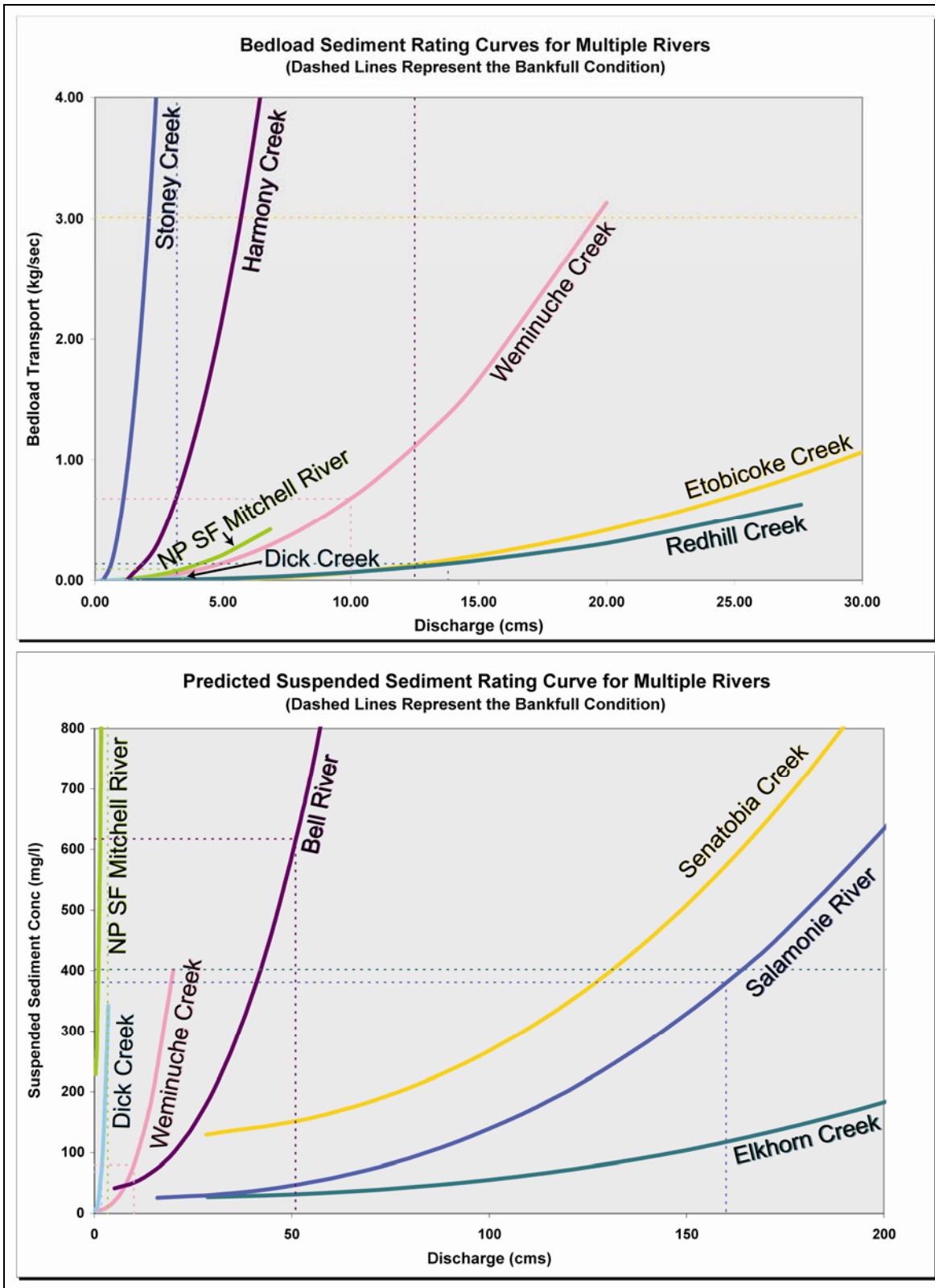


Figure 4 Combination of predicted SRCs from Figure 1 and Figure 2 for bedload and suspended sediment on linear plots indicating the diversity and character for a wide range of river types, scale and geographic locations. The predicted SRCs are generated from the same regression constants of their respective *Good/Fair* DSRC.

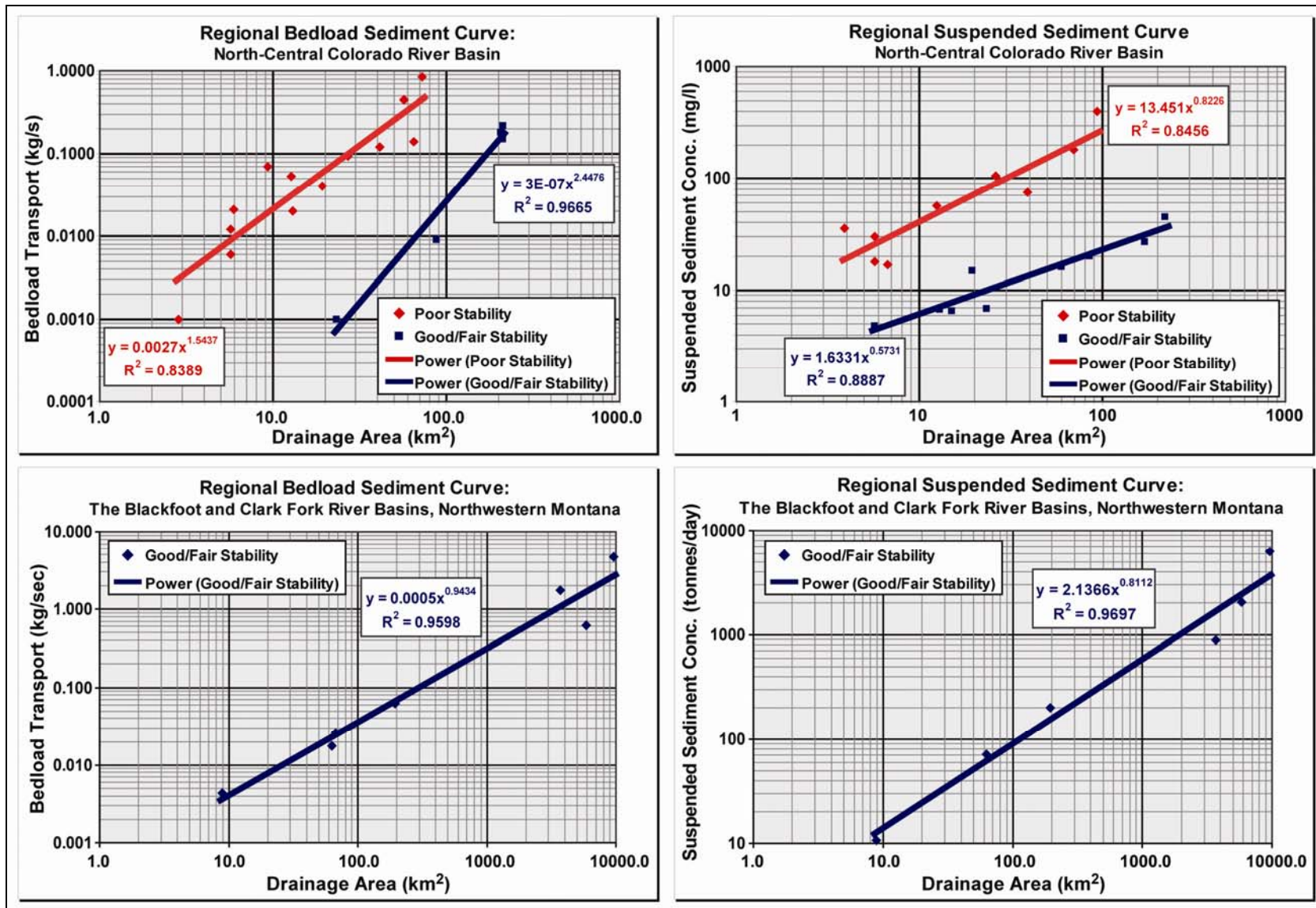


Figure 5 Regional sediment curves for the North-Central Colorado basin (for both *Good/Fair* and *Poor* stability) and the Blackfoot and Clark Fork River basins in Northwestern Montana (for *Good/Fair* stability) that span a range of drainage areas, stability ratings and geology.

model. The application of the regional bankfull sediment curves requires the drainage area and river stability for a given stream type. Then, bankfull sediment and bankfull discharge values are used to convert the appropriate DSRC to a dimensional SRC. It is important to note that a change in drainage area that reflects the scale change in rivers is a key stratification to changes in sediment supply. River stability is required to eventually be integrated into the relation as more data points are obtained. Additionally, bankfull discharge can also be obtained from available regional bankfull discharge curves by drainage area for a specific hydro-physiographic province (Rosgen, 2006b).

APPLICATIONS

DSRCs are a key component of the FLOWSED and POWERSED models (Rosgen, 2006a, 2006b). These models are used to: 1) predict riverbed stability, 2) predict total annual sediment yield, 3) evaluate restoration designs, 4) predict sediment disposition at bridges, culverts and other crossings, 5) evaluate sediment transport consequence of river structures, 6) evaluate flood levels due to change in sediment transport, 7) evaluate clean sediment TMDL's; and 8) predict reservoir filling rates. These models are being used in cumulative watershed assessments (WARSSS, Rosgen, 2006b) where disproportionate sediment contributions from streambanks, roads and other sources can be compared to total annual sediment yield.

SUMMARY

The application of DSRCs for both bedload and suspended sediment by stream stability has shown to be a valid approach to predict dimensional SRCs using the appropriate value for each independent and dependent variable at the bankfull stage. Although the predicted dimensional SRCs are derived from the same regression constants of the DSRCs, their individual character or sediment signature is retained as demonstrated when the predicted SRCs are plotted on a linear scale. This is due to the variation in the bankfull sediment and discharge values between streams when using the bankfull normalization parameter to convert from dimensionless to dimensional values. In addition, the potential use and required development of regional bankfull sediment curves show promise in obtaining bankfull bedload and suspended sediment values using drainage area and river stability of various stream types. This allows individuals to apply the model if they do not have a bedload or suspended sediment sampler, cannot wait for bankfull stage to occur, or physically cannot access the river at high flows.

Additional data comparisons and testing are recommended in the future to determine the accuracy in the *Good/Fair* versus *Poor* stability prediction values for their appropriate stream conditions. As additional test streams are added to this database, potential improved stratification of equations and regional sediment curves may help in the availability and accuracy of prediction. Existing regional curves for bankfull discharge are also helpful at ungaged streams along with bankfull sediment values as a function of drainage area and stability ratings to run the model. DSRCs when converted to dimensional values from measured bedload transport rates and suspended sediment concentration are an accurate reflection of the sediment supply, thereby reducing the previously documented large model prediction errors.

Regardless of the model, the need to accurately predict sediment yield and river behavior response is essential as society continues to put constraints on the river system due to continued land use demands. The DSRC model appears to be a relatively simple and practical approach to accurately predict bedload and suspended SRCs to provide timely and appropriate interpretations for future management recommendations.

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