DEVELOPING A "REFERENCE" SEDIMENT TRANSPORT RELATIONSHIP

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INTRODUCTION

In 1980, the Environmental Protection Agency (EPA) published "An Approach to Water Resources Evaluation of Non-Point Silvicultural Sources" (WRENSS). The document represented a then state-of-the-art approach for watershed analyses and prediction of the impact of non-point silvicultural activities on water quality. Land and water management practices continue to be one of the dominant contributors to water quality impairment through impacts on sediment loading to channel systems and transport process. This report addresses an attempt to develop a "Reference" sediment transport relationship, utilizing existing sediment transport data, that once developed could be used as the basis for documenting departure in impaired watersheds.

OBJECTIVES

There are two objectives, or specific hypotheses:

a. H_o: The reference condition (Natural Range of Variability) sediment transport relationship for stable systems (systems capable of carrying the sediment being delivered without change in dimension, pattern, or profile) can be defined.
b. H_o: In disturbed systems, departure of the sediment transport relationship from the reference condition can be documented.

METHODOLOGY

Attempts to develop a "reference relationship" for sediment transport have been an iterative process that initiated with the historical sediment transport data collected by D. Rosgen and several others and culminated by relying on fewer data sets from intensively studied watersheds elsewhere.

D. Rosgen provided sediment transport data (both bedload and suspended sediment) from approximately 160 watersheds located in Colorado, Wyoming, Alaska, Montana, and Idaho. Not all, but most, of the sites had data for both suspended sediment and bedload. For each of the watersheds the data consisted of a series of paired samples of sediment transport, either concentration of suspended sediment (mg/l) or rate of bedload movement (kg/s), through a cross-section and the discharge rate (cfs) at the time the sediment sample was collected. In addition, descriptive metrics that included channel type (Rosgen 1994), Pfankuch (1975) stability rating, and an estimate of bankfull discharge (the 1.5-year return interval discharge rate) were provided.

The expectation was that the historical, or Rosgen, data set could be useful in defining a reference sediment transport curve, stratified by stream type and stability rating, that could be used to document departure when compared with other systems. At the onset of this analysis, a basic assumption was made that the transport × discharge relationship needed to be presented in a dimensionless format. An assumption made because previous experience (EPA 1980) indicated virtually every stream has a unique sediment transport signature that reflects watershed size, stream type, discharge rate, sediment supply, etc. and transforming the data into a dimensionless form was necessary to diffuse much of this variability.

The process of dimensionless transformation is described in the following sequence for each watershed and sediment type (suspended, bedload). In their dimensional form, suspended sediment is a concentration and expressed in mg/l, bedload transport is a rate and is expressed in kg/s. Discharge, also a rate, is expressed in cfs.

1) Initially a linear model ($y = a + bx$) was fit to the discharge (x) and sediment (y) pairs for each watershed. If the model was not significant, meaning b was determined not to be different than 0, it was concluded that no slope exists in the relationship between sediment transport and discharge for that watershed based on the data available. Therefore, the mean value for transport rate or concentration estimates transport at all flow levels.

These watersheds were dropped from further analyses. If the slope proved to be significantly different than 0, the next step was to determine if a linear model or a power model best described the data by fitting a power function ($y = a + bx^c$) to the data. If *c* was significantly different than 1.00 it was concluded the data were nonlinear in nature. If *c* was not significantly different than 1.00 it was concluded that the linear model sufficiently described the data. As part of the fitting process the studentized deleted residuals from the models were used to test for outliers (Neter, Wasserman, and Kutner 1990). The p-value was set to 0.0001 so that only very extreme outliers were identified. These outliers were then graphically interpreted to only eliminate points that very obviously detracted from the model fit or form.

2) The fitted dimensional transport model for each sediment type and watershed were then used to predict the sediment transport that would occur at the predetermined estimate of "bankfull" discharge, or the 1.5-year event. Each value of sediment transport (y_i) for that watershed was subsequently made "dimensionless" by dividing it by the predicted value of sediment transport at bankfull discharge. The corresponding value of discharge (x_i) for each sediment and discharge pair was also made dimensionless by dividing by the estimate of bankfull discharge. The model fitting process explained above was then repeated for the transformed, dimensionless, data. In virtually every instance the model form remained the same.

   At times, when fitting the power function, there were difficulties in getting the *b* coefficient and the *c* exponent to converge. In these instances, the G-4 option in SAS (1989), which uses the Moore-Penrose inverse in the parameter estimation, was implemented to facilitate the process. Convergence problems can occur when fitting a power model if the coefficient *b* and exponent *c* are correlated. The G-4 option helps with convergence because a singular-value decomposition algorithm is used. It is important to note that for data with a strong nonlinear relationship, the model form and fit are exactly the same with or without using the G-4 option.

3) While finding the best dimensionless transport models for each watershed, the model residuals were examined for homogeneity of variance and normality. Watersheds containing sediment measurements distributed across all levels of discharge did not typically have a serious normality or heterogeneous variance problem. However, there were many sites, some with as few as 5 data points, for which these data were not distributed across all levels of flow. In these instances the range of data and amount of data collected did not allow us to adequately examine residuals, but the models fit appeared appropriate. Sites were then grouped by stream type and stability rating for further analysis. Tests were run to determine if the grouped, or combined, models within stream type and between stability rating classes (GOOD, FAIR, POOR) were similar by using an extra sum of squares analysis for nested models that determines if two or more models are significantly different than the pooled model (Bates and Watts 1988). The subsequent series of analyses compared bedload and suspended sediment transport within stability class, between stability classes, and within and between stream types.

4) The desired end product of the analysis was to be the definition of a reference expression for sediment transport, stratified by stream type, that would define the range of variability in sediment transport over a wide range in flow and from which human induced departure, of a test watershed, could be detected.

RESULTS

Historical Data Sets

Dave Rosgen, (Wildland Hydrology, Pagosa Springs, CO) provided suspended and bedload sediment transport data from approximately 160 watersheds located in Colorado, Alaska, Idaho, and Montana. The data, stored in both his and U.S. Forest Service archives, represented sampling done over the past 30 years. James Nankervis (Blue Mountain Consultants, Berthoud, CO) coordinated the electronic entry of the data, oversaw the verification or revision of either the channel type, as currently characterized by Rosgen, or the Phankuch (1975) stability rating, and determined initial model form. The final data set consisted of the sediment × discharge pairs, stream type, stability rating, and an estimate of bankfull discharge (approximately the 1.5-year maximum instantaneous flow).

Once model fitting for bedload (kg/s) and suspended sediment (mg/l) was completed as outlined, analysis was conducted to determine if the sediment transport relationships characteristic of the watershed were related to either the classification of stream type or the assignment of the Phankuch (1975) stability rating. Most of the more common, but not all stream types, were represented in the watershed sampling and fewer GOOD streams were sampled than FAIR or POOR streams (Figure 1). At first, some of the results of the analysis appeared somewhat unexpected, but understandable. As expected, bedload and suspended load respond to discharge differently and at different rates with suspended sediment being the larger component of the total sediment transport. For bedload transport, however, we failed to show significant differences between dimensionless transport within and between stream types for both GOOD and FAIR stability ratings. Streams with POOR stability ratings exhibit differences within and therefore, by default, between stream types. This implies POOR streams exhibit significantly different dimensionless sediment transport characteristics (departure) from each other as well as from either FAIR or GOOD streams. This pattern was not as clear, or well demonstrated, for suspended sediment transport as there appears to be more inherent variability both within and between stream types and stability rankings. However, the tendency to fail to show departure among streams and between stream types is still quite strong as 86% of all comparisons failed to document departure. Although differences in dimensionless suspended sediment transport appear to exist within stream types, we cannot conclude they are differences attributable to stream type.

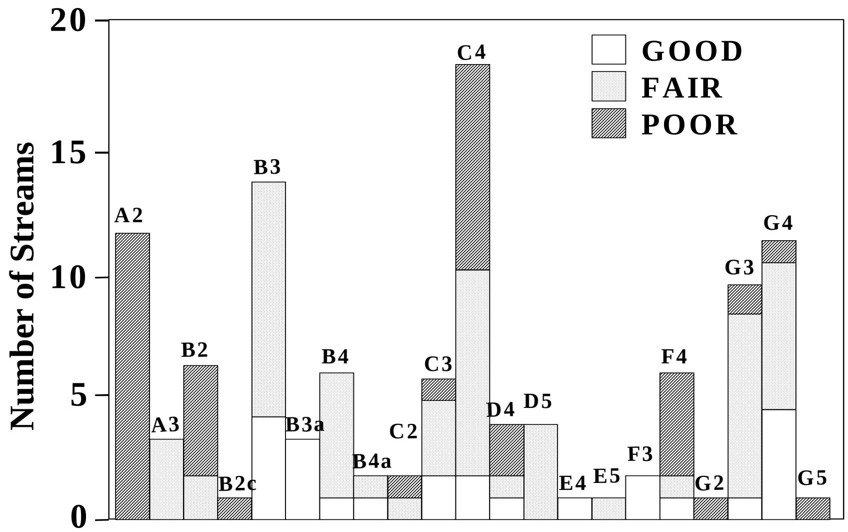

Figure 1. Stream type and channel stability rank.

It must be remembered that differences in the dimensional, or absolute, sediment transport/stream discharge relationship do exist, both within and between stream types and between stability ratings for both suspended and bedload transport. Every stream has its own sediment signature. It would appear that the transformation of data into a dimensionless format compensates for those differences. The similarity of transport response, apparent in the dimensionless format, reflects the continuity of mass and equilibrium that must exist within the system. Intuitively, one would expect continuity across or through stream types, if the system is in equilibrium. That continuity would be disrupted by poor stability caused by human intervention or a catastrophic event, as evidenced by the departure of POOR streams. This instability, or change in sediment supply, could cause either a departure from the dimensionless sediment transport relationship or a change (evolution) in stream type.

Transforming the data into a dimensionless format by dividing all sample pairs by bankfull discharge and sediment transport at bankfull discharge, forces all models through (1,1) on the (X,Y) axis. Although not specifically constrained in the fitting process, all models also tend toward (0,0). Only a few of the watersheds sampled in the historic data set were sampled at flow levels in excess of bankfull, therefore the preceding analysis was not very robust as the models tend to become constrained at both ends of the data range. Thus, there was little opportunity for differences to be documented when the observed range in data did not exceed bankfull, especially if the "best fit model" was linear. To evaluate the significance of this concern, and determine whether definition of a reference relationship was a truly viable concept, data from experimental watersheds at the Fraser Experimental Forest and from the East Fork of the Encampment River in Wyoming were added to the database.

Fraser Experimental Forest (FEF) Data Sets

Suspended sediment and bedload transport have been intensively sampled on numerous FEF experimental watersheds since 1993. To date, 100 or more data pairs for both suspended and bedload transport, are available for each watershed with the distribution of samples virtually encompassing the entire range of flows observed to have occurred over the past 60 years (Troendle and Olsen 1994, Ryan and Troendle 1996, Troendle et al. 1996, Wilcox et al. 1996). Troendle et al. (1996) noted that for only 12 days between 1943 and 1995 did mean daily stream flow from East St. Louis Creek exceed the maximum flow value for which sediment transport had been monitored. Maximum instantaneous flows on the same watershed have exceeded the highest flow sampled less than 25 times.
The experimental watersheds vary in size: Deadhorse Creek (DHOMA) is 640 acres, Fool Creek (LFCRK) is 714 acres, Lexen Creek (LEXEN) is 307 acres, East St. Louis Creek (ELOUI) is 1984 acres, and East Fork Encampment (UEFXS) is 2200 acres. These watersheds also have different geology (granites, sedimentary) and stream order (1^{st} – 2^{nd}). Bedload transport has also been monitored at 6 additional locations along St. Louis Creek, the 4^{th} order stream draining the 23,000-acre Fraser Experimental Forest (Ryan and Troendle 1996). Contributing areas for the 6 sites range from 8,300 to almost 14,000 acres. Bedload transport was monitored from 1992 to 1997 at these cross sections, 3 located above and 3 located below points of water diversion. The range of flows sampled is as intensive as the other FEF sampling. Suspended sediment was not available at the Main St. Louis Creek sites. In general, streams associated with each of the 11 cross sections have a GOOD stability rating with drainage areas from 600 to almost 14,000 acres and Rosgen (1994) Level 1 stream types of A, B, or C.

As with the historical data, sediment transport was transformed and dimensionless models estimated in the manner described earlier. Subsequent analysis failed to demonstrate differences in dimensionless transport × dimensionless discharge models for either suspended sediment (Figure 2) or bedload transport (Figure 3), when compared with the pooled model for all watersheds. A single dimensionless model, one each for suspended sediment (Figure 2) and bedload transport (Figure 3), best describes sediment transport. The datasets for suspended and bedload transport contain 293 and 1124 data pairs respectively. These data extended over a range in discharge that exceeds 2 times bankfull discharge and approaches the 1-in-25 year event. Due to lack of normality and homogeneous variance, bootstrapping methods were used to generate both the regression models (SPSS 1993) and the 95% individual prediction intervals (Stine 1985). The prediction intervals were generated using 5000 bootstrap iterations and then smoothed for presentation purposes. These intervals can be used to assess departure of individual transport × discharge pairs, sampled on other watersheds, from the reference models.

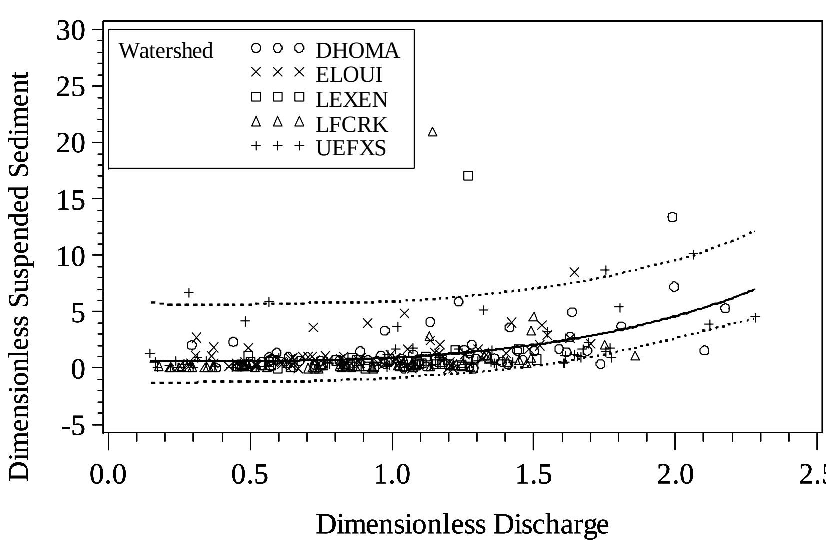

Figure 2. Reference suspended sediment transport model with 95% individual bootstrap prediction intervals.

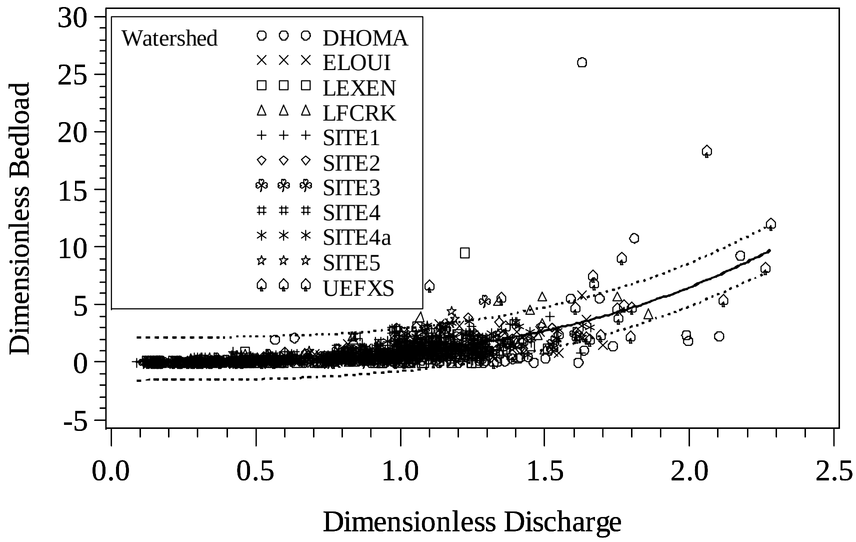

Figure 3. Reference bedload transport model with 95% individual bootstrap prediction intervals.

<u>Testing the Reference Curves</u>

The analysis to this point leads us to acceptance of the hypothesis that a single dimensionless sediment transport model, for either suspended sediment or bedload represents reference dimensionless transport for undisturbed systems. Two additional analyses were conducted as a further test of this hypothesis.

Sediment transport data for the GOOD and FAIR B3 and C3 streams in the historical data set were selected to compare with the reference curves for both suspended and bedload transport developed from experimental data. Dimensionless transport models for the historical data sets for suspended sediment (p=0.95) and bedload transport (p=0.99) were found to be the same as the respective reference relationships (Figures 4 and 5). As noted earlier, one of the deficiencies of the historical data is the limited range in discharge over which the historical data was collected and that limitation is apparent in Figures 4 and 5 as the sampling is skewed to lower flow levels of discharge relative to the reference curve.

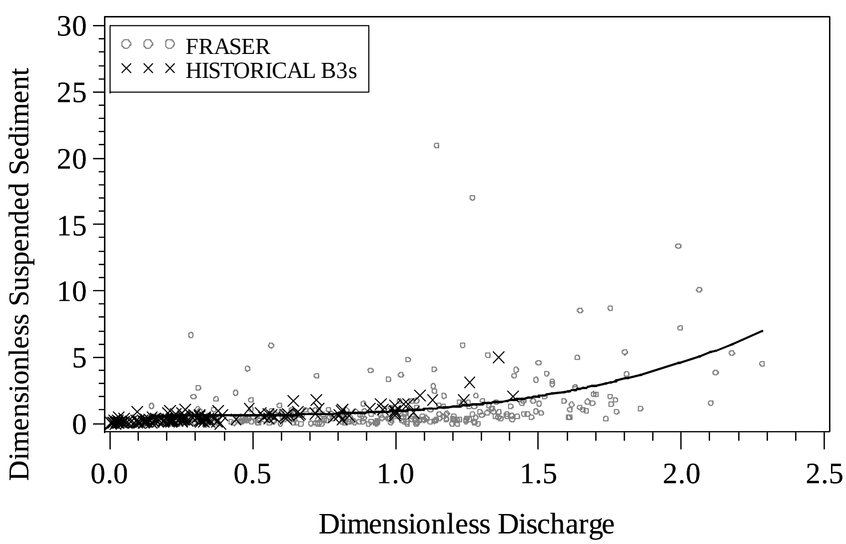

Figure 4. Suspended sediment for all historical B-3 streams plotted over pooled model for reference streams.

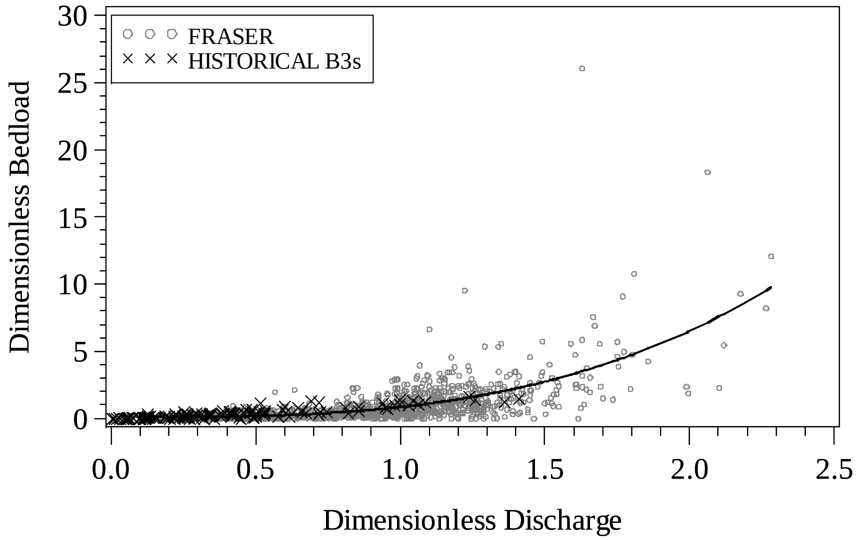

Figure 5. Bedload transport for all historical B-3 streams plotted over pooled model for reference streams.

Although not presented, the outcome was similar for all historical C3 streams as well (p=0.65 for suspended sediment test and p=0.99 for bedload test). This implies little difference exists between the reference curve and the historical data for GOOD and FAIR B3 and C3 streams.

The final assessment of the reference curve evaluated dimensionless suspended and bedload transport data from Coon Creek. Coon Creek is a 4,000-acre partially harvested watershed on the Medicine Bow National Forest, adjacent to Upper East Fork of the Encampment River, one of the reference watersheds. In 1989, roads were constructed in Coon Creek to allow a total of 24% of the watershed to be harvested in small clearcuts in 1990, 1991, and 1992. Suspended sediment and bedload transport from Coon Creek were not monitored until after timber harvest. Both suspended sediment and bedload transport data were collected on Coon Creek in 1993 and 1995 (Wilcox et al. 1995)

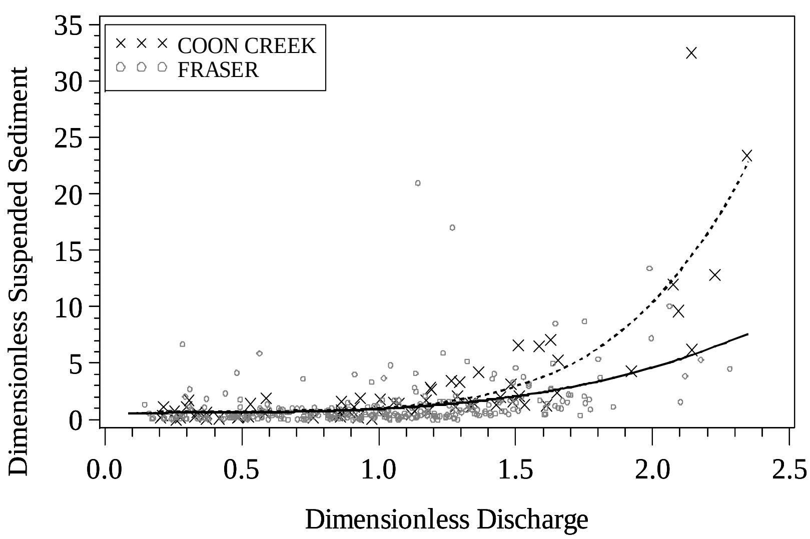

Figure 6. Comparison of the dimensionless suspended sediment model for Coon Creek and the pooled model for reference conditions.

Dimensionless suspended and bedload transport models were estimated for Coon Creek and compared with the pooled model for the respective reference condition. The dimensionless supended sediment model for Coon Creek significantly differs ($p<0.0001$) from those comprising the reference condition (Figure 6). In contrast, the dimensionless bedload transport relationship for Coon Creek (Figure 7) does not significantly differ from the reference curve. However, it should be noted that the p-value associated with differences between the 12 streams comprising the reference bedload transport curve is 0.94. Adding the 13th stream, Coon Creek, causes the p-value to drop to 0.17. The addition of the Coon Creek model increased departure, although not to the level of significance at $p = 0.05$.

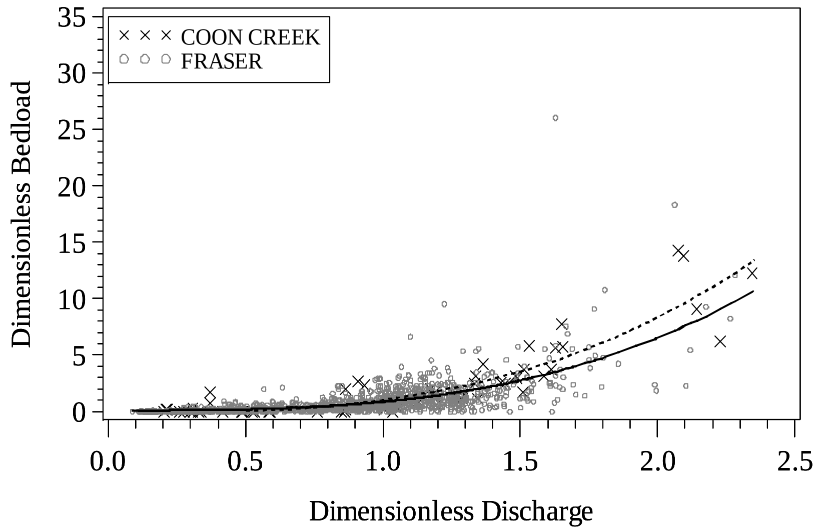

Figure 7. Comparison of the dimensionless bedload transport model for Coon Creek and the pooled model for reference conditions.

SUMMARY

The “Reference Sediment Transport” functions for suspended sediment and bedload transport appear to function well and indicate departure can be demonstrated. An interesting outcome of the analysis was the lack of ability to show differences in dimensionless sediment transport attributable to stream type. At first, this seemed inconsistent with expectations. Upon review, the outcome seems intuitively appropriate. If bankfull discharge is in fact the flow that maintains channel geometry and if streams in equilibrium are those that carry the sediment being delivered to them, then there should be continuity, even similarity, in the dimensionless sediment transport functions. Thus, sediment passing through one reach is passed on to the next, and so on, in a continuum. The same is true with flow. Unless a particular reach is unstable, the material is passed on with minimal deposition or scour. Where there is instability, aggradation or degradation occurs and the channel is in disequilibrium and the Rosgen Level 1 channel type changes. As channel morphology changes and stream type evolves, a new equilibrium is reached, and continuity appears to resume. As a working hypothesis, the reference curves should be a useful prototype in detecting departure while instability is present. If data pairs are available for a study stream and dimensionless transport $\times$ discharge can be calculated, the dimensionless data pairs can be plotted individually on the reference curve. The determination can then be made as to whether the individual point falls within or outside of the 95% prediction interval. If departure occurs, this may imply the study watershed is impaired and the sediment transport model for the study watershed warrants further investigation. Once a channel type change occurs (e.g. a C3 degrading to a G4) the sediment transport for the study watershed may not indicate departure. In the latter case, departure is better defined by knowing the channel type has been forced to evolve. Analysis of the historical data, as well as the Coon Creek test case, documents that departure in sediment transport from impaired streams from the reference condition can be detected. Departure implies channel instability, often do to either a change in sediment supply or flow regime. Instability may foster an evolution in stream type.

The dimensionless sediment transport curves can be transformed into a dimensional form, specific to any watershed, by reversing the transformation process. At a minimum, an estimate of the bankfull discharge and at least 1 sediment transport × discharge pair must be available for the watershed of concern, and ideally the discharge pair taken should be at or near bankfull discharge. In any event, the dimensionless discharge for the sediment sample collected is calculated by dividing the sample discharge rate by the bankfull discharge rate. The ratio, or dimensionless discharge estimate (x), can then be entered on the appropriate dimensionless sediment transport curve to determine the dimensionless sediment transport associated with the sample discharge. An alternative is to use the prediction model also presented on Figure 2 or 3 to estimate the dimensionless sediment transport directly. Once the dimensionless sediment transport ratio (sediment transport divided by the sediment transport at bankfull) is determined, the observed estimate of sediment transport (dimensional) is divided by the sediment transport ratio to estimate the dimensional sediment transport that should be expected at bankfull discharge. The scale on the (X,Y) axis on the dimensionless reference curve can be transformed into dimensional values by multiplying by the estimate of bankfull discharge (X axis) or by the estimate of sediment transport at bankfull discharge (Y axis). The dimensional curve represents an estimate of the sediment transport curve for the watershed of interest. Any additional sediment × discharge pairs can then be plotted over the predicted curve to validate appropriateness of fit.

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