FLOWSED/POWERSED – PREDICTION MODELS FOR SUSPENDED AND BEDLOAD TRANSPORT

David L. Rosgen, Hydrologist/Geomorphologist, Wildland Hydrology, 11210 North County Road 19 North, Fort Collins, Colorado 80524, wildlandhydrology@wildlandhydrology.com

Abstract: FLOWSED and POWERSED are sediment transport models based on empirical and analytical methods used to predict both suspended load and bedload. The models predict changes in degradation and/or aggradation processes associated with impaired streams. The FLOWSED model involves the application of dimensionless sediment rating curves developed from reference streams that reflect sediment supply associated with a given stream type and stability rating. Measured bankfull discharge, as well as bankfull suspended and bedload sediment values are used as normalization parameters. Flow-duration curves from gage station data are also converted to a dimensionless form in order to develop localized flow-duration curves at ungaged sites. Measured bankfull values from the study stream are used to convert dimensionless to dimensional sediment rating and flow-duration curves. Annual sediment yields can then be determined using the predicted sediment rating and flow-duration curves.

Regionalized dimensionless sediment relations can be developed from measured data and tested against the dimensionless bedload and suspended sediment relations derived from the Colorado data presented in FLOWSED. Predicted sediment rating curves using this model are compared to observed values over a range of independent data sets representing small to large rivers in a variety of hydro-physiographic provinces.

The POWERSED model converts sediment rating curves from stream discharge to unit stream power. Changes in channel dimension, pattern, profile and velocity due to stability problems and/or proposed channel design options are evaluated in terms of sediment transport potential. Hydraulic geometry by stage is calculated to convert discharge to unit stream power. This conversion allows the user to predict sediment transport rates at different stages and channel response to changes in slope, depth and/or velocity for a given sediment supply. Sediment supply is determined from the dimensionless sediment rating curves stratified by stream type and stability using the FLOWSED model. Predicted annual suspended and bedload sediment yield values from both reference (stable) and impaired (unstable) reaches using POWERSED are compared to measured annual sediment yield. Applications of the models are presented for a) stability examinations; b) watershed and/or sediment supply assessments (WARSSS); c) fish habitat enhancement structures; d) flood level computations; e) bridge design; f) prediction of future reservoir capacity; and g) natural channel design for river restoration.

INTRODUCTION

Field practitioners must be able to accurately predict the sediment capacity of river channels in order to assess physical and biological function and stability. Recent stream restoration and fish enhancement projects have failed due to a lack of understanding of sediment transport and the importance of incorporating sediment transport into projects. For example, failure to include sediment transport estimates in calculating bridge hydraulics may result in the continued deposition of sediment in many of the bridge cells. Changes in the dimension, pattern, profile, materials and roughness of stream channels need to be assessed not only for sediment competency, but also for capacity. As channel boundary conditions and flow regimes change, it is imperative to ensure that the stream can transport the sediment made available from its catchment. Unfortunately, simple and accurate approaches to these problems are unavailable due to the inherent complexity and uncertainty of sediment transport prediction.

Using measured hydraulic and sediment data, Lopes et al. (2001) tested 7 bedload equations on 22 streams and concluded that the best overall sediment transport equations were developed by Schoklitsh (1962) and Bagnold (1980). Gomez and Church (1989) hypothesized that, when presented with limited hydraulic information, bedload is best predicted using equations incorporating the stream power concept. After testing 410 bedload events in gravel-bed rivers, however, Gomez and Church (1989) concluded that out of the 12 equations assessed, none performed consistently due to the limitation of the data and the complexity of the sediment phenomena. The authors concluded that sediment transport prediction involves 1) "*the need to collect localized bedload and suspended sediment rating curve data to establish sediment supply values; and, 2) the need to calibrate sediment transport models based on absolute values.*" Without observed sediment values, predicted transport rates will continue to differ significantly from actual transport rates. It is not uncommon for existing sediment transport models to overpredict or underpredict by two or three orders of magnitude, all on the same data sets (Parker, et al., 1982).

Purpose: Clearly, the need for a more accurate suspended and bedload transport model has not lessened. Since 1968, the author has measured suspended and bedload data on a wide range of flows for 160 rivers. The Rosgen data sets, combined with USDA Forest Service Rocky Mountain research data from sites in Colorado and Wyoming, were used to develop and test dimensionless relations of both suspended and bedload sediment rating curves by stream type/stability categories (Troendle, et al., 2001). The normalization parameter used to transform the sediment rating curves to dimensionless form was bankfull stage values of discharge, suspended and bedload sediment. With one exception, the relations found were power functions. The equations were tested and found to be statistically significantly ($p < 0.05$) different from one another, based on broad stream type groupings and associated "good/fair" versus "poor" stability ratings. Stream type alone was not significant, since stability ratings are needed to establish sediment supply (Rosgen, 2001). Where changes in stream type infer a stability shift, such as a change from an E5 to F5, there is an inferred relationship of not only a change in sediment supply with stream type change, but a shift in the sediment rating curve. The stream types are those described by Rosgen (1994), while the stability ratings are those by Pfankuch (1975), modified by Rosgen (2001). USGS sediment rating curves on Redwood Creek, California, were stratified into different sediment rating curves based on the Pfankuch stability ratings (USEPA,1980), explaining a range of 5 orders of magnitude in sediment supply for the same discharge. Bedload sediment rating curve data, published by Williams and Rosgen, (1989) were stratified by stream type to reduce the variability in the scatter of the data (Rosgen, 1996). The steeper slope of the sediment rating curves was related to a sediment supply condition and to channel processes described by stream type. Such relations eventually provide dimensionless sediment rating curves from measured values that represent the *supply* function in the sediment transport relations. Much like calibrating a model with measured values, bedload discharge, suspended and bedload sediment data are measured in order to convert the empirically derived dimensionless relation equation to a dimensional form for a given river reach. The FLOWSED model utilizes dimensionless sediment rating curves and dimensionless flow-duration curves. Dimensionless flow-duration curves were first presented by Emmett (1975).

One criticism of dimensionless ratio sediment rating curves offered by Kuhnle and Simon (2000) is that they will collapse into the same curve when the sediment rating curves of two rivers of different types are converted to a dimensionless form. This would be true if the stability/stream type/sediment supply relations were similar; however, tests of significance of "poor" versus "good/fair" stability were significantly different when made dimensionless (Troendle, et al., 2001). To demonstrate this point, USGS sediment rating curve data from Western Tennessee (Simon, 1986) from the Hatchie river (E5 stream type) and the South Fork of the Forked Deer river (F5 stream type), shown in Figure 1, indicate that for similar flows the South Fork of the Forked Deer river has 3 orders of magnitude higher sediment supply compared to the Hatchie river. When these relations were transformed to a dimensionless form, the curves did not collapse into one curve as asserted by Kuhnle and Simon (2000), but rather remained separate, as seen in Figure 1. If the curves had collapsed into the same relation, this would indicate a lack of statistically significant difference. In such a case, one dimensionless power function of discharge would then fit both streams.

The POWERSED model uses the output from FLOWSED, but simulates changes in stream power to predict transport relations due to stream channel dimension, pattern and profile changes. Thus, the combination of simple power functions from empirical and analytical relations of hydraulic geometry/stream power by stage are combined to provide a model that produces reasonable numbers. The empirical and analytical models and their validation over a wide range of geographic regions are presented below.

MODEL DESCRIPTION

FLOWSED: The framework for this model involves selecting streams of various types and stability ratings that have measured suspended and bedload sediment rating curves available. The streams selected should represent a "reference" condition for streams of various morphology and stability within a region. The sediment rating curves are then transformed to a dimensionless form over the entire range of flows using the bankfull stage values as the normalization parameter. Variations in the form of the relation describing the exponent and coefficient values depend on the nature of the streams in the region. Rivers of similar type and stability are grouped as in Troendle et al. (2001). Thus, the derived empirical relations can be extrapolated to similar rivers elsewhere. For the development of dimensionless suspended sediment and bedload sediment rating curves, data from C4 stream types (gravel-bed, meandering, streams with floodplains, point bars, width/depth ratios >12, on slopes less than 0.02) (Rosgen, 1994) were selected to represent "good/fair" stability in the Pagosa Springs region of Southwestern Colorado. Two equations were established, one for suspended sediment and another for bedload sediment (Figure 2). Separate equations were developed for "poor" stability ratings for a region.

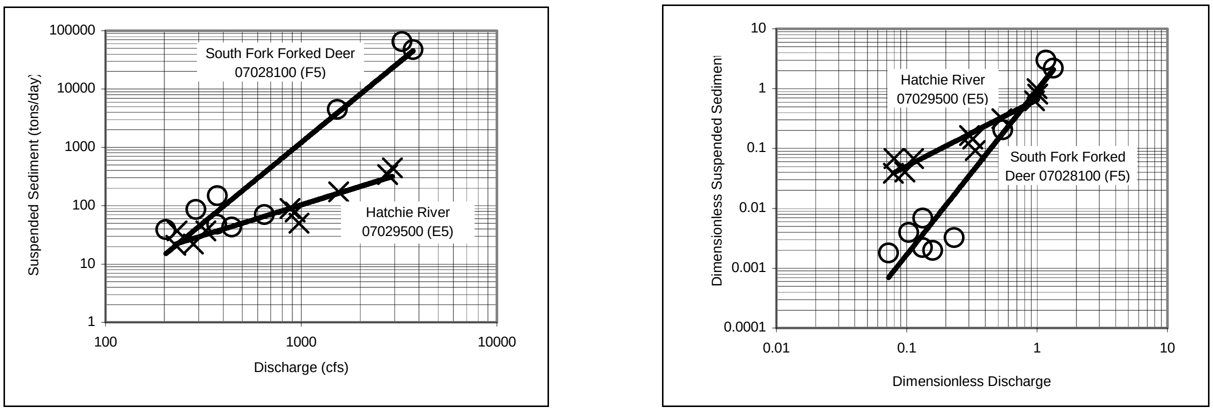


Figure 1 *Left graph*: Suspended sediment rating curves from West Tennessee for the South Fork forked Deer (F5 stream type) and Hatchie Rivers (E5 stream type). Data is from the USGS in English units as published by Simon, 1989. *Right graph:* Dimensionless ratio suspended sediment rating curves; separation of curves from one another.

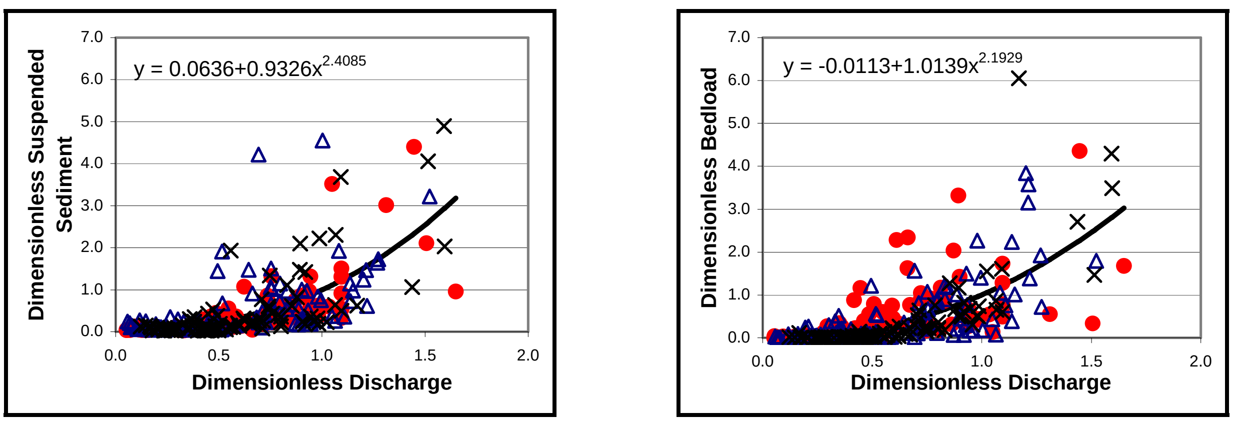


Figure 2 *Left graph*: Dimensionless ratio suspended sediment rating curves for "good/fair" stability categories. *Right graph*: Dimensionless bedload rating curves for "good/fair" stability categories. Both curves using data from Wolf Creek, the West Fork of the San Juan river and Fall Creek, Pagosa Springs, Colorado (1997 – 2001).

Flow-duration curves from USGS gage sites are also converted to dimensionless flow-duration curves using bankfull discharge as the normalization parameter. Since bankfull is a momentary maximum value, it must be converted to a "mean daily bankfull" value. USGS data is used to obtain the mean daily discharge on the day that the bankfull stage occurs. A ratio of mean daily discharge to the momentary maximum value is developed to establish the "mean daily bankfull" value. This value is used to normalize the flow-duration curve data. The use of dimensional flow-duration curves representing a hydro-physiographic province are used to obtain flow-duration curve data at ungaged sites once bankfull discharge is determined. Bankfull discharge is obtained from field investigations, measurement or extrapolation from regional curves for a hydro-physiographic region. The combination of sediment rating curves for both suspended and bedload sediment and flow-duration curves allows the calculation of total annual sediment yield. To convert the dimensionless sediment rating curve to dimensional values, measured suspended and bedload sediment must be obtained for the stream being studied. Regional bankfull sediment values such as those for suspended sediment (Simon, et al., 2004) could be used in the absence of locally measured values, but would require validation. Since direct measurements are necessary to calibrate sediment models, then these same data can be used to convert a dimensionless relation in order to predict a sediment rating curve if the data collected is at or near the bankfull stage.

POWERSED: This model uses sediment supply data from the dimensionless suspended and bedload rating curves and dimensionless flow-duration cures in FLOWSED, but converts the full range of stream discharge into stream power. Stream power (ω) is defined as

$$(\omega) = \gamma QS \quad (1)$$

where, γ is the specific weight of the fluid, Q is stream discharge, and S is the water surface slope. Stream power is calculated for each stage from hydraulic geometry relations. The hydraulic geometry relations are predicted using various resistance equations and roughness coefficients for a wide range of flows. Thus, changes in slope, hydraulic radius (depth), and velocity by stage are reflected in an altered stream power and a corresponding altered sediment transport rate. The sediment consequences and resulting channel stability of over-widened streams, multiple cell bridges, and/or structures that alter the slope, depth and/or velocity of flow can be determined. The suspended sediment data for POWERSED is further separated into the sand portion of the suspended sediment sample and the wash load since the sand portion is more controlled by energy than the wash load. Washload is defined as a portion of the suspended load at sediment sizes less than .062mm, the remaining concentration represents the suspended sand material load. Ratios of suspended sand concentrations versus total suspended sediment concentrations are used in the analysis.

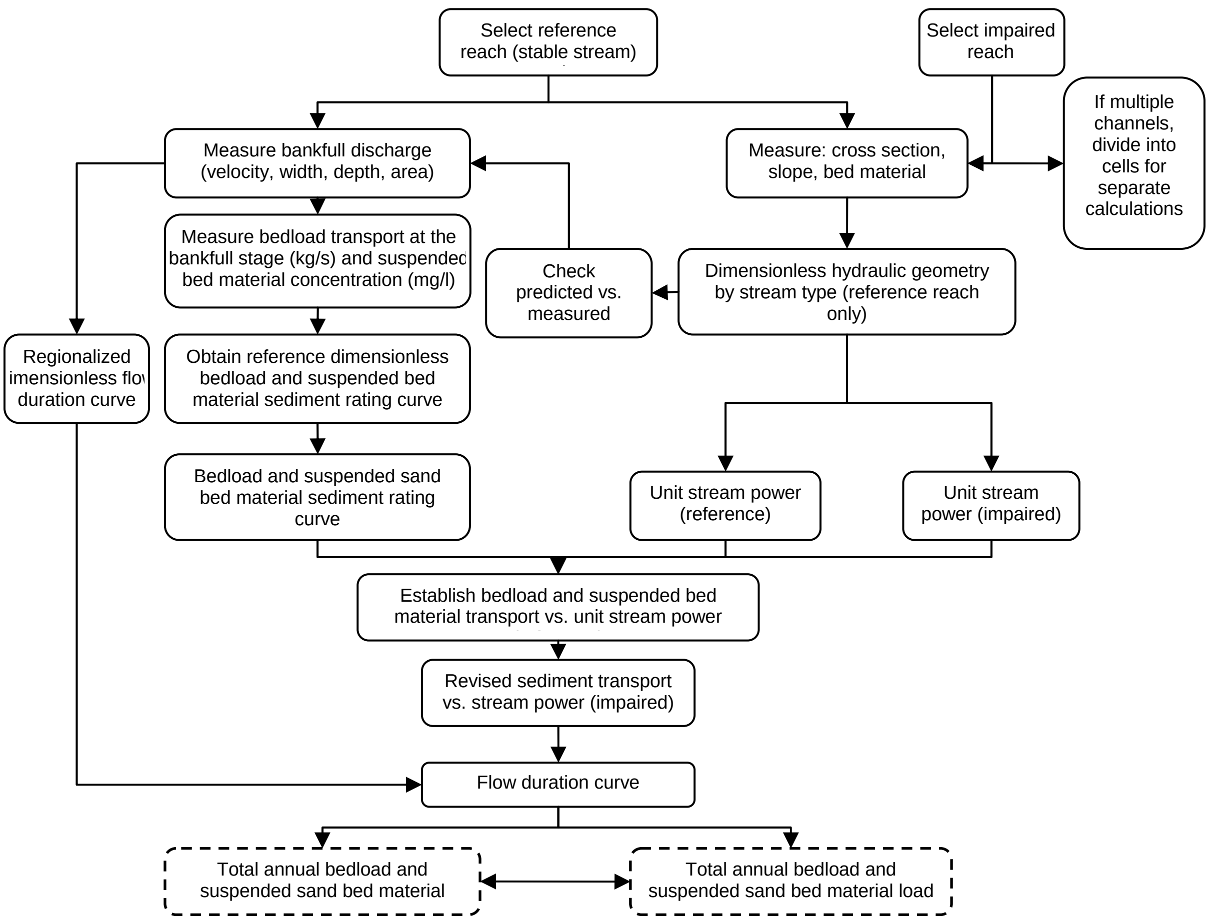


Figure 3 Flow chart for FLOWSED/POWERSED models when impaired and reference streams have the same discharge.

A flow chart depicting both models is shown in Figure 3. The user has an option to either route the same sediment supply through the impacted reach from the upstream reach or to measure sediment and flow at bankfull stage and re-enter the model to adjust sediment supply for the downstream reach. This option allows the user to insert locally derived power function equations that best represent the altered stream. These models have been successfully used for river assessment, fish habitat structure evaluations and river restoration designs since 2001. The models are presently installed in a software program in RIVERMorph$_{TM}$ to assist users with rapid, multiple applications.

RESULTS AND DISCUSSION

Validation of both the FLOWSED and POWERSED models has been conducted using measured suspended and bedload data for a wide range of river sizes over diverse geographical areas. One measured data point representing discharge, suspended sediment and bedload sediment, all collected at the bankfull stage, was used to predict a sediment rating curve for each location. These rivers represented independent data sets, as none of the empirical dimensionless sediment rating curves tested were used to develop the relations. For validation, US Geological Survey data was obtained for measured bedload and suspended sediment in Alaska, Tennessee, Arkansas, Wyoming, Nevada, North Carolina and other states (Figure 4).

The reference dimensionless sediment rating curves for suspended and bedload sediment used for these predictions were the power function relations shown in Figure 2, from the Pagosa data. The comparison shows very good agreement between the predicted sediment rating curve and the measured values over a wide range of flows (Figure 4). The predicted sediment rating curves were derived from only one data point each representing the bankfull discharge, suspended sediment and bedload sediment values as depicted (dashed line) on each relation in Figure 4.

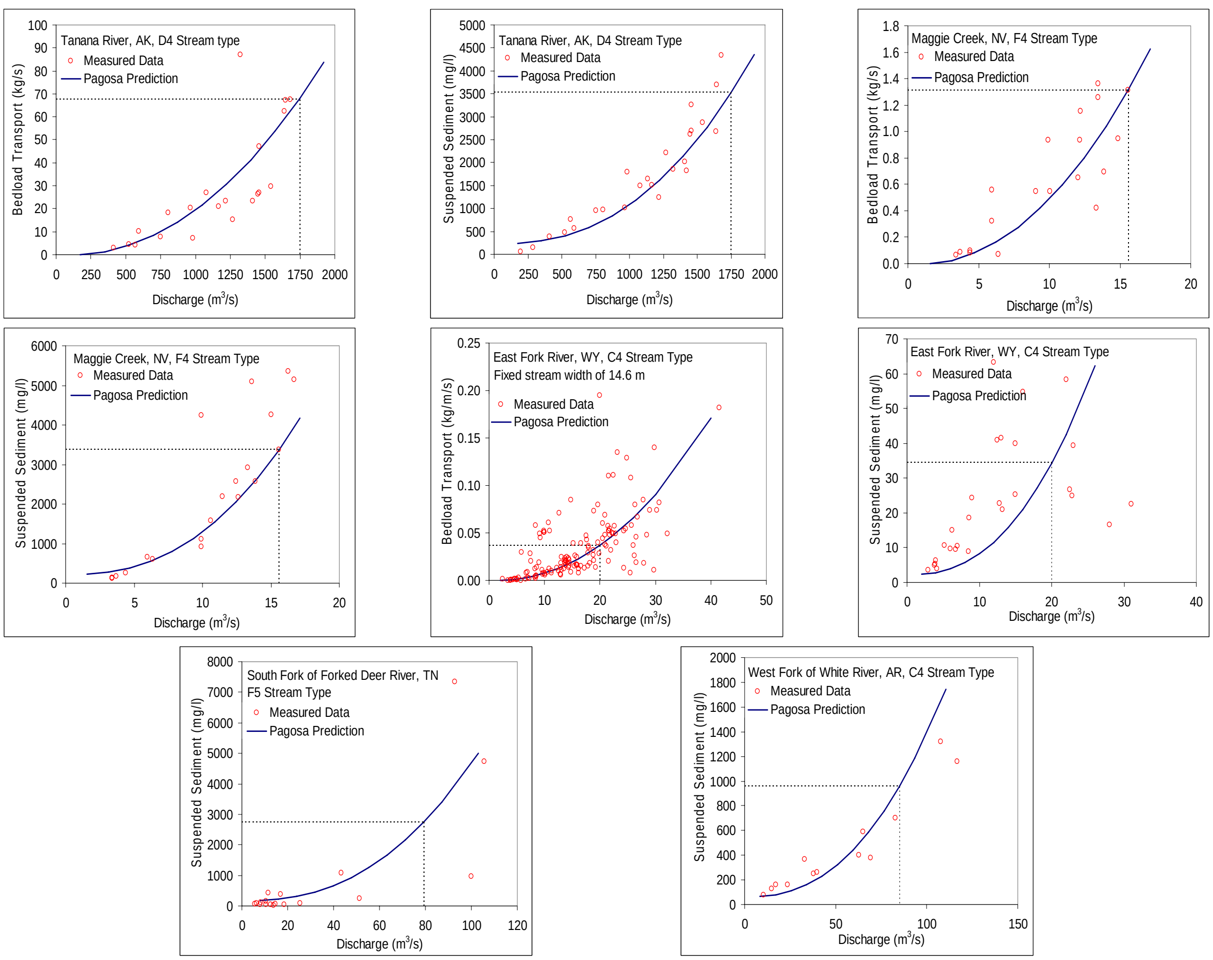


Figure 4 Predicted suspended and bedload sediment rating curves compared to observed data for a wide range of river sizes and geographical areas, using the FLOWSED model.

Field validation of the POWERSED model was recently conducted on Weminuche Creek in Southwestern Colorado. Annual suspended sediment and bedload sediment yield were measured at two locations on the same river for the same flows, but not the same stability. Bedload and suspended sediment, streamflow and hydraulic geometry data were collected concurrently on both reaches over a wide range of flows during snowmelt runoff. The upper reach was a C4 stream type with a width of 9.8 meters, width/depth ratio of 11, slope of 0.0047 and a D_{50} of 33 mm. The lower reach, 0.8 km downstream was a D4 (braided) stream type but of the same flow with a width of 72 meters, width/depth ratio of 412, slope of 0.0026 and a D_{50} of 22mm. The braided reach instability was caused by spraying willows and heavy grazing pressure, which caused excessive streambank erosion and channel aggradation. The braided channel sediment data included measuring 30 cells of individual verticals of suspended sediment and bedload data for a wide range of flows up to two times bankfull stage. Particle size analysis of each vertical was also collected and analyzed. The hydraulic geometry was also measured at each vertical including velocity, width, depth, and slope; used to calculate both discharge and stream power. This data was collected over the entire snowmelt runoff period in 2005 to calculate a transport rate for a range of flows on the braided channel by individual cell as well as for the total annual suspended, suspended sand and bedload transport. The same data was collected at the bridge site on the C4 stream type. Continuous streamflow data was also collected during the runoff season. A 152mm (6 inch) Helley Smith bedload sampler and a DH-48 depth-integrated suspended sediment sampler were used at both sites following standard field and lab analysis techniques. Due to an unusually heavy snowpack, stream flows reached twice the bankfull stage for Weminuche Creek in 2005.

Prediction of the measured suspended (sand) sediment and bedload rating curves for Weminuche Creek are shown in Figure 5. The prediction should be reasonable, as the reference dimensionless sediment rating curves were obtained from Southwestern Colorado, although not from Weminuche Creek. The next prediction represented annual sediment yield for both stream reaches. The same sediment supply function from the upstream C4 stream type was used for the downstream reach to determine how well the downstream reach could accommodate the sediment made available. In the case of the D4 stream type there was a major change in width, depth and velocity for the same discharge, thus a shift in stream power was predicted. The relation between stream discharge and stream power for the C4 and D4 stream type are depicted in Figure 6.

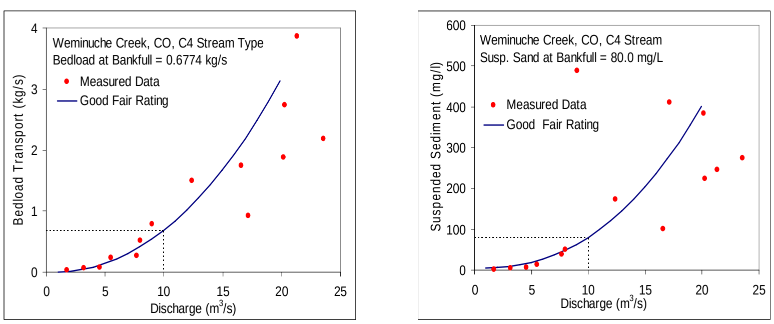


Figure 5 *Left graph*: Predicted suspended sand sediment rating curve compared to observed data. *Right graph*: Predicted bedload sediment rating curve compared to observed data using FLOWSED, C4 stream type, Weminuche Creek, Colorado, 2005.

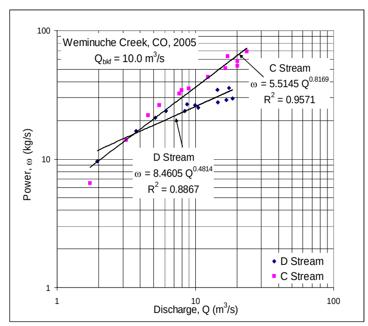
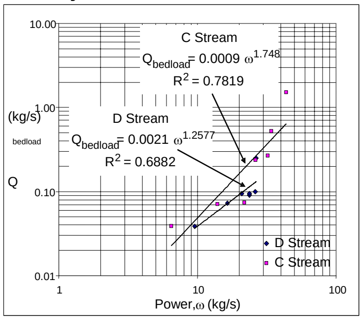


Figure 6 Relationship of stream discharge versus stream power for the C4 and D4 reaches of Weminuche, Colorado, 2005.

The relationship between measured suspended sediment and bedload measurements versus stream power are shown in Figure 7 for each stream type. The D4 stream type stream power data reflects only reach averaged conditions rather than individual cells. The first POWERSED run using $\text{RIVERMorph}_{\text{TM}}$ on the braided reach did not separate the reach into cells across the section, but used reach averaged hydraulic geometry by stages to predict sediment transport. The resultant prediction was very low, (87 tons/year for bedload, 390 tons/year suspended sediment and a total of 477 tons/year, compared to an upstream supply on a C4 stream type of 2,557 tons/year of bedload, 1,852 suspended sediment tons/year, with a total of 4,452 tons/year). The next run, however on the braided reach was subsequently divided into three cells to develop hydraulic geometry and sediment transport separately.

The excellent results for both stream reaches of predicted versus measured values are shown in Table 1. The predicted total sediment yield for the C4 stream type was a 3.1% underestimate. The predicted annual sediment yield for the D4 stream type was 6.0% below the measured values. Predicted bedload was very close to that produced for the C4 and the D4 stream type, as shown in Table 1. These results are very encouraging, as they suggest the field practitioner's ability to rapidly and accurately predict both sand-sized suspended and bedload transport rates and annual yields. The sand portion of the suspended sediment induced deposition on the stream bed when changing from a C4 stream type (1,895 tons/year measured versus 2,153 tons/year predicted), to a braided D4 stream type (878 tons/year measured versus 949 tons/year predicted) represents a reduction in sand size suspended



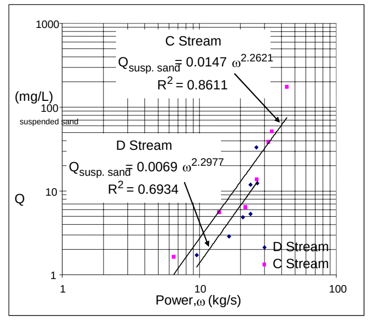


Figure 7 *Left graph*: Relationship of measured bedload sediment to stream power for C4 and D4 stream type. *Right graph*: Relationship of measured suspended sand sediment versus stream power – both relationships from Weminuche Creek, Colorado (2005).

sediment transport of 916 tons/year measured versus 1,275 tons/year predicted. The reduction in bedload transport when changing from a C4 stream type (2,557 tons/year measured versus 2,160 tons/year predicted), to a braided D4 stream type (636 tons/year measured versus 612 tons/year predicted) is 1,921 tons/year for the measured value and 1,548 tons per year for the predicted value. This excess deposition is the result of a reduction in stream power due to the consequence of an increased width to depth ratio (11 for the C4 stream type compared to 412 for the D4 stream type). The change in stream power for the braided D4 stream type was largely due to the reduction of mean depth and velocity. The hydraulic geometry by stage prediction of the POWERSED model closely approximates the measured values. In other words, the combined FLOWSED/POWERSED models not only predict the annual suspended sand and bedload yield, but they also accurately predict the channel consequence of aggradation rate (Table1).

A similar prediction was accomplished on the North Prong of the South Fork of the Mitchell River (12.6 km^2) near Jonesville, North Carolina from work initiated in 2004. The upstream stable reference reach cross-section was used to predict the suspended and bedload sediment using the Pagosa data (Figure 2). A very close agreement between the predicted and measured suspended and bedload data was observed. The downstream, impacted reach had a width/depth ratio of 24-29 compared to a width/depth ratio of 12 for the upstream reference. The POWERSED model indicated that approximately 40% of the total annual sediment yield would be deposited, including sand-sized particles. Twelve permanently monumented cross-sections were resurveyed one year later, all of which showed aggradation ranging from 0.06m to 0.18m and a shift to a higher percentage of sand. Interestingly, the competence of the river was maintained, as a 95-mm particle was predicted to be entrained and 100-mm particles were entrained in the bed, scouring down to 0.12m. The bed subsequently aggraded over the scour chains, depositing excess fine gravel and sand on the recession limb of the hydrograph over the previously installed scour chains. This study and model validation indicated that a stream may have adequate sediment *competence*, but lack the sediment *capacity* to maintain stability. The model was successful in that it predicted an aggradation process that matched field observations.

CONCLUSIONS

The close agreement between predicted versus observed data of both suspended and bedload sediment rating curves is very encouraging. Study results indicate that 1) a reference dimensionless sediment rating curve is appropriate to represent sediment supply in the region being studied; 2) a dimensionless flow-duration curve represents the hydro-physiographic province of the study site; and 3) near bankfull values are obtained in the field to transform the dimensionless relations to dimensional values. Researchers/practitioners could establish a range of dimensionless sediment rating curves for a given region and bankfull suspended and bedload sediment data by drainage area. Continued field measurements and comparisons of model prediction-to-observed values are recommended over a wide range of regions. The initial development and testing of FLOWSED/POWERSED shows promise in predicting river behavior for stability assessment, fish habitat enhancements, bridge design, reservoir studies and river restoration applications.

Table 1 Comparison of predicted suspended (sand), bedload and total sediment loads to measured values for the C4 and D4 stream types on Weminuche Creek, Colorado, 2005.

STREAM LOCATION	PREDICTED VALUES (TONS/YEAR)	MEASURED VALUES (TONS/YEAR)	DIFFERENCE (%)
C4 Stream Type			
Bedload	2,160	2,557	
Suspended load (sand only)	2,153	1,895	
C4 Stream Type Total Sediment Load	**4,313**	**4,452**	**3.1% under**

STREAM LOCATION	PREDICTED VALUES (TONS/YEAR)	MEASURED VALUES (TONS/YEAR)	DIFFERENCE (%)
D4 Stream Type Cell 6.1			
Bedload	547	530	
Suspended load (sand only)	788	806	
Total	1,335	1,336	
D4 Stream Type Cell 6.2			
Bedload	65	104	
Suspended load (sand only)	83	141	
Total	148	245	
D4 Stream Type Cell 6.3			
Bedload	0	2	
Suspended load (sand only)	7	2	
Total	7	4	
D4 Stream Type Total			
Bedload	612	636	
Suspended load (sand only)	878	949	
D4 Stream Type Total Sediment Load	**1,490**	**1,585**	**6.0% under**

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