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How the Choice of Bed Material Load Equations and Flow Duration Curves Impacts Estimates of Effective Discharge

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A thesis submitted to the faculty of
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Master of Science

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ABSTRACT

How the Choice of Bed Material Load Equations and Flow Duration
Curves Impacts Estimates of Effective Discharge

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The purpose of this study is to analyze how estimates of an important geomorphic parameter, effective discharge, are impacted by the choice of bed material load equations and flow duration curves (FDCs). The Yang (1979), Brownlie (1981), and Pagosa equations developed by Rosgen (2006) were compared for predicting bed material load. To calculate the bed material load using the Pagosa equations, the bedload and suspended load are calculated separately and the results are added together. To compare the effectiveness of the equations, measured bed material load data from the USGS Open-File Report 89-67 were used. Following the calculations, the equation results were compared to the measured data. It was determined that the Pagosa equations performed the best overall, followed by Brownlie and then Yang. The superior performance of the Pagosa equations is likely due to the equations being calibrated.

USGS regression equations for FDCs were compared to a method developed by Dr. David Rosgen in which a dimensionless FDC (DFDC) is developed. Weminuche Creek in southwestern Colorado was used as the study site. Rosgen's DFDC method requires the selection of a streamgage for a stream that exhibits the same hydro-physiographic characteristics as the site of interest. An FDC is developed for the gaged site and made dimensionless by dividing the discharges by the bankfull discharge of the gaged site. The DFDC is then made dimensional by multiplying by the bankfull discharge of the site of interest and the resulting dimensional FDC is taken as the FDC of the ungaged site. The USGS regression equations underpredicted the discharges while Rosgen's DFDC method overpredicted them. Rosgen's DFDC method produced more accurate results than the USGS regression equations for Weminuche Creek.

To calculate the effective discharge, the FDC was used to develop a flow frequency curve which was then multiplied by the sediment rating curve. Effective discharge calculations were performed for Weminuche Creek using several combinations of bed material load prediction equations and FDCs. The USGS regression equations, Rosgen's DFDC method, and streamgage data were all used in conjunction with the Yang and Pagosa equations. The Brownlie equation predicted zero bed material load for Weminuche Creek, and was thus not used to calculate the effective discharge. When the USGS regression equations were used with the Yang and Pagosa equations, the calculated effective discharge was approximately 4.5 cms for both bed material load prediction equations. When Rosgen's DFDC method and streamgage data were used with the Yang and Pagosa equations, the effective discharge was approximately 13.5 cms. From these results, it was determined that the bed material load prediction equations had little impact on the effective discharge for Weminuche Creek while the FDCs did influence the results.

Keywords: bed material load, sediment transport, sediment rating curve, Yang, Brownlie, Rosgen, flow duration curve, effective discharge

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1 INTRODUCTION

1.1 Objective

The purpose of this study is to analyze how estimates of an important geomorphic parameter, effective discharge, are impacted by the choice of bed material load equations and flow duration curves (FDCs). Several equations and procedures for computing these inputs will be compared to the measured data. The quantity of sediment that is transported within a stream determines its shape, planform, and stability (Leopold et al, 2012). Sediment transport within streams is important to consider in conjunction with stream restoration, reservoir sedimentation, bank erosion, and aquatic habitat, among others. For such purposes, a number of sediment transport prediction equations have been developed that can be used to predict the amount of sediment that will be transported within streams. The equation inputs are often the hydraulic variables associated with the stream.

In addition to estimating the quantity of sediment that is transported within a stream, knowledge of stream discharge and its frequency of occurrence is also important to consider. Hydropower production, water availability, and aquatic organism and fish habitats are all dependent on the magnitude of discharge. The development of FDCs allows the exceedance probability that is associated with varying stream discharges to be determined. Because most streams are not gaged, the ability to develop FDCs for ungaged areas is essential. Several methods exist for creating FDCs for ungaged sites; input parameters for such methods may include hydrologic or hydraulic variables.

Effective discharge is the product of sediment transport and flow duration. Effective discharge is sometimes equated to channel forming discharge, which is the theoretical discharge that would transport the same quantity of sediment over time as the variable flows within a stream if allowed to continuously flow (Goodwin, 2004). The effective discharge controls the morphology of the stream and is thus responsible for size and shape of the stream channel. The calculation of effective discharge is fundamental to all stream restoration efforts.

1.2 Scope

Various bed material load prediction equations were used to estimate the quantity of sediment that would be transported in a number of United States streams. The accuracy of each equation was assessed by calculating the error associated with each measurement. Methods were also compared for creating FDCs for an ungaged site in southwestern Colorado. The predicted FDCs were compared to an FDC developed using USGS streamgage data. Finally, the effective discharge of the site in southwestern Colorado was calculated using various combinations of FDCs and bed material load prediction equations. The methods detailed herein can easily be applied to other locations when required data are available.

1.3 Effective Discharge

The calculation of the effective discharge of a stream is simple and can be done using three steps: (1) create an FDC using stream discharge data, (2) create a sediment rating curve using sediment data or a sediment transport prediction equation, and (3) integrate the FDC and sediment rating curve to produce a histogram whose peak represents the effective discharge (United States Department of Agriculture, 2007). The size and shape of stream channels, such as Salina Creek in Utah pictured in Figure 1, are determined by the effective discharge.

Figure 1: Salina Creek in Utah

1.4 Report Outline

The remainder of the report includes a literature review, the bed material load equations, the data sources and selection, the computational methodology, results, discussion, and conclusions and recommendations.

2 LITERATURE REVIEW

The comparison of sediment transport prediction equations is not a new concept. Studies have been conducted in which the performance of several sediment transport equations has been assessed. Nakato (1990) conducted a study in which the Ackers and White (1973), Einstein and Brown (1950), Engelund and Fredsoe (1976), Engelund and Hansen (1976), Inglis and Lacey (1968), Karim (1981), Meyer-Peter and Mueller (1948), Rijn (1984), Schoklitsch (1935), Toffaleti (1969), and Yang (1976) sediment transport equations were all compared. The equations in the study included those for estimating bedload, suspended load, and total load. Field data collected at two USGS streamgages on the Sacramento River in California were used to compare the eleven equations. The author concludes that because estimating sediment transport within streams is difficult, hydraulic engineers should carefully consider which equation to employ. It is important to evaluate several equations using field data before making a final choice of which equation to use.

Brownlie (1981) also conducted a study in which the Ackers and White (1973), Bagnold (1966), Bishop et al (1965), Einstein (1950), Engelund and Fredsoe (1976), Engelund and Hansen (1967), Graf (1971), Laursen (1958), Ranga Raju et al (1981), Rottner (1959), Shen and Hung (1971), Toffaleti (1968), and Yang (1973) equations for predicting bed material load were compared. Included amongst the equations was the approach developed by Brownlie using both flume and field data. The results of the comparison study showed that the Brownlie equation was effective in predicting bed material load for the streams in the study.

The fall velocity of sediment particles may impact suspended sediment transport within a stream. Determining the fall velocity of sediment particles within a fluid requires an iterative approach as the fall velocity of individual particles may be affected by nearby particles, coalescence, or proximity of the particle to the edge of the study container. To simplify the determination of fall velocity, equations which eliminate the traditional iterative approach have been developed. Cheng (1997) and Zhiyao et al (2008) both developed simplified settling velocity formulas based upon the Stokes fall velocity for laminar flows.

Flow duration curves are often needed for ungaged stream reaches. To develop FDCs for ungaged streams, the USGS has developed a series of calculation methods for different regions of the United States. Among the regions for which methods have been developed to produce FDCs for ungaged sites are the Connecticut River Basin, Colorado, New York, Massachusetts, and Pennsylvania (Archfield et al, 2012; Capesius and Stephens, 2009; Gazoorian, 2015; Archfield et al, 2010; Stuckey, Koerkle, and Ulrich, 2014). Some regions, such as Colorado, have regression equations that can be applied to calculate specific exceedance probabilities, while other regions, such as the Connecticut River Basin, involve procedures that require spreadsheets that are available for download from the USGS website.

Flow duration curves are used for a variety of applications. The United States Federal Highway Administration employs FDCs for culvert design for aquatic organism passage and for design for fish passage at roadway-stream crossings (*Federal Highway Administration,* 2010; *Federal Highway Administration,* 2007). Aquatic organism and fish passage is highly dependent on stream discharge. Flow duration curves can be used to determine the exceedance probabilities that are associated with the high and low flows within a stream that are suitable for aquatic organism and fish passage.

The channel forming discharge of a river can be calculated using the river's associated sediment rating curve and FDC. Doyle et al (2007) explained that three common channel forming discharge surrogates are (1) effective discharge, (2) bankfull discharge, and (3) return interval discharge (generally ranging from one to two years). The authors compared the three channel forming discharge calculations at four sites. Agreement levels between the three channel forming discharge measurements varied by site and were found to be the most similar in snowmelt-driven, non-incised channels with coarse beds. The authors concluded that although the effective discharge calculation required the most data and analysis, the results provided the greatest information on channel processes.

Crowder and Knapp (2005) calculated the channel forming discharge for several streams in Illinois. Effective discharge was calculated using both the power curve method, which involves multiplying the sediment rating curve by the flow frequency curve produced from an FDC, and the mean approach. In the mean approach, a sediment load versus discharge plot is created with discharge class intervals on the abscissa. The sediment loads within each of the discharge class intervals are averaged and are multiplied by the flow frequency curve to determine the effective discharge. The authors found that although the 1.5-year flow is often used as the bankfull discharge to represent the channel forming discharge, the power curve and mean approaches calculated the effective discharge to be larger than the mean flow, but smaller than the 1.1-year flow.

Lenzi et al (2006) performed a channel forming discharge study on the Rio Cordon River in the Italian Alps. Both the power curve and mean approaches were used to calculate the effective discharge. The authors found that the number and size of the discharge intervals greatly affected the magnitude of the effective discharge when using the power curve method. They also found that the effective discharge calculated using suspended sediment produced an effective discharge that was much smaller than the bankfull discharge, which suggests that suspended sediment plays a smaller role than the bedload in channel forming processes.

Wolman and Miller (1960) studied the impact of extreme or catastrophic events on geomorphic processes in rivers. As natural channels were observed, the shape and dimensions of the channels appeared to be the result of flows at or near the bankfull flow. The authors suggested that because bankfull flow occurs on average once every year or two, flowrates at or near the bankfull flow have the largest impact on the shape and dimensions of a stream channel. Thus, in the channel forming process, the smaller, more frequent flood events carry greater amounts of sediment in the long run than the larger, more infrequent, catastrophic floods events.

3 BED MATERIAL LOAD EQUATIONS

Effective discharge requires estimates of bed material discharge. In this study, the bed material load in rivers was calculated using three common but different prediction equations. The results of the three equations were compared to both each other and to the field-measured bed material load associated with each stream. The impact of the equations on the calculation of effective discharge was then determined.

3.1 Yang Unit Stream Power Equation for Total Load

Yang (1973) developed a unit stream power equation for estimating total sediment concentration. Criteria for incipient motion was incorporated into the equation to improve its accuracy. However, because of the difficulty in determining incipient motion conditions, Yang (1979) later adapted the equation for use without incipient motion criteria for total sediment concentrations greater than 100 parts per million (ppm). The Yang equation incorporates the hydraulic parameter of stream power. It can be applied to both small and large alluvial streams with a variety of bed forms. The equation takes the form:

$$\log(C_{est}) = 5.165 - 0.153\log\left(\frac{\omega d}{\nu}\right) - 0.297\log\left(\frac{U^*}{\omega}\right) + \Big[1.780 -$$

$$0.360\log\left(\frac{\omega d}{\nu}\right) 0.480\log\left(\frac{U^*}{\omega}\right)\Big]\log\left(\frac{VS}{\omega}\right) \quad (1)$$

Where

C_{est} = computed total concentration [ppm]

ω = terminal fall velocity of sediment particles [m/s]

d = median sieve diameter of bed surface sediment [m]

ν = kinematic viscosity of water [m^2/s]

U* = shear velocity [m/s]

V = mean flow velocity [m/s]

S = slope [m/m]

VS = unit stream power [m/s]

3.2 Brownlie (1981) Equation

The Brownlie (1981) equation was developed using both flume and field data and uses both the grain Reynolds number and the grain Froude number. The data used to develop the Brownlie equation and to compare it to other sediment transport prediction equations consisted of sediment in the sand size range with median particle diameters ranging from 0.062-2 mm. In addition to the median bed surface particle size, Brownlie's equation also requires the geometric standard deviation of bed surface particle sizes. When compared to the other equations in Brownlie's study, the Brownlie equation performed well. The equation takes the form:

$$C = 7115 c_f \left(F_g - F_{g0}\right)^{1.978} S^{0.6601} \left(\frac{r}{D_{50}}\right)^{-0.3301} \tag{2}$$

Where

C = mean sediment concentration [ppm]

c_f = coefficient for field data; 1 for laboratory data and 1.286 for field data

S = slope [m/m]

r = hydraulic radius [m]

D_{50} = median sieve diameter of bed surface sediment [m]

$$F_g = \frac{V}{\sqrt{\frac{(\rho_s - \rho) g D_{50}}{\rho}}}$$

F_g = grain Froude number [dimensionless]

V = mean flow velocity [m/s]

ρ_s = density of sediment [kg/m^3]

ρ = density of water [kg/m^3]

g = acceleration of gravity [m/s^2]

$$F_{g0} = 4.596 {\tau_{*0}}^{0.5293} S^{-0.1405} \sigma_g^{-0.1606}$$

F_{g0} = critical grain Froude number [dimensionless]

σ_g = geometric standard deviation of particle sizes [dimensionless]

$$\tau_{*0} = 0.22Y + 0.06(10)^{-7.7Y}$$

τ_{*0} = critical dimensionless shear stress for initiation of motion

$$Y = \left(\sqrt{\frac{\rho_s - \rho}{\rho}} (R_g) \right)^{-0.6}$$

$$R_g = \frac{\sqrt{g D_{50}^3}}{\nu}$$

R_g = grain Reynolds number [dimensionless]

3.3 **Pagosa Good/Fair Equations**

Rosgen (2006) developed equations for predicting suspended load and bedload for streams with so-called good/fair bank stability, both of which are based on field data. The data used for developing the equations was collected from Wolf Creek, Fall Creek, and the West Fork River near Pagosa Springs in Colorado. The equations developed by Rosgen are commonly known as the Pagosa equations for suspended sediment and bedload. The bed material load in a stream can be determined using the Pagosa equations by individually calculating the suspended load and bedload and then adding the two resulting values together. The Pagosa equations require the bankfull discharge and sediment loads of the river as input values. The suspended load equation is:

$$G_* = 0.0636 + 0.9326\ Q_*^{2.4085} \tag{3}$$

Where

G_* = suspended sediment transport term equal to the ratio of the given transport rate to the transport rate at bankfull [dimensionless]

Q_* = discharge term equal to the ratio of the given discharge to the bankfull discharge [dimensionless]

The Pagosa bedload equation is:

$$G_* = -0.0113 + 1.0139\ Q_*^{2.1929} \tag{4}$$

Where

G_* = bedload transport term equal to the ratio of the given transport rate to the transport rate at bankfull [dimensionless]

Because the Pagosa equations require the known measurements of bankfull discharge and the sediment transport rate at bankfull, the equations are termed calibrated. The performance of calibrated equations is often superior to the performance of uncalibrated equations as calibrated equations are based upon known field measurements. It was thus expected that the Pagosa equations would perform well in this study.

4 DATA SOURCES AND SELECTION

Four important sources of data for bed material load were reviewed for possible use in this study. Shah-Fairbank (2009) developed a new method for calculating total sediment discharge based upon the Modified Einstein Procedure. The new procedure is a series expansion of the Modified Einstein Procedure. Flume data are from Coleman and from Guy, Simons, and Richardson. Field data are from 93 United States streams in a USGS report; Idaho rivers; the South Platte, North Platte, and Platte Rivers in Colorado and Nebraska; the Niobrara River near Cody, Nebraska; the Enoree River in South Carolina; the Middle Rio Grande in New Mexico; and the Mississippi River.

In the USGS Open-File Report 81-207 (Kircher, 1981), data are provided for the South Platte River in Colorado and Nebraska and the North Platte and Platte Rivers in Nebraska and consist of suspended sediment, bedload, and bed material load. Hydraulic variables of the streams such as discharge, depth, and velocity are additionally provided as well as sediment concentrations and particle size distributions of the suspended sediment, bedload, and bed material load.

Nordin (1964), Nordin and Beverage (1965), and Nordin and Dempster (1963) studied sediment transport in the Rio Grande in New Mexico. Sediment concentrations were both observed and calculated using hydraulic data from the Rio Grande. Flow resistance and velocity profiles were also studied. Sediment data from the studies were reported in papers published by the USGS.

In the USGS Open-File Report 89-67, the bedload and suspended load for 93 United States streams is presented along with the associated hydraulic variables (Williams and Rosgen, 1989). The report contains measurements for water discharge, mean flow velocity, water surface width, mean flow depth, water surface slope, water temperature, suspended sediment concentration, suspended load, and bedload. In addition to the bedload, suspended load, and hydraulic variables, the particle size distributions for the suspended load, bedload, and bed material load are provided.

In addition to the properties of water such as the density, kinematic viscosity, and unit weight required for the Yang, Brownlie, and Pagosa equations, the D_{16}, D_{50}, and D_{84} particles sizes, mean depth, slope, mean velocity, bankfull discharge, and bankfull sediment transport rates were also required for the three equations. Because the USGS Open-File Report 89-67 by Williams and Rosgen contained the needed hydraulic variables for the equations for a variety of streams in the United States, this report was chosen for this study.

5 METHODOLOGY

5.1 Sediment Transport Calculations

Data from the USGS Open-File Report 89-67 were used to test the performance of the three bed material load equations. For the sites in the open-file report, the bedload for all but one site was measured using a Helley-Smith sampler. The bedload for Oak Creek near Corvallis, Oregon was measured using a slot or pit sampler. Suspended loads were measured at 3-20 verticals across the channel width using D-49, D-74, DH-48, P-61, or P-63 depth-integrating discharge-weighted samplers for each of the sites. Of the 93 sites contained in the open-file report, 20 were used to test the performance of the three equations. The 20 sites that were used to test the equations contained 306 sediment transport measurements. Sites that were missing hydraulic variable measurements required by one or more of the three prediction equations or sites with median particle sizes outside of the range used to develop and test the Brownlie equation were not used. Streams used for the comparison were located in Alaska, Idaho, Colorado, and Wisconsin.

Log-linear interpolation was used to determine the D_{16} and D_{84} particle sizes for calculating the geometric standard deviation for the Brownlie equation and the D_{50} particle size for the Yang and Brownlie equations. The chosen equations required particle sizes of the bed surface material. For this study, it was assumed that because there was sufficient suspended sediment within the streams to merit measurement, there was negligible streambed armoring. It was therefore assumed that the particle size distribution of the bedload was representative of the particle size distribution of the bed surface material. Thus, in comparing the three equations, the particle size distribution of the bedload was used to determine the needed particle sizes.

The Brownlie equation required the hydraulic radius, however the USGS Open-File Report 89-67 did not contain data for the hydraulic radius. Because neither hydraulic radius nor the cross-sectional area and wetted perimeter necessary to calculate the hydraulic radius were available in the data, the mean flow depth was used in place of the hydraulic radius parameter.

The Pagosa equations required stream and sediment discharge at bankfull conditions. Because bankfull measurements were not contained in the USGS Open-File Report by Williams and Rosgen, the measurements for bankfull discharge, bankfull suspended sediment, and bankfull bedload were all obtained directly from the authors for many of the sites in the report.

Results from the Yang, Brownlie, and Pagosa equations were used to create sediment rating curves for each of the 20 sites and were compared to USGS Open-File Report collected data. Sediment rating curves allow for a quick visual assessment of predicted results.

A commonly employed statistical approach for comparing the difference between predicted and measured values is the root mean square error (RMSE):

$$RMSE = \sqrt{\frac{\sum_{i=1}^{n}\left(x_{p,i}-x_{m,i}\right)^2}{n}} \tag{5}$$

Where

x_p = predicted sediment transport rate [kg/s]

x_m = measured sediment transport rate [kg/s]

n = number of samples

One issue associated with the RMSE method is that the errors associated with higher stream discharge values (and thus higher bed material load transport rates) are accentuated. For example, the difference between two larger values of bed material load will result in a larger error than the difference between two smaller values of bed material load even though the percent differences are the same. Thus, the magnitude of the values used in the RMSE equation create a bias in the calculations.

To eliminate the potential bias associated with the RMSE method, a base-10 logarithmic transform was applied to both the predicted and measured bed material load values. To avoid numerical error, a value of 1 was added to each of the predicted and measured values for instances in which zero bed material load was measured or predicted. After applying the log transform, the RMSE was calculated, which is known as the root mean square error of the logarithmic values (RMSEL):

$$\mathrm{RMSEL} = \sqrt{\frac{\sum_{i=1}^{n}\left[\log_{10}(x_{p,i}) - \log_{10}(x_{m,i})\right]^2}{n}} \tag{6}$$

This approach reduces bias and is a more stable method to compare measured and predicted results.

5.2 **Flow Duration Curve Development**

Flow duration curves describe the probabilities that are associated with stream discharges of interest. When a stream is gaged, the FDC is easily developed using the measured discharge data. However, FDCs are often needed for stream reaches with no gage information making it necessary to estimate the FDC. A number of regression equations have been developed by the USGS and a unique method was developed by Dr. David Rosgen of Wildland Hydrology in which dimensionless flow duration curves (DFDCs) are created.

To compare the accuracy of the USGS regression equations and the DFDC method developed by Rosgen to measured data, an FDC was first created using measured streamgage data for Weminuche Creek in southwestern Colorado. Flow duration statistics were calculated using 12 years of gage information and USGS StreamStats.

USGS StreamStats was also used to create an FDC using the USGS regression equations. The equations are based on watershed- and meteorologically-based variables and thus represent a hydrologic-based method. The drainage area of Wemiuche Creek is approximately 40.6 square miles with a mean annual precipitation of 29.93 inches. Because the mean annual precipitation for the Weminuche Creek watershed varies by location due to differences in elevation, USGS StreamStats provides the mean annual precipitation that is associated with the average elevation of the watershed. The USGS regression equations for the southwest region of Colorado are:

$$Q_{10} = 10^{-5.44} A^{1.02} P^{3.79} \quad (7)$$

$$Q_{25} = 10^{-5.27} A^{1.00} P^{3.40} \quad (8)$$

$$Q_{50} = 10^{-5.08} A^{0.98} P^{3.01} \quad (9)$$

$$Q_{75} = 10^{-5.99} A^{1.02} P^{3.37} \quad (10)$$

$$Q_{90} = 10^{-7.30} A^{1.01} P^{4.11} \quad (11)$$

Where

A = drainage area [mi^2]

P = mean annual precipitation [in]

The southwest region of Colorado is one of five regions created by the USGS in developing the Colorado regression equations. A map of the five regions, four of which have regression equations, and their corresponding regression equations are provided in APPENDIX A. The largest discharge calculated by the USGS regression equations is associated with the 10 percent exceedance. However, because the discharges associated with the exceedance probabilities below 10 percent are high and transport large quantities of sediment, it was essential to include them for the effective discharge calculations.

To determine the discharges below the 10 percent exceedance for the FDC developed using the USGS regression equations, the relationship between the USGS regression equations and the measured streamgage data was calculated. The difference in discharge was found to be approximately equal for each of the USGS regression equation exceedance probabilities. Ratios were established between the USGS regression equations and streamgage discharges for probabilities greater than 50 percent. The average of the ratios was 0.32. The streamgage discharges below the 10 percent exceedance were reduced by this ratio to estimate discharges to be used in conjunction with the regression equations. The extended FDC is show in Figure 2.

Rosgen's DFDC method requires the identification of a gaged stream that exhibits the same hydro-physiographic characteristics as the stream of interest and measurements at bankfull conditions. This method can be referred to as being geomorphic-based. An FDC is created for the gaged stream using the streamgage data. A DFDC is then created by dividing the discharges of the FDC for the gaged site by the bankfull discharge of the gaged site. If the mean daily flow on the day bankfull discharge occured is less than the bankfull discharge, a ratio of mean daily flow to bankfull discharge is taken and the bankfull discharge is decreased by the ratio to make the DFDC.

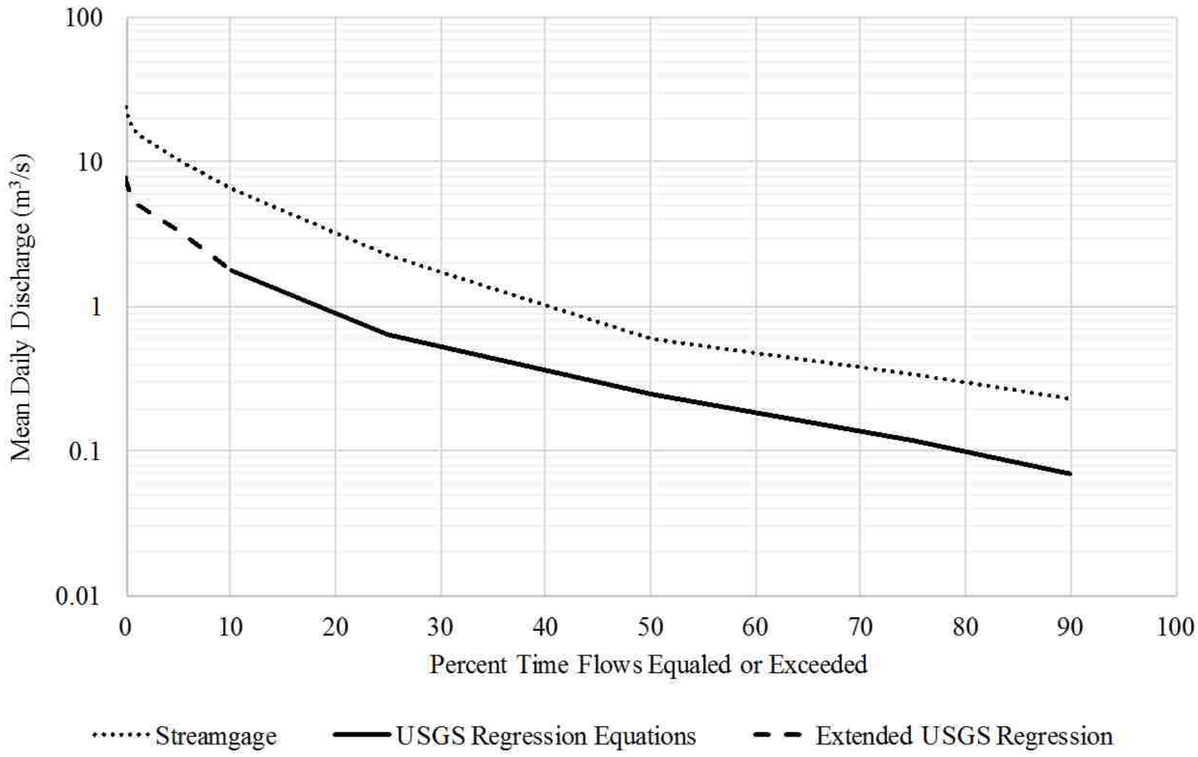

Figure 2: Extended USGS Regression Equation FDC

To create the FDC for the ungaged site, the dimensionless discharges of the DFDC are multiplied by the bankfull discharge of the ungaged site. If the mean daily discharge at the gage was less than the bankfull discharge at the gage on the day bankfull discharge occurred, the bankfull discharge at the ungaged site is first reduced by the aforementioned ratio. The reduced bankfull discharge is then used to make the FDC for the ungaged site.

Wolf Creek was used as the stream with the same hydro-physiographic characteristics as Weminuche Creek. An FDC for Wolf Creek was created using a USGS streamgage. The bankfull discharge at the Wolf Creek gage site was approximately 6 cubic meters per second (cms) and was used to create the DFDC. Because Wolf Creek is a snowmelt-dominated system, the ratio between mean daily flow and bankfull discharge at the site was 1.0. Thus, the bankfull discharge for Wolf Creek did not need to be reduced before the DFDC was created.

Once the DFDC was created, the dimensionless discharges were multiplied by the bankfull discharge of Weminuche Creek of approximately 10.8 cms to make the curve dimensional. The resulting FDC was taken as the FDC of the ungaged site.

5.3 **Effective Discharge Calculations**

To calculate the effective discharge for Weminuche Creek, the FDC was used to develop a flow frequency curve, which was multiplied by the sediment rating curve. Flow frequency curves were made using the FDCs developed using the USGS regression equations, Rosgen's DFDC method, and streamgage data. Log-linear interpolation was used to calculate the discharges between the exceedance probabilities calculated by the USGS regression equations.

The discharges from the FDCs were divided into class intervals to create flow frequency curves. A total of 25 class intervals were used for each FDC according to the method outlined by Crowder and Knapp (2005). Following the determination of the number of class intervals, the log interval method was used to determine the size of the intervals.

$$I = \frac{\log(Q_{max}) - \log(Q_{min})}{n} \quad (12)$$

Where

I = log interval [log m^3/s]

Q_{max} = maximum discharge [m^3/s]

Q_{min} = minimum discharge [m^3/s]

n = number of class intervals

The frequency of discharges occurring in each class interval was determined and the average discharge in each interval was used to predict the bed material load using the Yang, Brownlie, and Pagosa equations. Using FDCs from the USGS regression equations, Rosgen's DFDC method, and streamgage data with each of the three bed material load equations to calculate the effective discharge allowed all possible combinations to be explored.

The results of the bed material load prediction equations for each of the class intervals were multiplied by the respective frequency of discharge events corresponding to the class intervals. Effective discharge plots were developed and the highest peak on the plot was taken as the effective discharge.

6 RESULTS

6.1 Sediment Transport Equation Results

In Figure 3 the sediment rating curves for the Susitna River near Talkeetna in Alaska are shown for the measured data and for each of the three predictive equations. The sediment load predictions produced by the Yang equation are the furthest away from the measured values while the predictions from the Brownlie equation are the closest to the measured values for both high and low flows. The estimates produced using the Pagosa equations are more accurate for high flows than for low flows.

The RMSEL values for the Susitna River near Talkeetna are displayed in Table 1 for each of the three equations. As depicted by Figure 3, the Brownlie equation was the most accurate in its predictions with a RMSEL value of 0.202. The Pagosa equations were only slightly less accurate than the Brownlie equation with a RMSEL value of 0.252.

In Figure 4 the sediment rating curves for the Clearwater River at Spalding in Idaho are displayed. As discharge increases, the Brownlie equation begins to overpredict the sediment transport values. The Yang equation is generally high in its predictions and the Pagosa equations appear to be the most accurate.

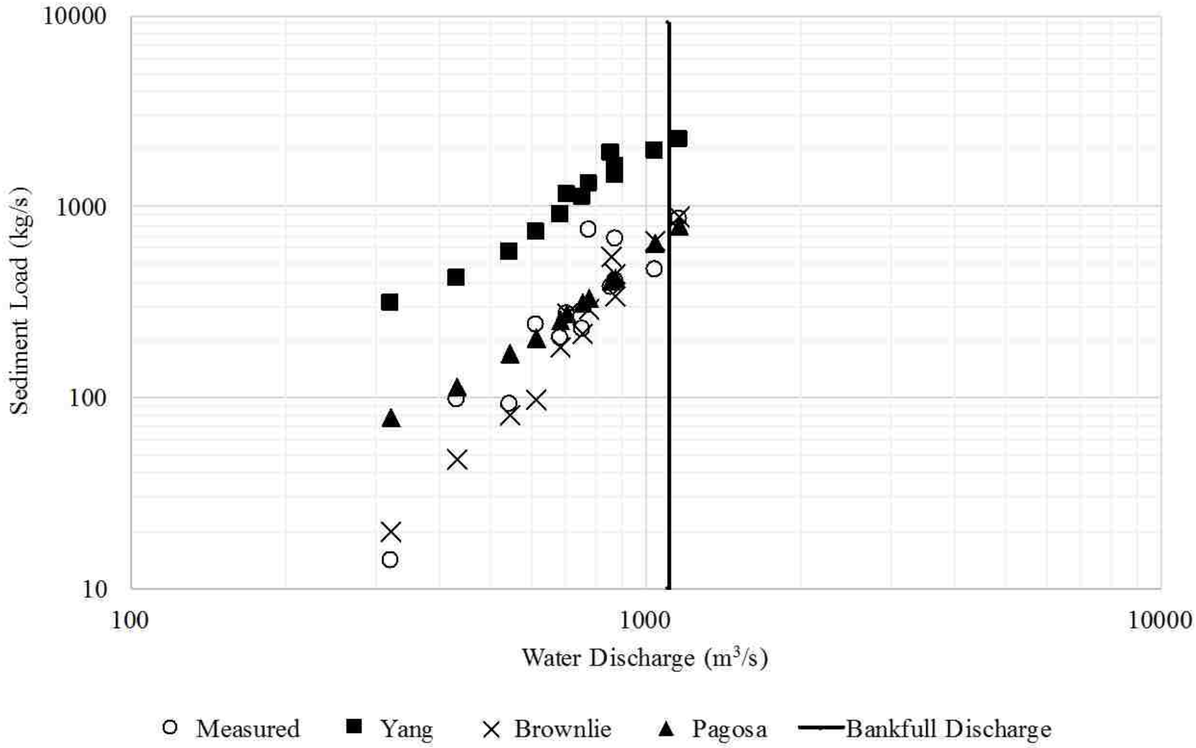

Figure 3: Sediment Rating Curves for the Susitna River near Talkeetna in Alaska

Table 1: RMSEL Values for the Susitna River near Talkeetna in Alaska

Equation	RMSEL
Yang	0.669
Brownlie	0.202
Pagosa	0.252

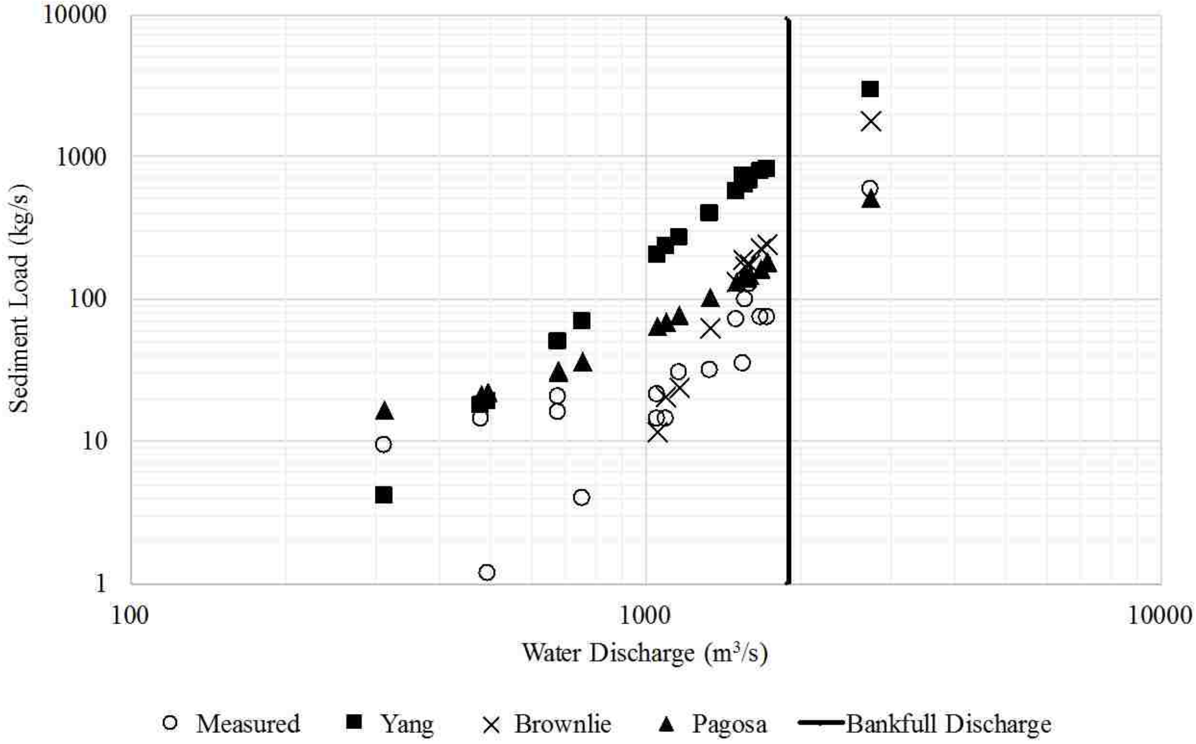

Figure 4: Sediment Rating Curves for the Clearwater River at Spalding in Idaho

Table 2 shows the RMSEL values for the Clearwater River at Spalding. The RMSEL value for the Yang equation is the highest with a value of 0.900. The Pagosa equations were the most accurate with a RMSEL value of 0.479.

Table 2: RMSEL Values for the Clearwater Creek at Spalding in Idaho

Equation	RMSEL
Yang	0.900
Brownlie	0.660
Pagosa	0.479

The sediment rating curves for the North Fork of South Platte River at Shawnee in Colorado are displayed in Figure 5. Both the Yang and Brownlie equations overpredicted the amount of sediment that would be transported; the Yang equation consistently overpredicted the values while the overprediction associated with the Brownlie equation increased with increasing flow. The predictions associated with the Pagosa equations are lower than the measured values.

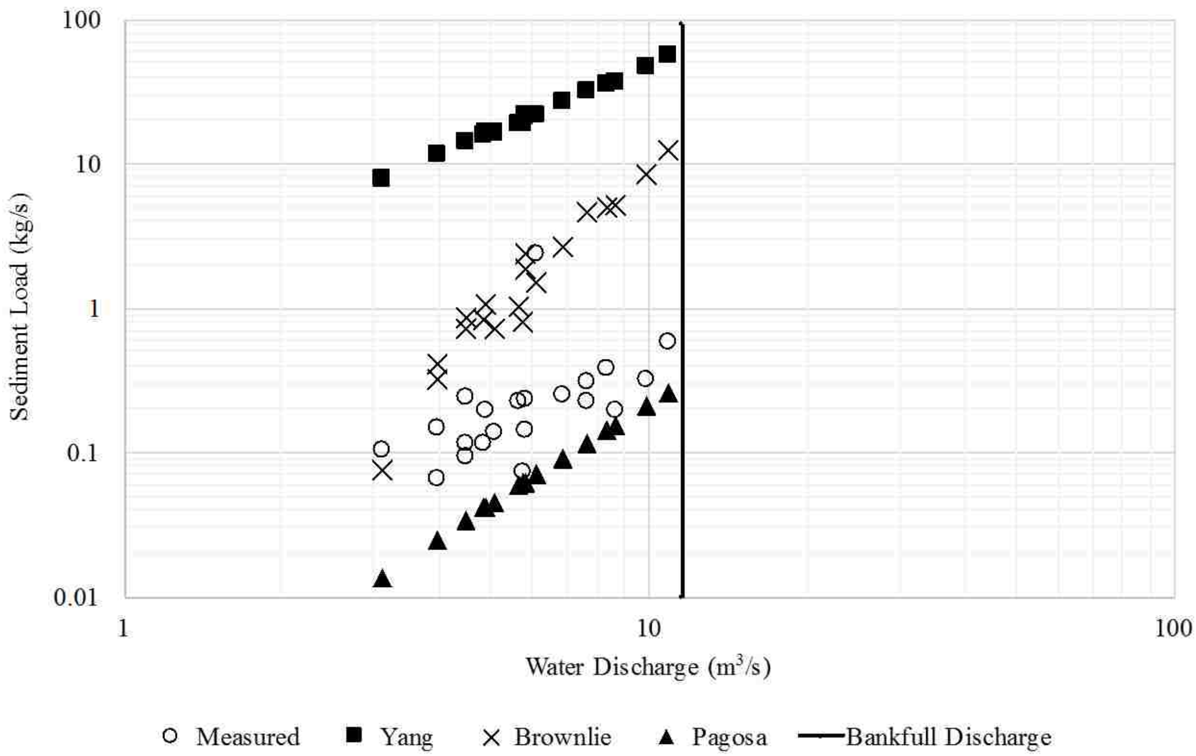

Figure 5: Sediment Rating Curves for the North Fork of South Platte River at Shawnee in Colorado

The RMSEL values for the North Fork of South Platte River at Shawnee in Colorado are found in Table 3. The error associated with the Yang equation is high with a value of 1.251. The Pagosa equations had an error that was much lower at 0.120.

Table 3: RMSEL Values for the North Fork of South Platte River at Shawnee in Colorado

Equation	RMSEL
Yang	1.251
Brownlie	0.452
Pagosa	0.120

For the Wisconsin River at Muscoda in Wisconsin, the sediment rating curves are shown in Figure 6. In the figure, the results of the Yang and Pagosa equations are relatively close, with the Yang equation being more accurate. The Brownlie equation predicts the lowest sediment transport values.

The RMSEL values for the Wisconsin River at Muscoda in Table 4 show that the Yang equation is slightly more accurate than the Pagosa equations with error values of 0.329 and 0.393, respectively. The error associated with the Brownlie equation was much higher with a value of 0.971.

Figure 7 shows the sediment rating curves for all 20 study sites and the remaining sediment rating curves and error tables for individual sites can be found in APPENDIX A. A summary of the RMSEL values for the 20 study sites for each of the three equations is displayed in Table 5.

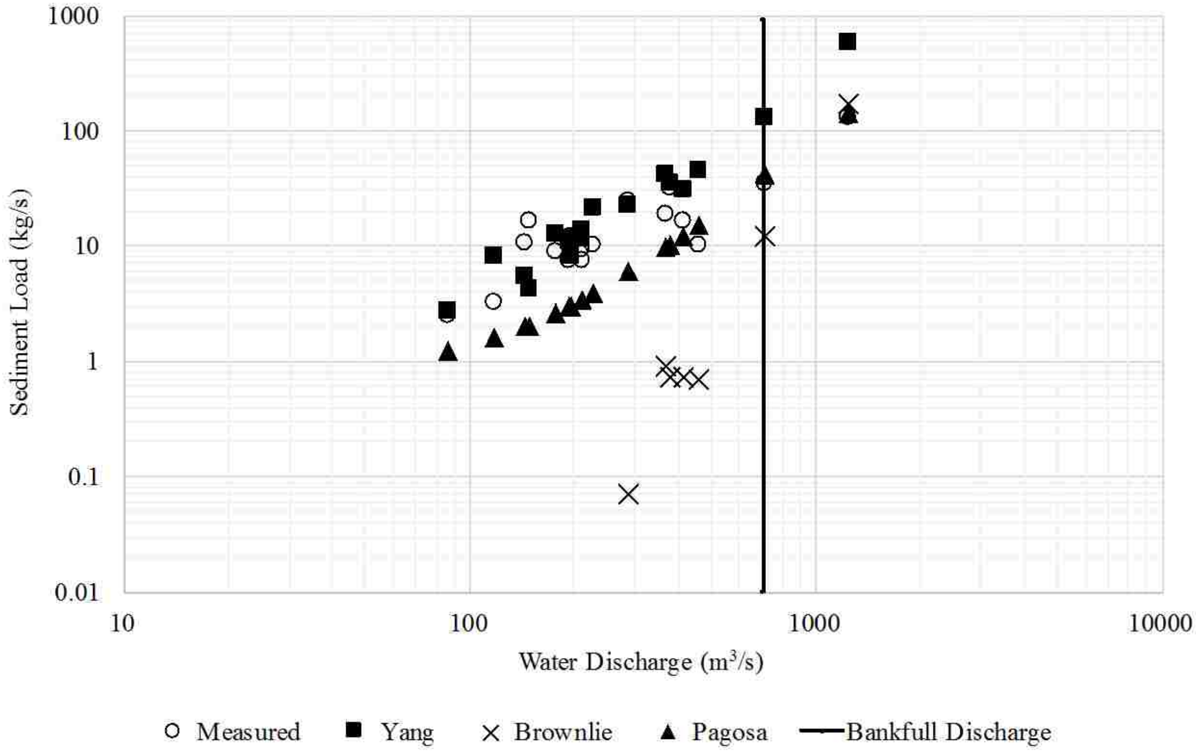

Figure 6: Sediment Rating Curves for the Wisconsin River at Muscoda in Wisconsin

Table 4: RMSEL Values for the Wisconsin River as Muscoda in Wisconsin

Equation	RMSEL
Yang	0.329
Brownlie	0.971
Pagosa	0.393

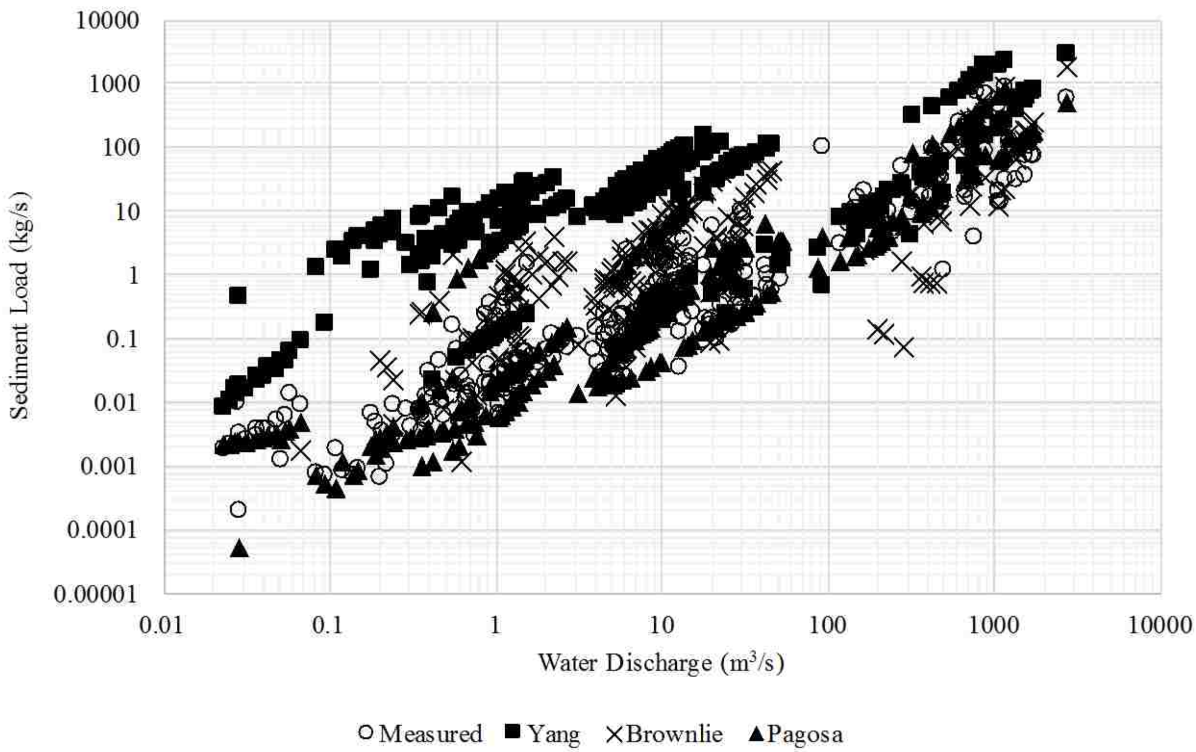

Figure 7: Sediment Rating Curves for all 20 Study Sites

The distribution of the RMSEL values for the Yang, Brownlie, and Pagosa equations are shown in the box plots in Figure 8 for the 20 study sites. The plots show that the Yang equation has the largest distribution of errors, followed by the Brownlie equation and then the Pagosa equations.

Table 6 contains the box plot statistics for the Yang, Brownlie, and Pagosa equations. The Yang equation has an even error distribution while the Brownlie and Pagosa equations have narrow error distributions for errors below the median.

Table 5: Summary of RMSELValues for Each Study Site

State	Site	RMSEL		
		Yang	Brownlie	Pagosa
AK	Susitna River near Talkeetna	0.669	0.202	0.252
ID	Clearwater River at Spalding	0.900	0.660	0.479
CO	Mad Creek (Site 1) near Empire	0.691	0.003	0.001
CO	Mad Creek (Site 3) near Empire	0.807	0.155	0.004
CO	Jefferson Creek near Jefferson	0.760	0.047	0.019
CO	Craig Creek near Bailey	0.993	0.220	0.007
CO	Geneva Creek near Grant	0.870	0.185	0.011
CO	Pony Creek near Antero Reservoir	0.014	0.003	0.002
CO	North Fork of South Platte River at Shawnee	1.251	0.452	0.120
CO	North Fork of South Platte River at Crossons	1.193	0.217	0.037
CO	North Fork of South Platte River at Buffalo	1.584	0.578	0.606
CO	North Fork of South Platte River above Vermillion Creek	0.187	0.363	0.270
CO	South Fork of South Platte River at Trumbull	1.385	0.264	0.289
CO	Buffalo Creek at Buffalo	0.094	0.141	0.536
CO	Blue River below Green Mountain Reservoir	1.620	1.024	0.077
CO	Williams Fork near Leal	1.484	0.776	0.074
CO	Rich Creek near Weston Pass	1.090	0.251	0.004
CO	Wisconsin River at Muscoda	0.329	0.971	0.393
CO	Black River near Galesville	0.790	0.980	0.551
CO	Chippewa River at Durand	0.232	0.768	0.311
	Average	0.847	0.413	0.202

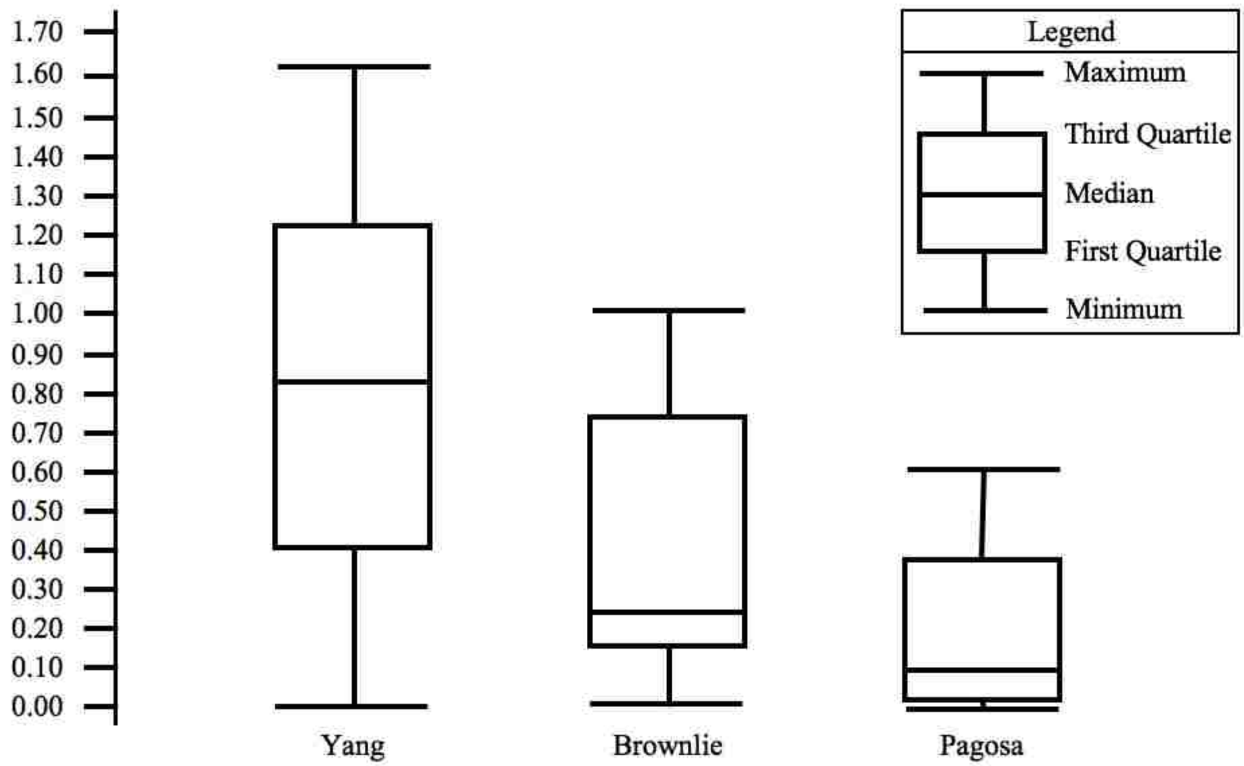

Figure 8: Box Plots for the Yang, Brownlie, and Pagosa Equation Errors

Table 6: Box Plot Statistics for the Yang, Brownlie, and Pagosa Equations

Statistic	Yang	Brownlie	Pagosa
Minimum	0.0140	0.0030	0.0010
First Quartile	0.4140	0.1625	0.0080
Median	0.8385	0.2575	0.0985
Third Quartile	1.2365	0.7410	0.3725
Maximum	1.6200	1.0240	0.6060

To demonstrate the skew of the distribution of RMSEL values for each of the bed material load equations, histograms were created. Figure 9 shows the histogram for the Yang equation. The histogram shows a fairly even distribution of error values, with a peak near the median. Figure 10 shows the histogram for the Brownlie equation. Following the initial peaks from the first two quartiles, the graph shows a skew to the right. The histogram for the Pagosa equations is shown in Figure 11. Like the histogram for the Brownlie equation, the histogram for the Pagosa equations shows an initial peak corresponding to the first quartile followed by a skew to the right.

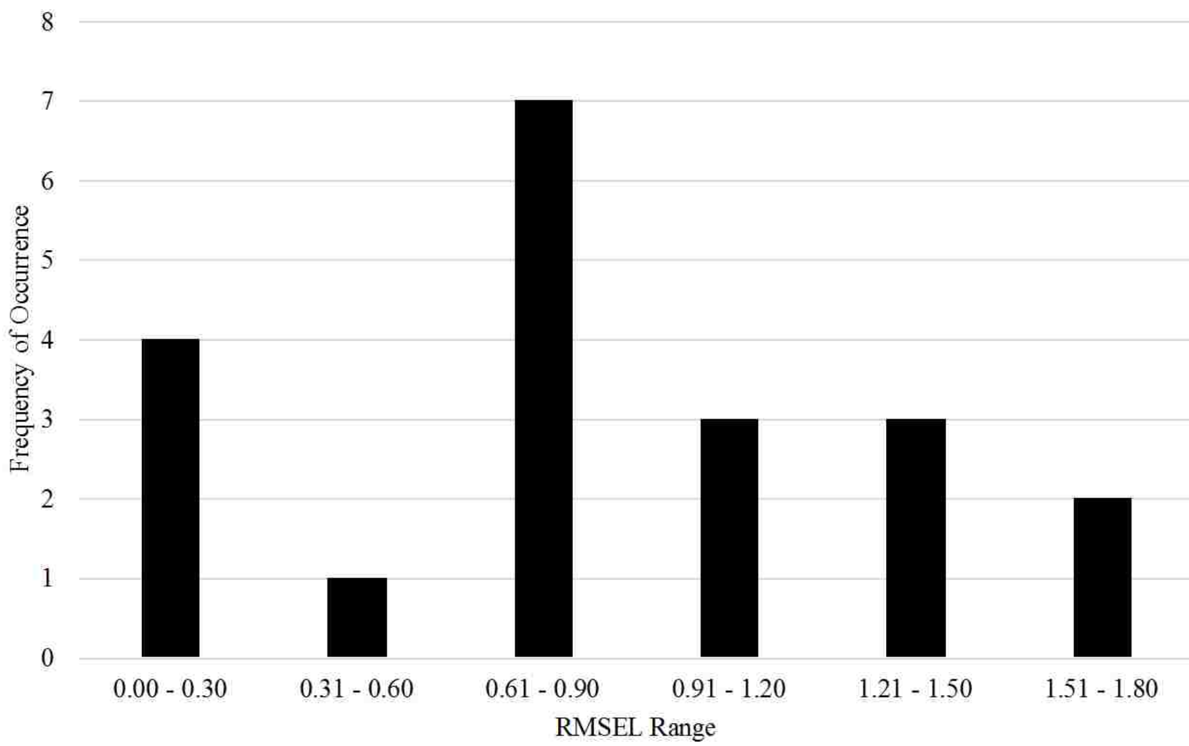

Figure 9: Histogram of RMSEL Values for the Yang Equation

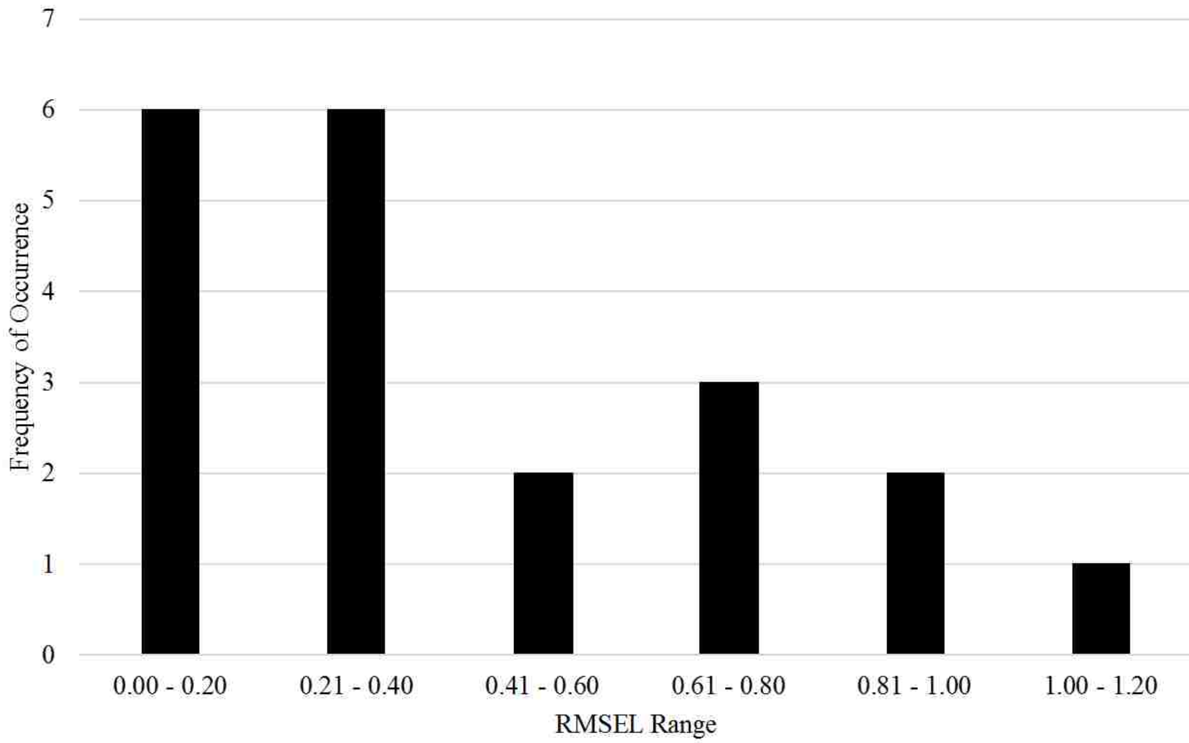

Figure 10: Histogram of RMSEL Values for the Brownlie Equation

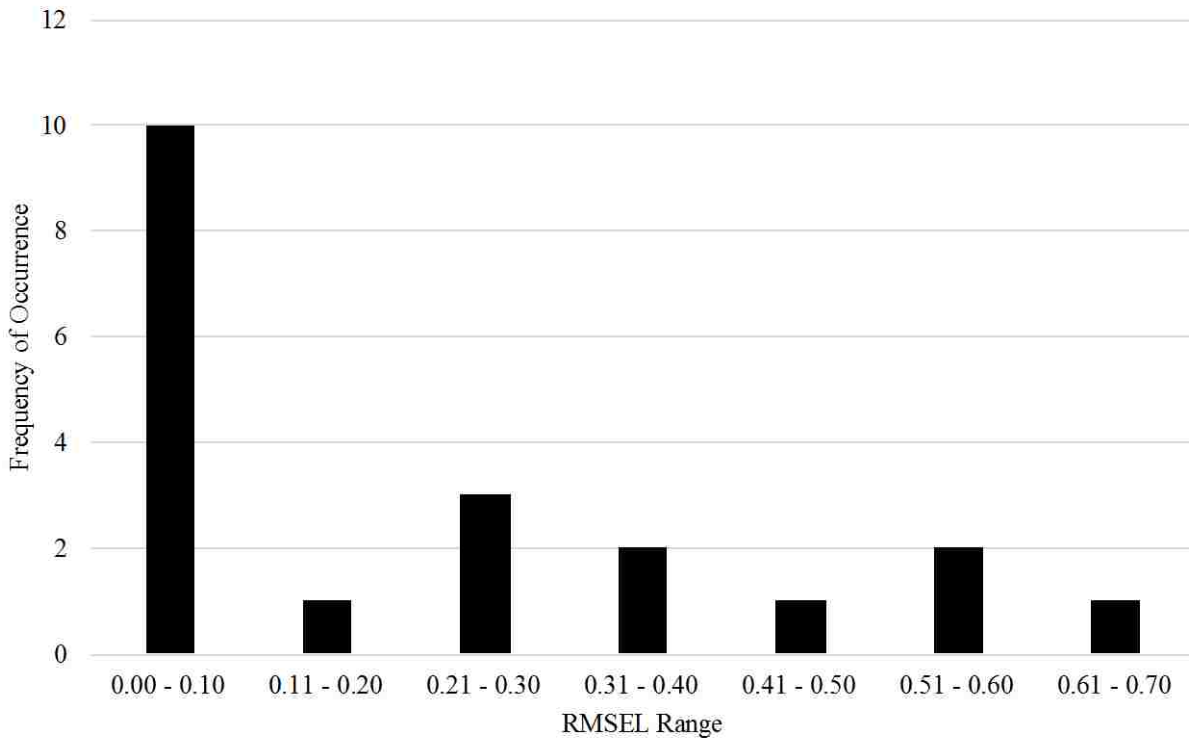

Figure 11: Histogram of RMSEL Values for the Pagosa Equations

6.2 Flow Duration Curve Results

The FDCs for Weminuche Creek are shown in Figure 12. The graph shows that the USGS regression equations underpredicted the discharges that were measured by the streamgage while Rosgen's DFDC method overpredicted them.

The RMSEL values were calculated for the USGS regression equations and Rosgen's DFDC method. The results of the RMSEL calculations are shown in Table 7. The error associated with the USGS regression equations was 0.246 while the error associated with Rosgen's DFDC method was 0.111.

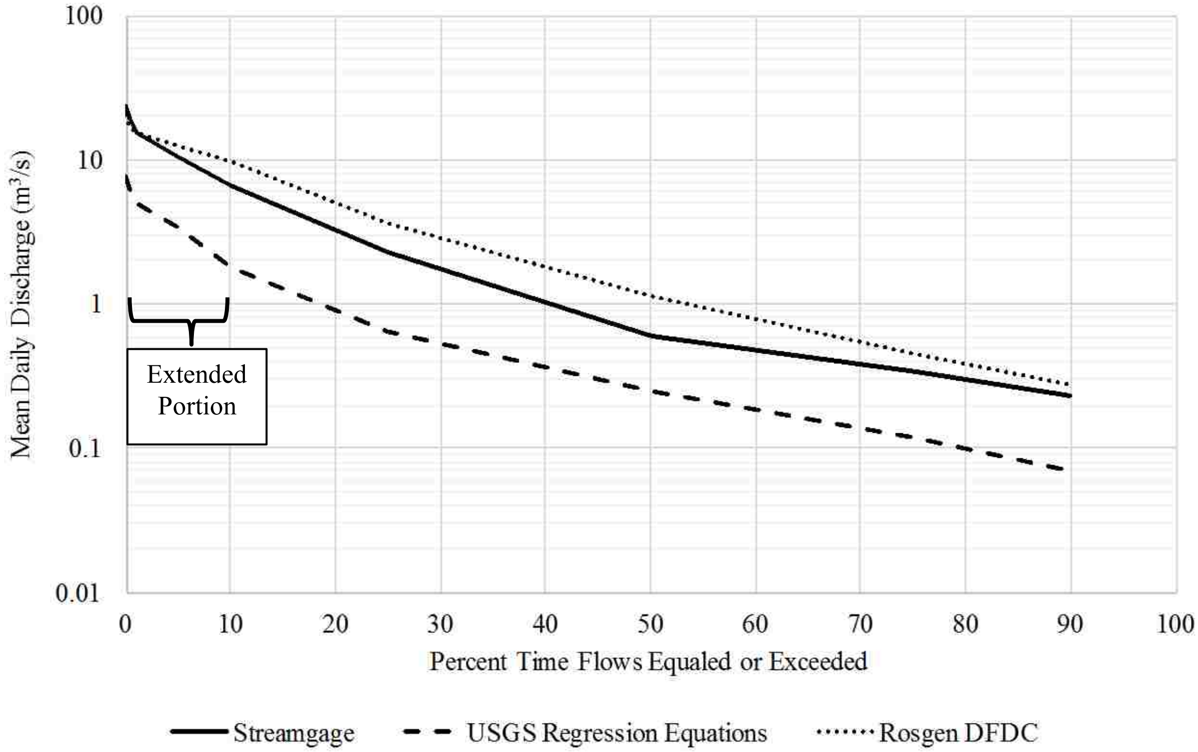

Figure 12: Flow Duration Curves for Weminuche Creek in Colorado

Table 7: RMSEL Values for FDC Methods

Method	RMSEL
USGS Regression Equations	0.246
Rosgen DFDC Method	0.111

6.3 Effective Discharge Results

Figure 13 shows the effective discharge calculation results using the USGS regression equations with the Yang and Pagosa equations. The Yang and Pagosa equations both resulted in an effective discharge of approximately 4.5 cms when used with the USGS regression equations.

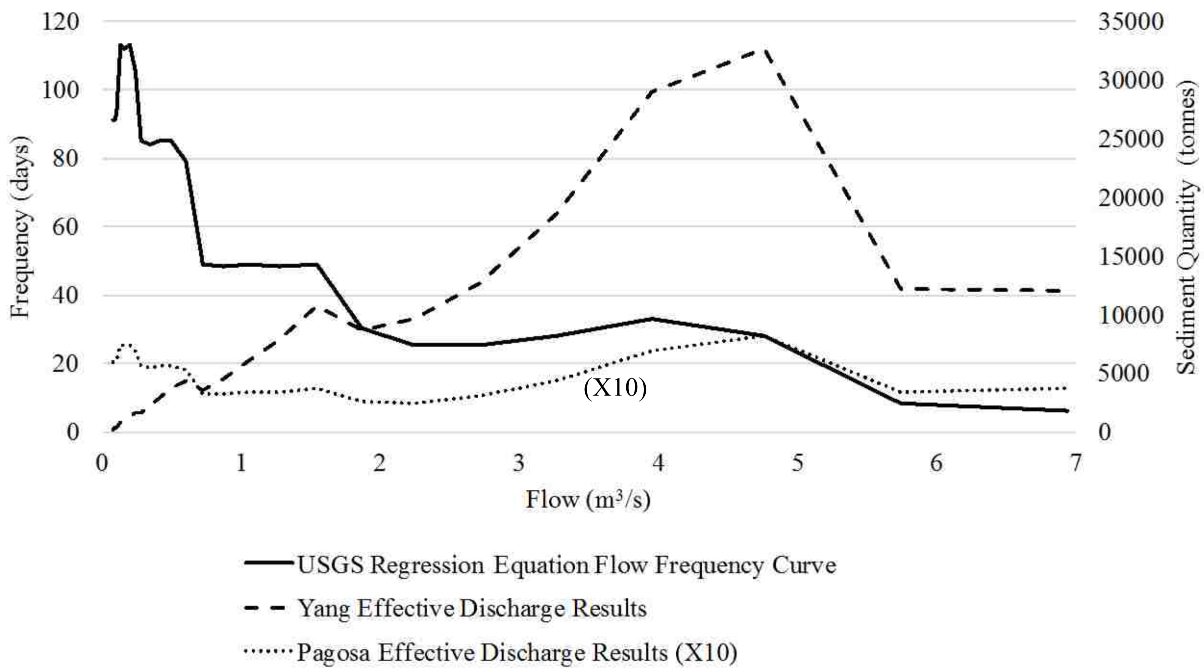

Figure 13: Effective Discharge Calculation Results using the USGS Regression Equations with the Yang and Pagosa Equations

Figure 14 shows the effective discharge calculation results using the Rosgen DFDC method with the Yang and Pagosa equations. The Yang and Pagosa equations both resulted in an effective discharge of approximately 13.5 cms when used with the Rosgen DFDC method.

Figure 15 shows the effective discharge calculation results using streamgage data with the Yang and Pagosa equations. The Yang and Pagosa equations both resulted in an effective discharge of approximately 13.5 cms when used with streamgage data.

The Brownlie equation was also used to calculate bed material load. However, it predicted zero bed material load for the site. Thus, effective discharge calculations could not be performed using the Brownlie equation. Table 8 provides a summary of the effective discharge results that were calculated in this study along with the 2-year flood and bankfull discharge.

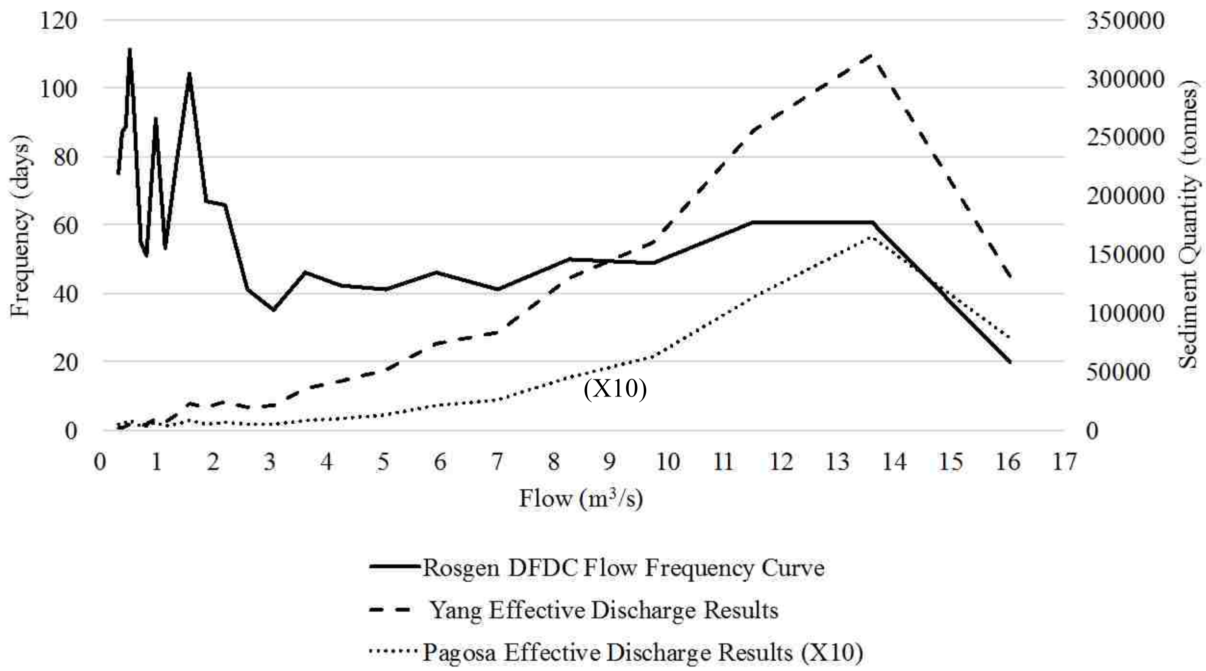

Figure 14: Effective Discharge Calculation Results using the Rosgen DFDC Method with the Yang and Pagosa Equations

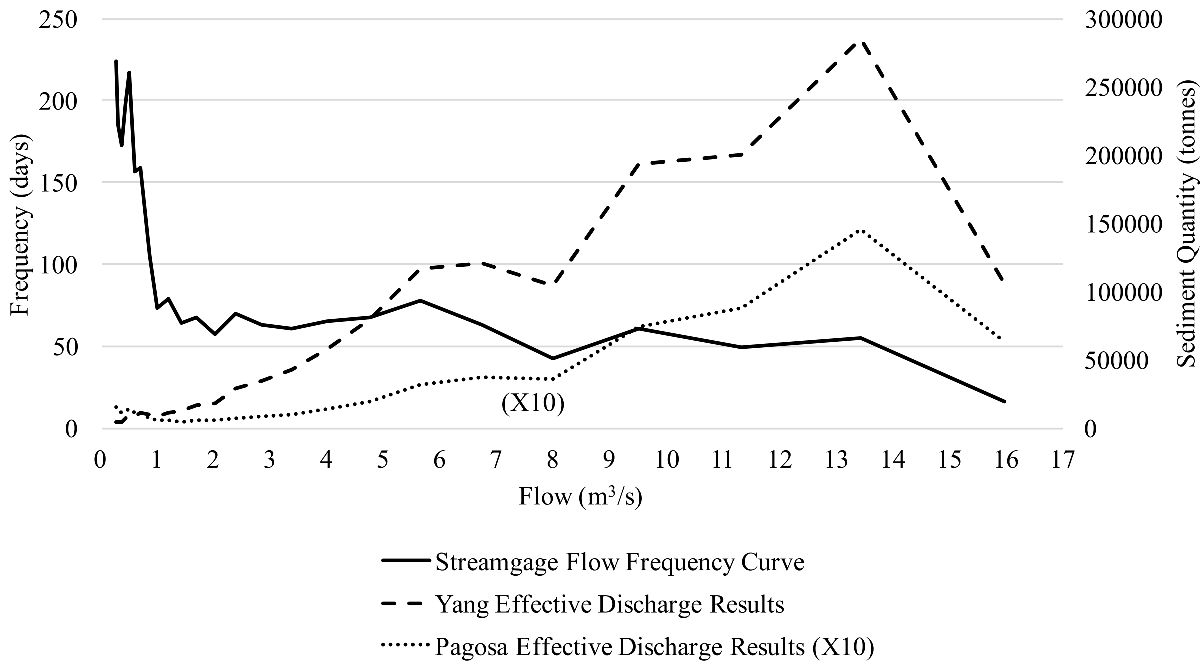

Figure 15: Effective Discharge Calculation Results using Streamgage Data with the Yang and Pagosa Equations

Table 8: Summary of Effective Discharge Calculation Results

FDC Method	Bed Material Load Equation	Effective Discharge (cms)	2-Year Flood (cms)	Bankfull Discharge (cms)
USGS Regression Equations	Yang	4.5	9.8	10.8
USGS Regression Equations	Pagosa	4.5	9.8	10.8
Rosgen DFDC	Yang	13.5	9.8	10.8
Rosgen DFDC	Pagosa	13.5	9.8	10.8
Streamgage	Yang	13.5	9.8	10.8
Streamgage	Pagosa	13.5	9.8	10.8

7 DISCUSSION OF RESULTS

7.1 Sediment Transport Discussion

From Table 5, the Yang equation had the lowest RMSEL value for the North Fork of South Platte River above Vermillion Creek in Colorado, Buffalo Creek at Buffalo in Colorado, the Wisconsin River at Muscoda in Wisconsin, and the Chippewa River at Durand in Colorado. Thus, the Yang equation predicted the bed material load most accurately for 20% of the study sites. Also from Table 5, the Brownlie equation had the lowest RMSEL value for the Susitna River near Talkeetna in Alaska, the North Fork of South Platte River at Buffalo in Colorado, and the South Fork of South Platte River at Trumbull in Colorado. The Brownlie equation performed most accurately for 15% of the study sites. The bed material load of the remaining 13 sites, or 65% of the study sites, was predicted most accurately by the Pagosa equations.

Although the Yang equation predicted the bed material load mostly accurately for more sites than the Brownlie equation, the average RMSEL value for the 20 sites was lower for the Brownlie equation than for the Yang equation. From Table 5, the Yang equation had an average RMSEL value of 0.847 while the Brownlie equation had an average RMSEL value of 0.413. The high error value for the Yang equation resulted from overprediction of bed material load for many of the sites. For the sites in this study, the Brownlie equation performed better than the Yang equation.

The average RMSEL value for the 20 study sites for the Pagosa equations was 0.202 (see Table 5). This error value is lower than the average errors value for both the Yang and Brownlie equations. For the 20 study sites in the USGS Open-File Report 89-67, the Pagosa equations developed by Rosgen performed the best overall at predicting bed material load. The superior performance of the Pagosa equations over the Yang and Brownlie equations is likely due to the Pagosa equations being calibrated while the Yang and Brownlie equations are uncalibrated. The accuracy of the Pagosa equations may also result from their purely empirical nature. While the Yang and Brownlie equations were developed using a combination of both field and laboratory flume data, the Pagosa equations were developed using only field data.

7.2 Flow Duration Curve Discussion

In Figure 12, Rosgen's DFDC method overpredicted the discharges and the USGS regression equations underpredicted the discharges. The underpredictions associated with the USGS regression equations may result from the manner in which the mean annual precipitation for the watershed was determined. The RMSEL value for the USGS regression equations was 0.246 and the RMSEL value for Rosgen's DFDC method was 0.111 (see Table 7). Although both methods contained errors, the error associated with Rosgen's DFDC method was smaller than the USGS regression equation error. For Weminuche Creek, Rosgen's DFDC method was more accurate than the USGS regression equations.

7.3 Effective Discharge Discussion

Although the bed material load predictions for the Yang and Pagosa equations were significantly different for each class interval, both equations resulted in an effective discharge of approximately 4.5 cms when used with the USGS regression equations. The shape of the curves for the effective discharge calculation results associated with the Yang and Pagosa equations in Figure 13 are similar for flows above approximately 2 cms.

When the Yang and Pagosa equations were used with the Rosgen DFDC method and streamgage data, the effective discharge was calculated to be approximately 13.5 cms for all cases. With each FDC, the shape of the curves for the effective discharge calculation results for the Yang and Brownlie equations are very similar for all discharges (see Figure 14 and Figure 15).

When used with the same FDC, the choice of bed material load prediction equations did not affect the magnitude of the effective discharge for Weminuche Creek. However, the choice of FDC did impact the effective discharge when used with the same bed material load prediction equations in some cases. The FDCs developed using Rosgen's DFDC method and streamgage data were similar to one another and had higher discharges than the FDC developed using the USGS regression equations. The effective discharge that was calculated using Rosgen's DFDC method and streamgage data was approximately 9 cms higher than the effective discharge that was calculated using the USGS regression equations.

8 CONCLUSIONS AND RECOMMENDATIONS

The purpose of this study was to analyze how estimates of an important geomorphic parameter, effective discharge, were impacted by the choice of bed material load equations and FDCs. The Yang, Brownlie, and Pagosa equations for predicting bed material load were compared using 306 measurements from 20 sites in Alaska, Idaho, Colorado, and Wisconsin from the USGS Open-File Report 89-67. After comparing the bed material load equations, the Pagosa equations for bed material load had the lowest error, followed by Brownlie and then Yang. The superior performance of the Pagosa equations is likely due to the equations being calibrated while the Yang and Brownlie equations are uncalibrated. The purely empirical nature of the Pagosa equations may also have contributed to their accuracy.

To compare methods used to develop FDCs for ungaged sites, USGS regression equations and Rosgen's DFDC method were compared to the FDC developed using streamgage data for Weminuche Creek in southwestern Colorado. Rosgen's DFDC method predicted discharges that were higher than the measured discharges while the USGS regression equations predicted discharges that were lower than the measure discharges. Although both methods contained errors in their estimates, Rosgen's method of developing a DFDC was more accurate for Weminuche Creek than the USGS regression equations.

To compare the impact that FDCs and bed material load prediction equations have on the effective discharge, six different combinations of FDCs and bed material load prediction equations were used to calculate the effective discharge of Weminuche Creek. The effective discharge was calculated by multiplying the flow frequency curve produced from the FDC and the sediment rating curve. When used with the USGS regression equations, the Yang and Pagosa equations both produced an effective discharge of approximately 4.5 cms. When the Yang and Pagosa equations were used with Rosgen's DFDC method and streamgage data, the effective discharge was calculated to be approximately 13.5 cms for both equations. For Weminuche Creek, the bed material load prediction equations did not affect the magnitude of the effective discharge while the FDCs did influence the effective discharge in some cases.

The methodology employed in this study serves as a template for future research. For this study, Weminuche Creek was the only site for which adequate information was available to perform calculations. It is thus recommended that the outlined methods be applied to other streams and locations to strengthen the statistical significance of the results and conclusions of this study. The calculation of effective discharge is fundamental to all stream restoration efforts. Continued research in this area of study will provide further insights into the behavior of streams.

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APPENDIX A

Sediment Transport Equation Results

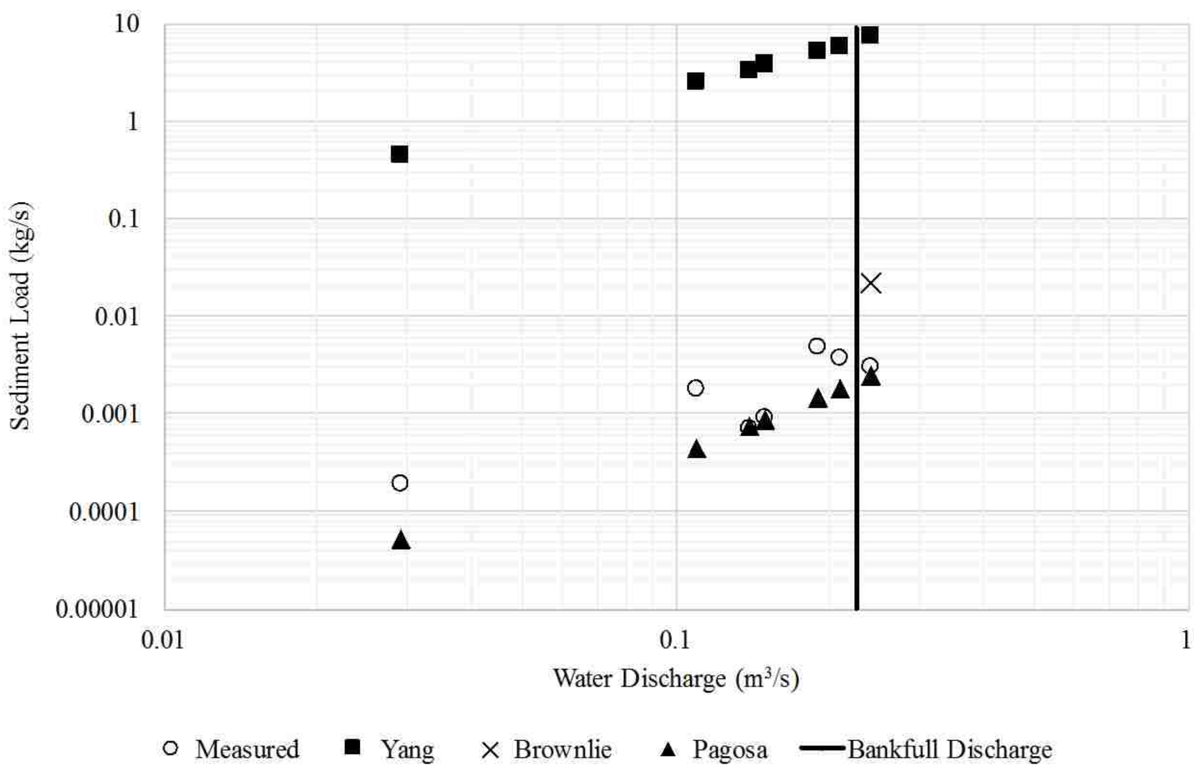

Figure 13: Sediment Rating Curves for Mad Creek (Site 1) near Empire in Colorado

Table 9: RMSEL Values for Mad Creek (Site 1) near Empire in Colorado

Equation	RMSEL
Yang	0.691
Brownlie	0.003
Pagosa	0.001

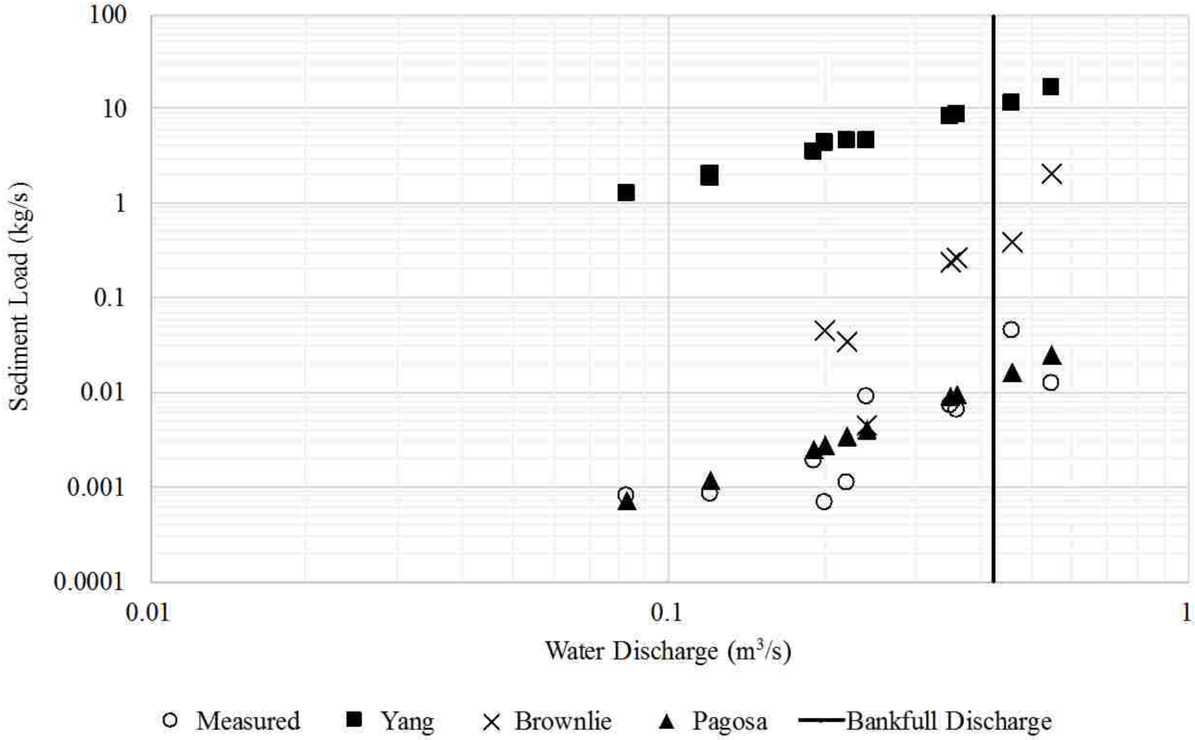

Figure 14: Sediment Rating Curves for Mad Creek (Site 3) near Empire in Colorado

Table 10: RMSEL Values for Mad Creek(Site 3) near Empire in Colorado

Equation	RMSEL
Yang	0.807
Brownlie	0.155
Pagosa	0.004

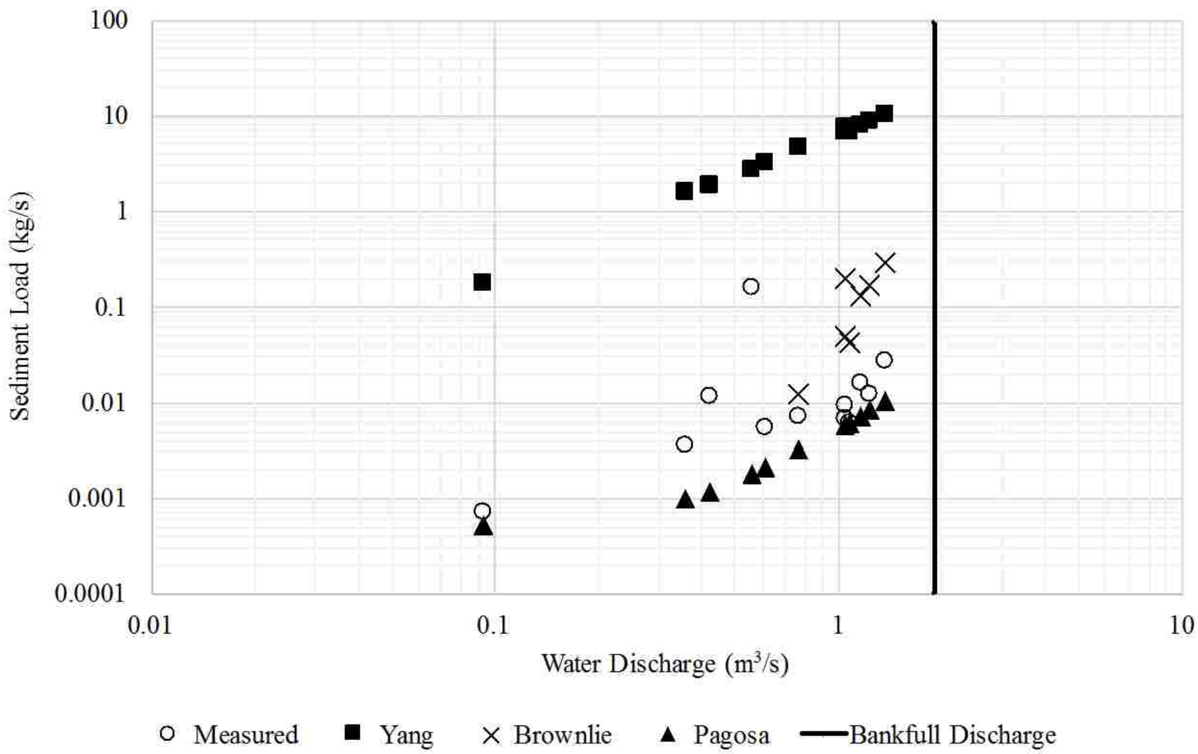

Figure 15: Sediment Rating Curves for Jefferson Creek near Jefferson in Colorado

Table 11: RMSEL Values for Jefferson Creek near Jefferson in Colorado

Equation	RMSEL
Yang	0.760
Brownlie	0.047
Pagosa	0.019

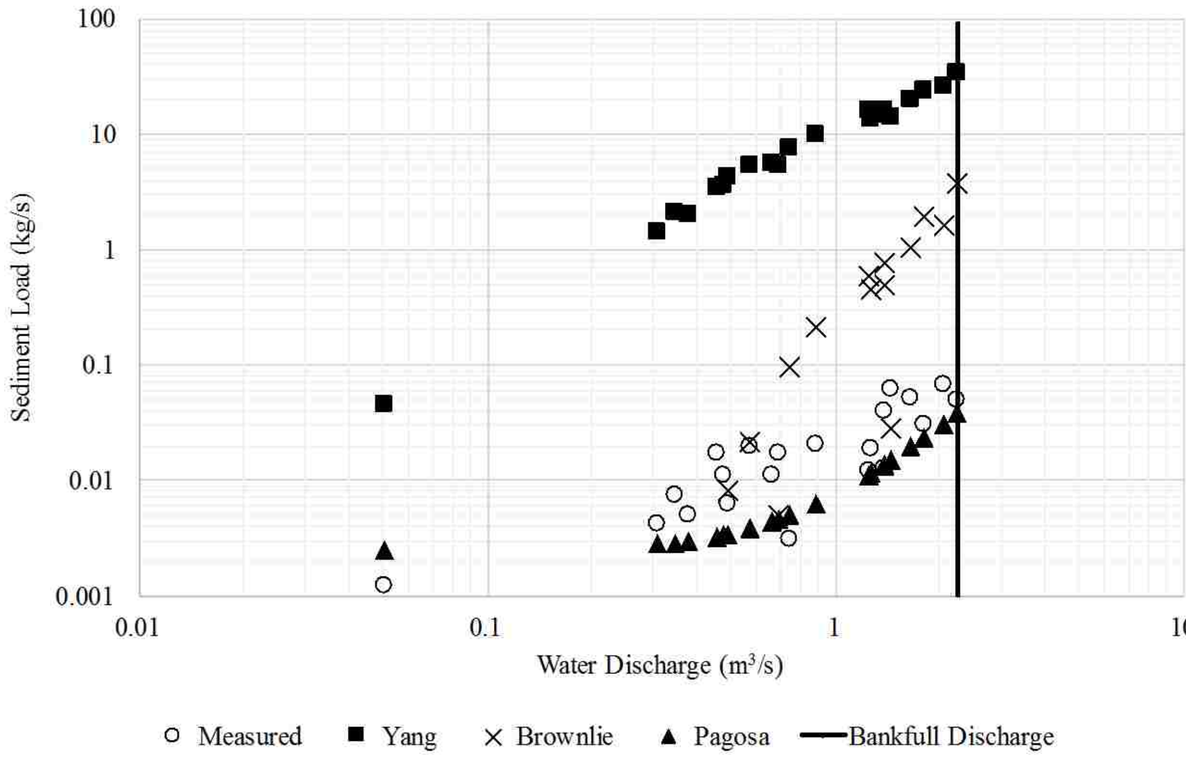

Figure 16: Sediment Rating Curves for Craig Creek near Bailey in Colorado

Table 12: RMSEL Values for Craig Creek near Bailey in Colorado

Equation	RMSEL
Yang	0.993
Brownlie	0.220
Pagosa	0.007

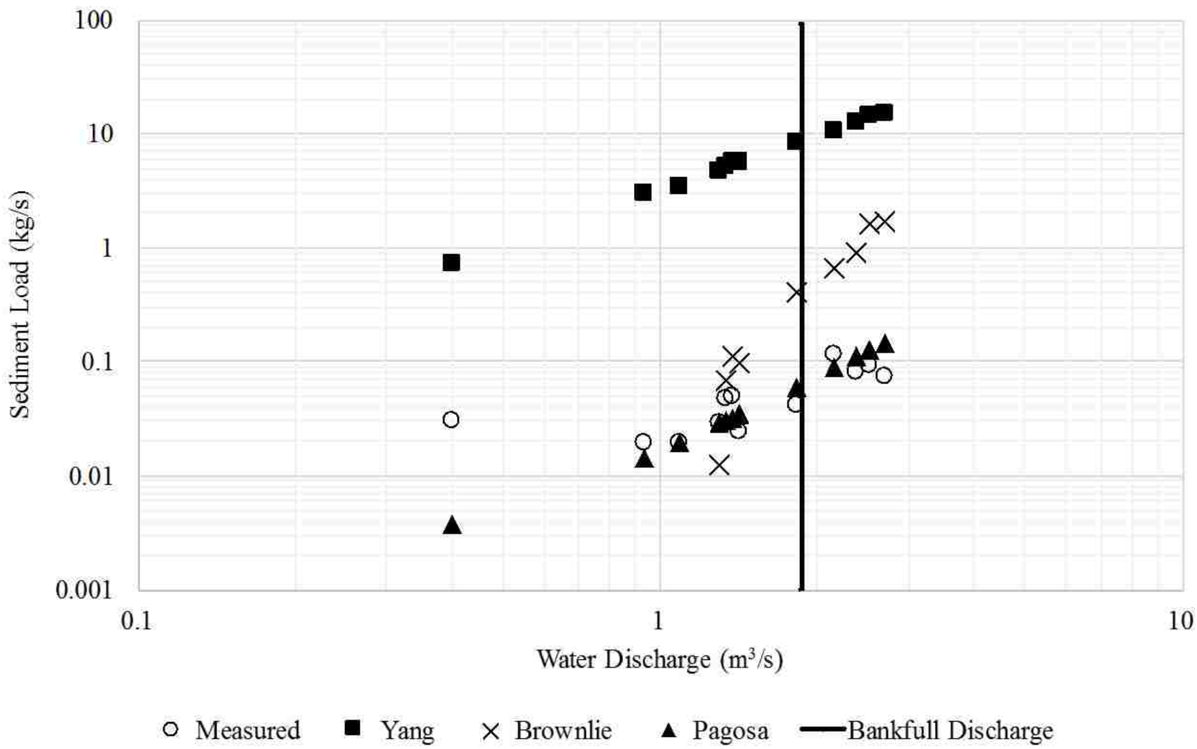

Figure 17: Sediment Rating Curves for Geneva Creek near Grant in Colorado

Table 13: RMSEL Values for Geneva Creek near Grant in Colorado

Equation	RMSEL
Yang	0.870
Brownlie	0.185
Pagosa	0.011

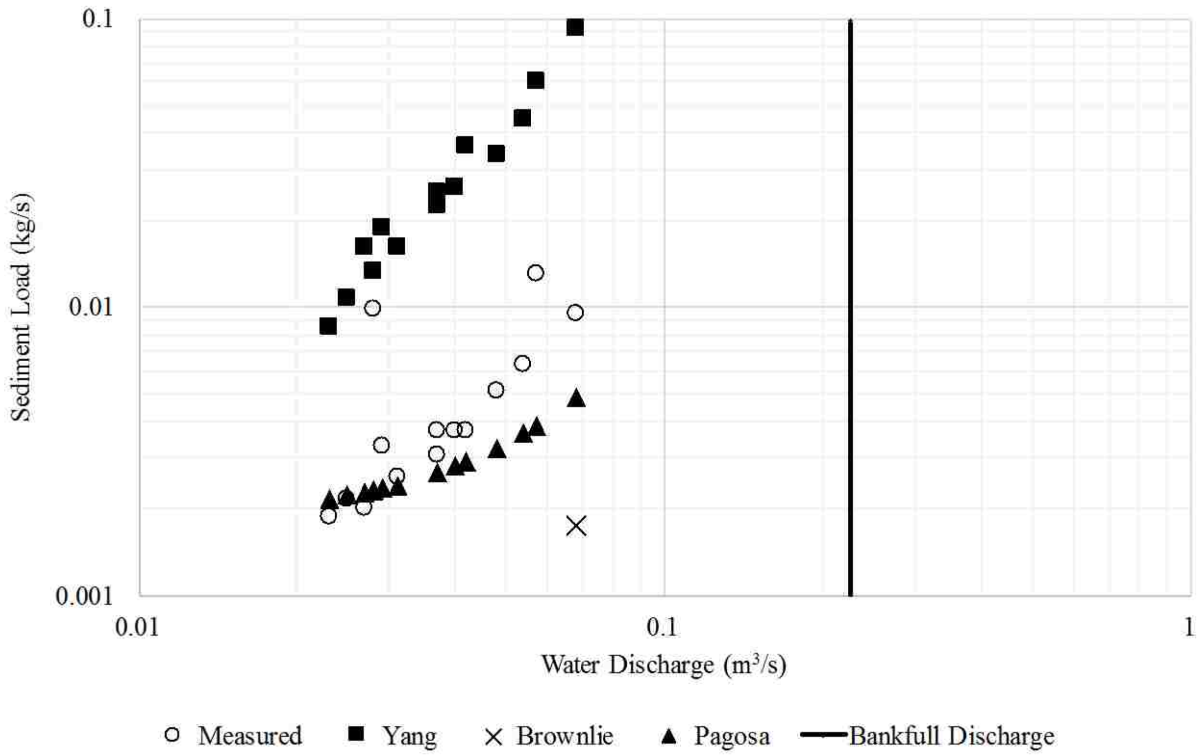

Figure 18: Sediment Rating Curves for Pony Creek near Antero Reservoir in Colorado

Table 14: RMSEL Values for Pony Creek near Antero Reservoir in Colorado

Equation	RMSEL
Yang	0.014
Brownlie	0.003
Pagosa	0.002

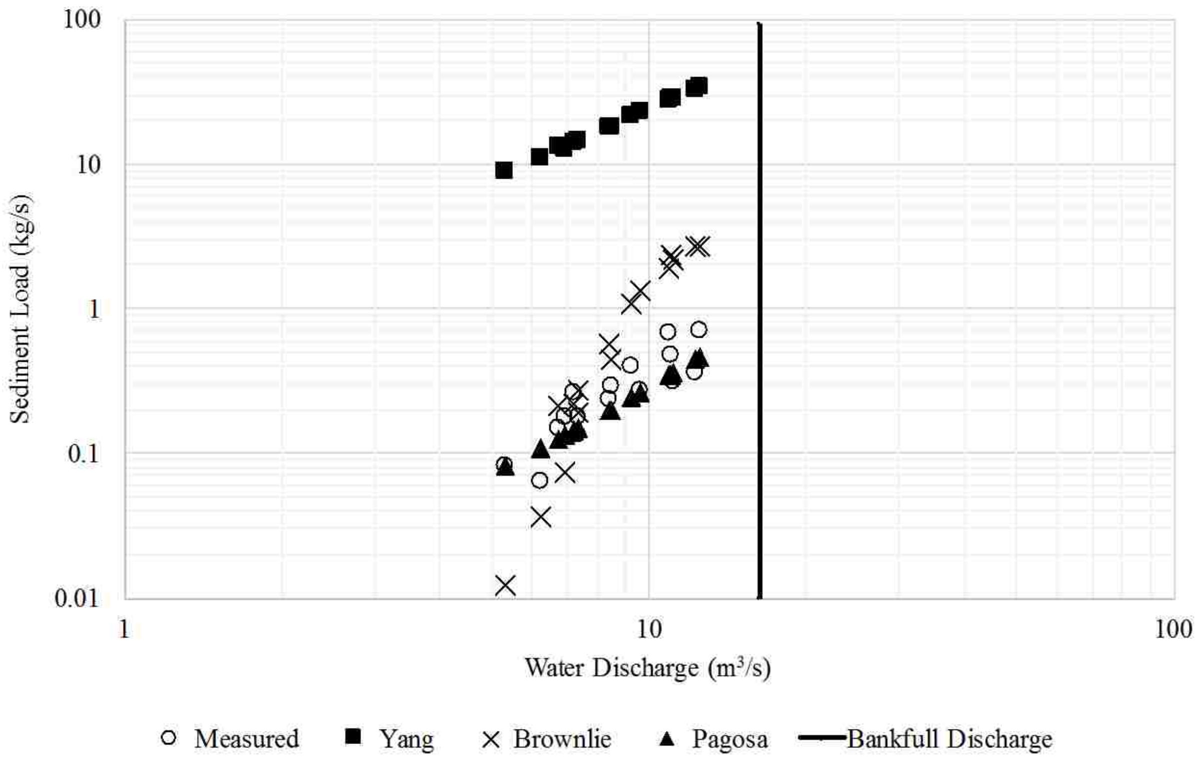

Figure 19: Sediment Rating Curves for the North Fork of South Platte River at Crossons in Colorado

Table 15: RMSEL Values for the North Fork of South Platte River at Crossons in Colorado

Equation	RMSEL
Yang	1.193
Brownlie	0.217
Pagosa	0.037

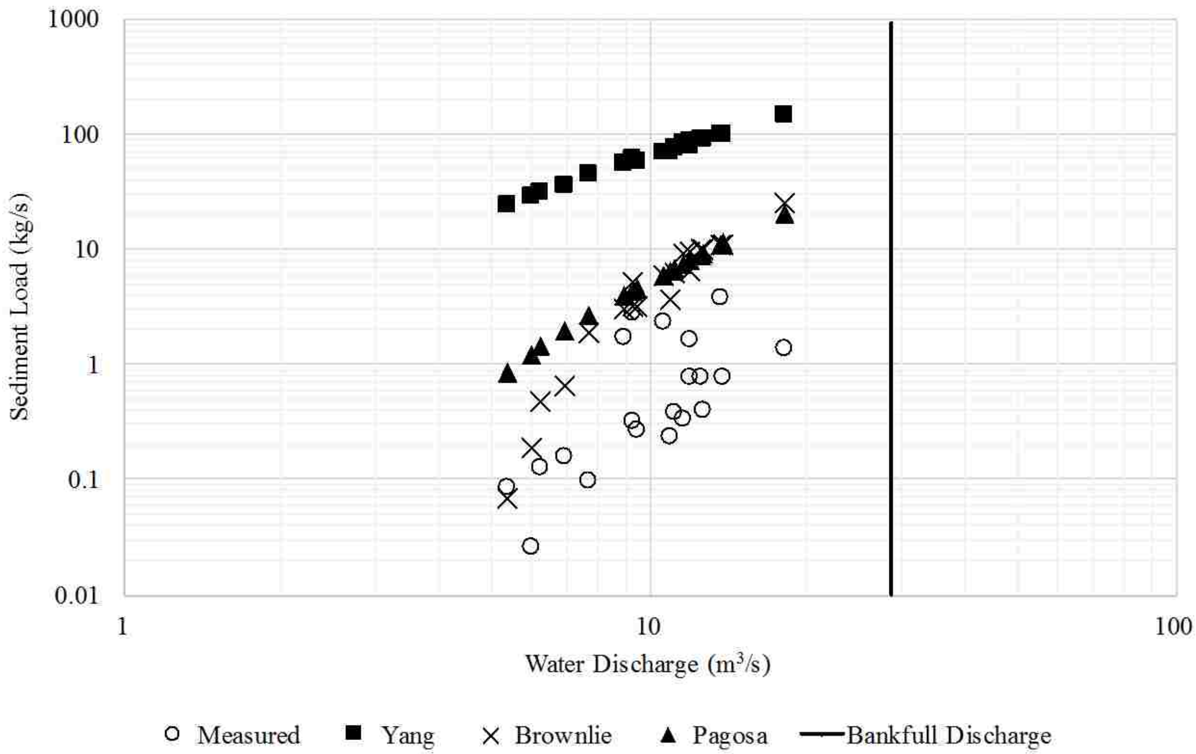

Figure 20: Sediment Rating Curves for the North Fork of South Platte River at Buffalo in Colorado

Table 16: RMSEL Values for the North Fork of South Platte River at Buffalo in Colorado

Equation	RMSEL
Yang	1.584
Brownlie	0.578
Pagosa	0.606

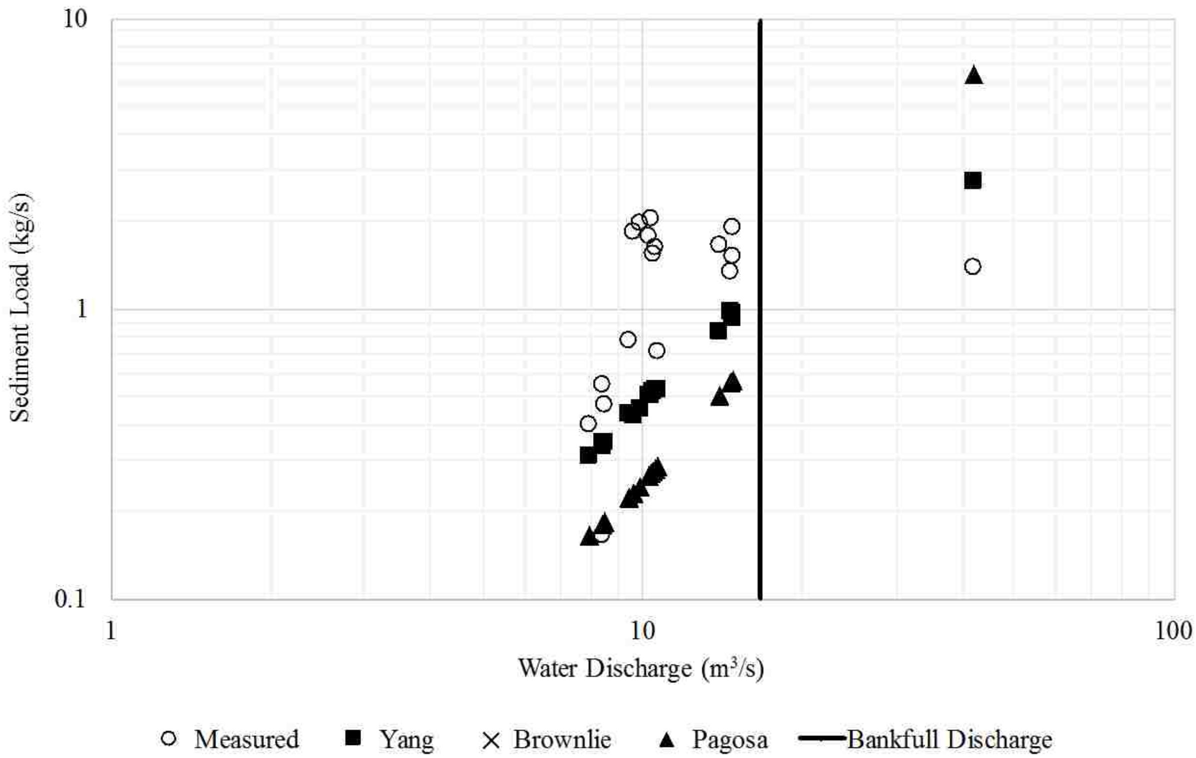

Figure 21: Sediment Rating Curves for the North Fork of South Platte River above Vermillion Creek in Colorado

Table 17: RMSEL Values for the North Fork of South Platte River above Vermillion Creek in Colorado

Equation	RMSEL
Yang	0.187
Brownlie	0.363
Pagosa	0.270

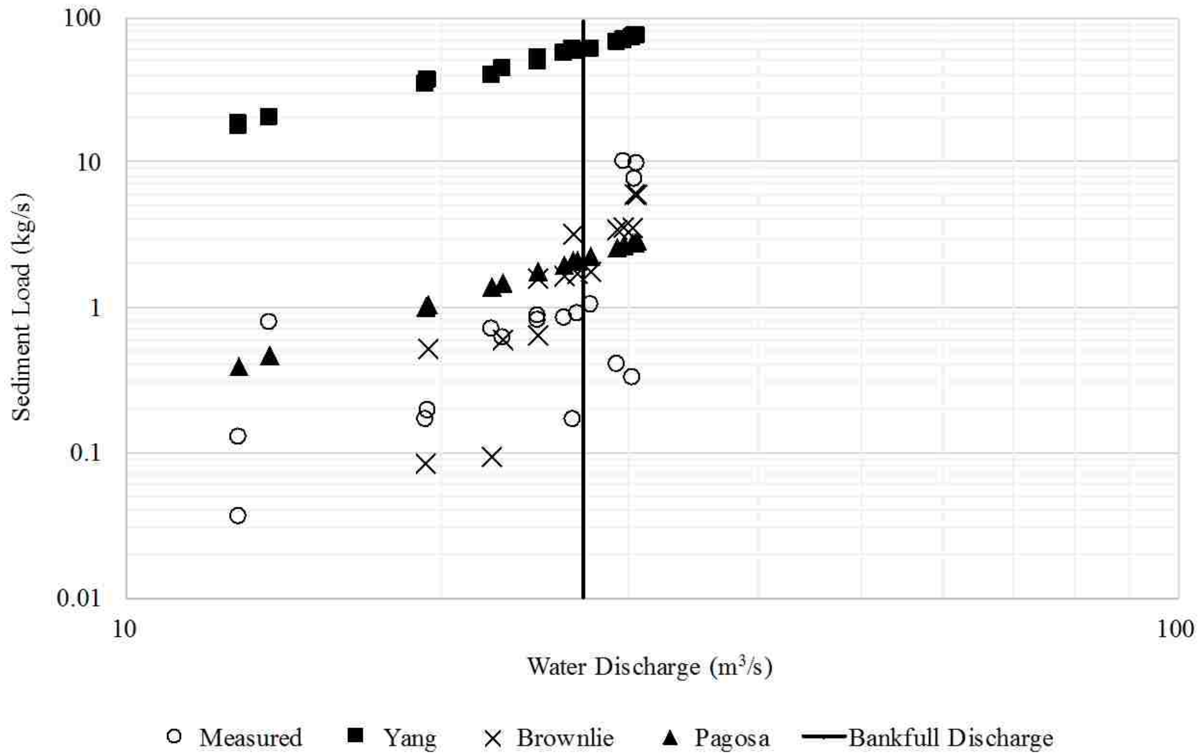

Figure 22: Sediment Rating Curves for the South Fork of South Platte River at Trumbull in Colorado

Table 18: RMSEL Values for the South Fork of South Platte River at Trumbull in Colorado

Equation	RMSEL
Yang	1.385
Brownlie	0.264
Pagosa (2006)	0.289

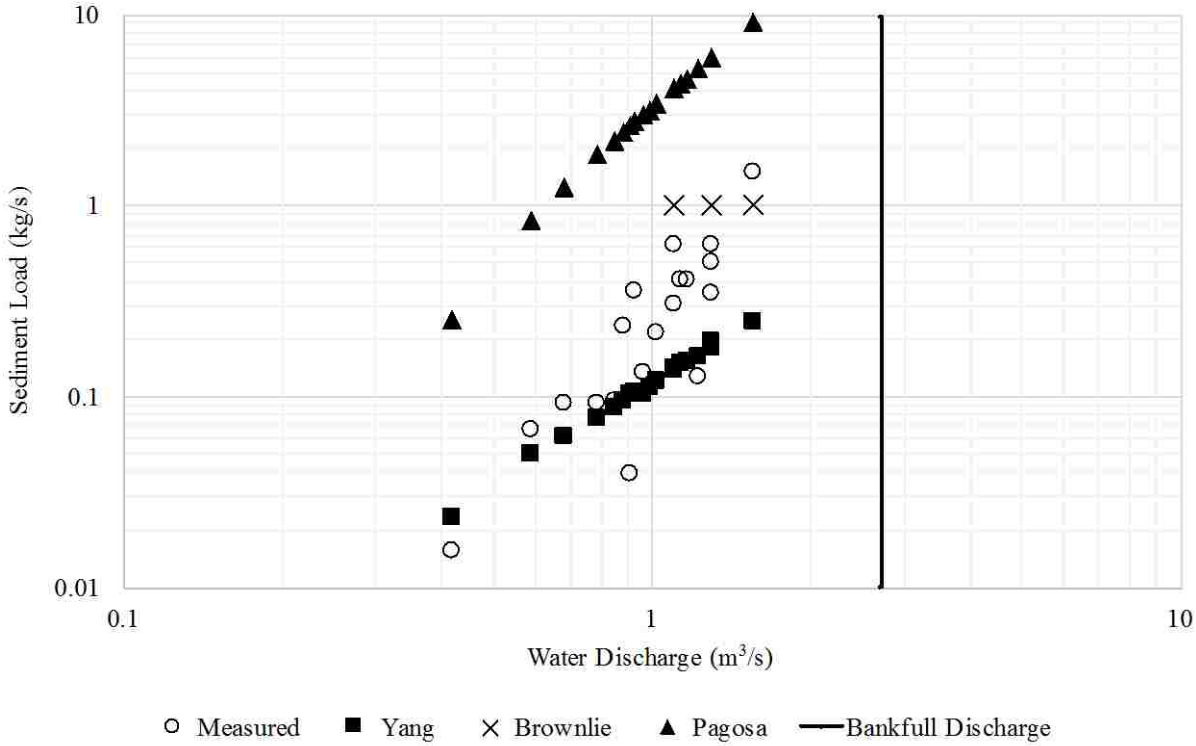

Figure 23: Sediment Rating Curves for Buffalo Creek at Buffalo in Colorado

Table 19: RMSEL Values for Buffalo Creek at Buffalo in Colorado

Equation	**RMSEL**
Yang	0.094
Brownlie	0.093
Pagosa	0.536

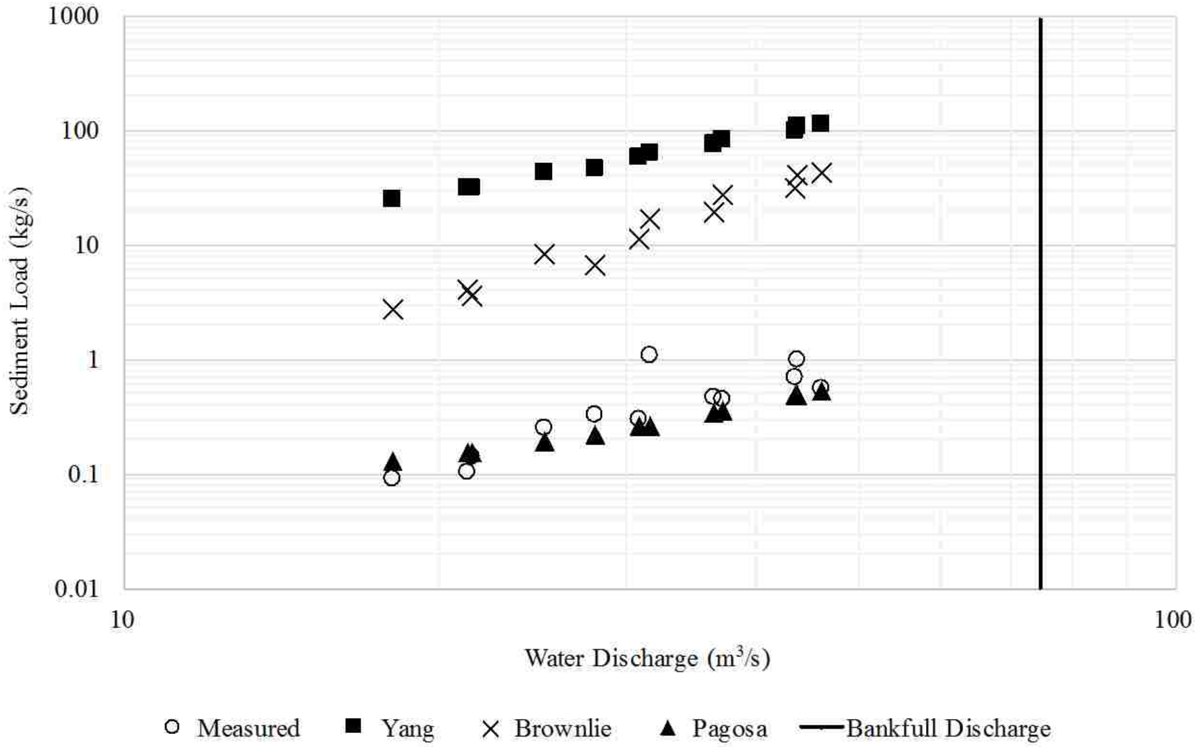

Figure 24: Sediment Rating Curves for the Blue River below Green Mountain Reservoir in Colorado

Table 20: RMSEL Values for the Blue River below Green Mountain Reservoir in Colorado

Equation	RMSEL
Yang	1.620
Brownlie	1.024
Pagosa	0.077

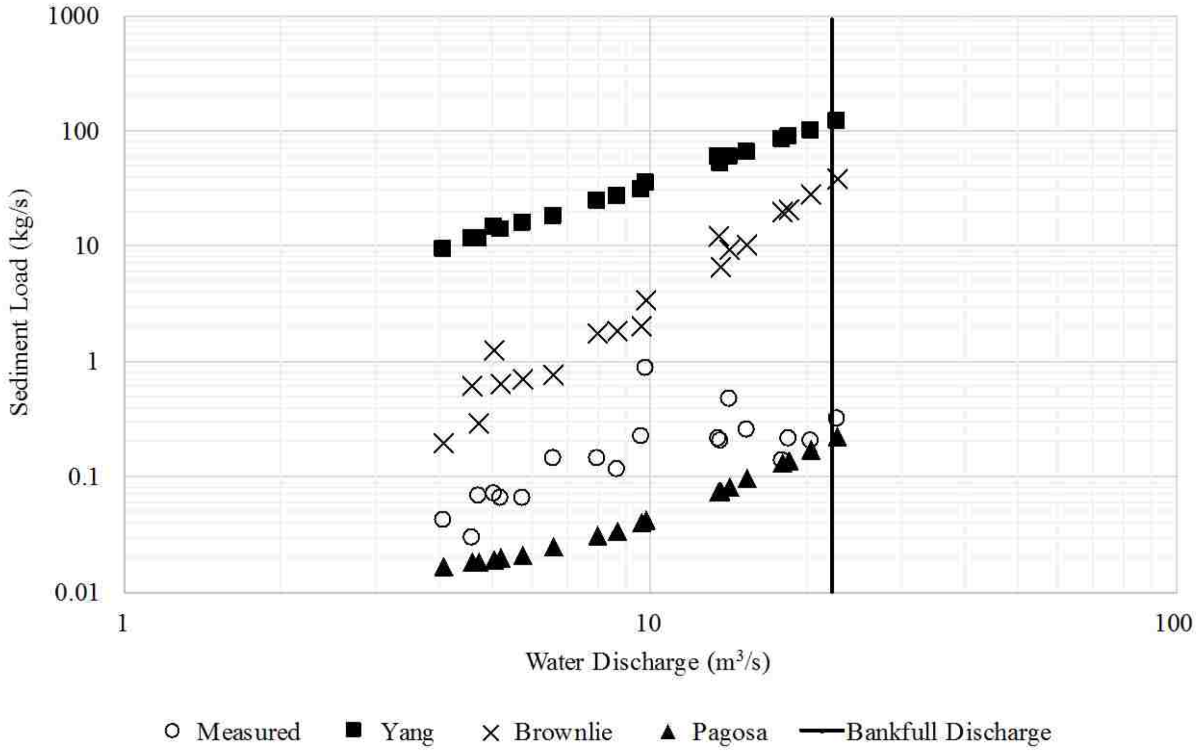

Figure 25: Sediment Rating Curves for Williams Fork near Leal in Colorado

Table 21: RMSEL Values for Williams Fork near Leal in Colorado

Equation	**RMSEL**
Yang	1.484
Brownlie	0.776
Pagosa	0.074

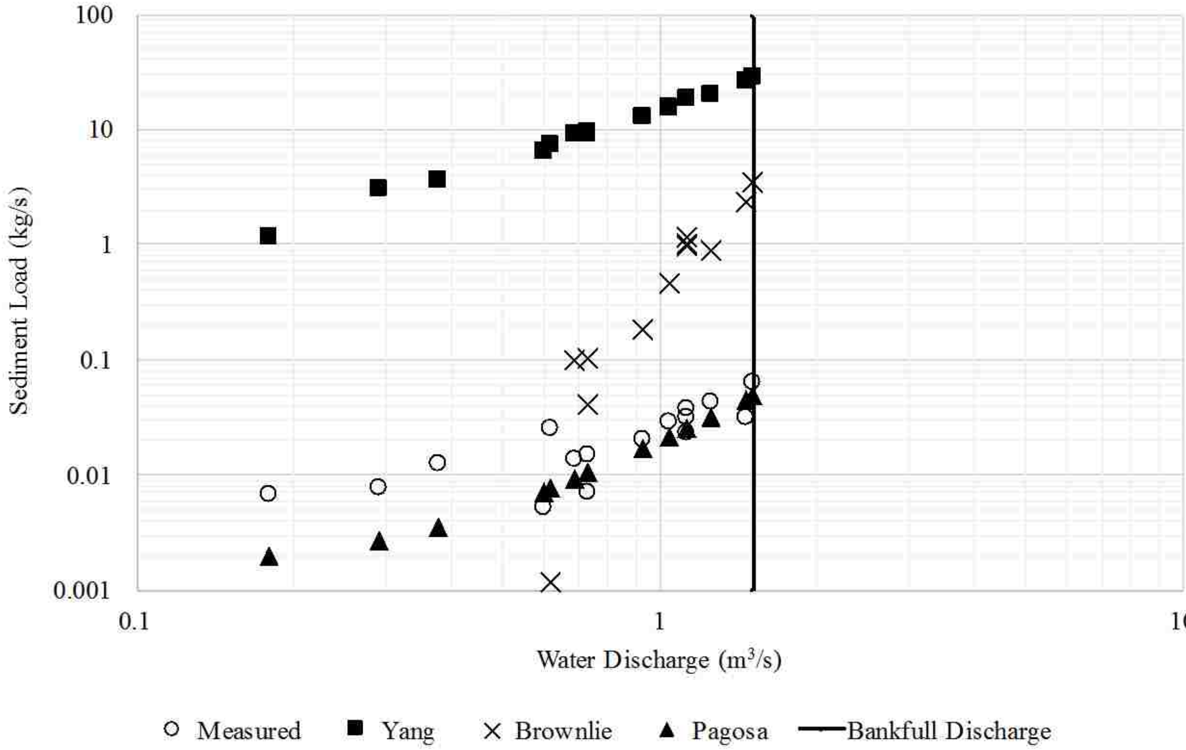

Figure 26: Sediment Rating Curves for Rich Creek near Weston Pass in Colorado

Table 22: RMSEL Values for Rich Creek near Weston Pass in Colorado

Equation	RMSEL
Yang	1.090
Brownlie	0.251
Pagosa	0.004

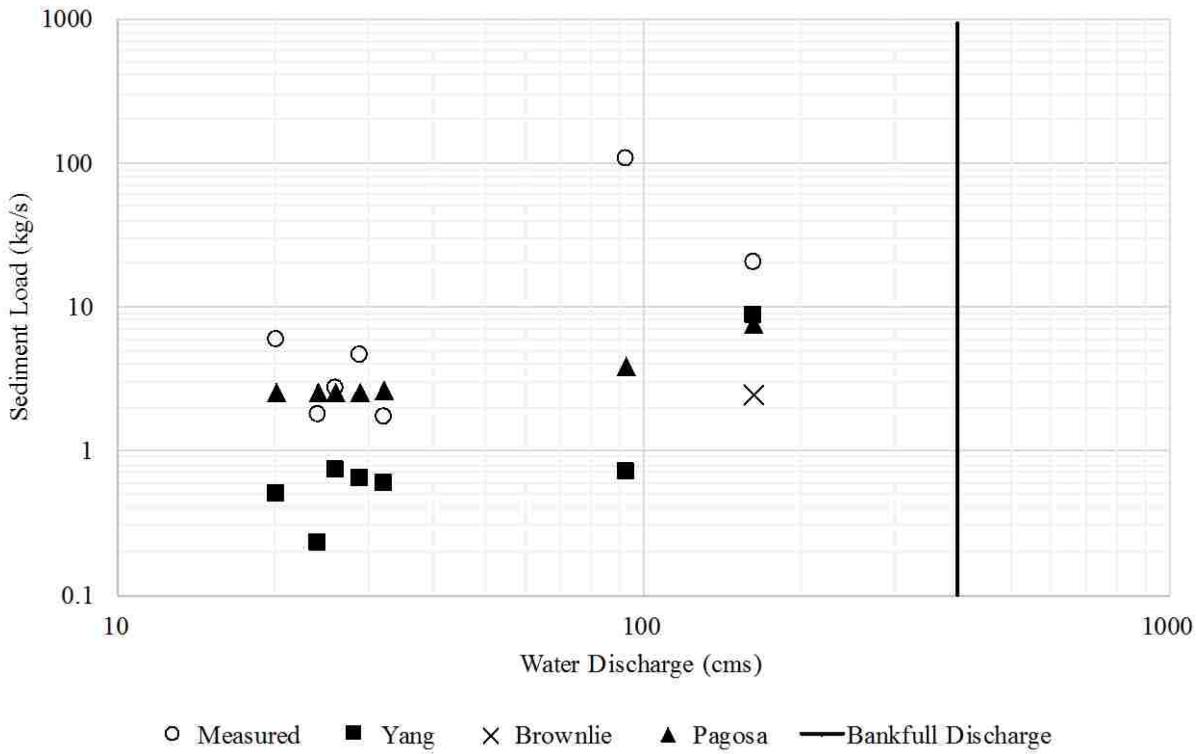

Figure 27: Sediment Rating Curves for the Black River near Galesville in Wisconsin

Table 23: RMSEL Values for the Black River near Galesville in Wisconsin

Equation	RMSEL
Yang	0.790
Brownlie	0.980
Pagosa	0.551

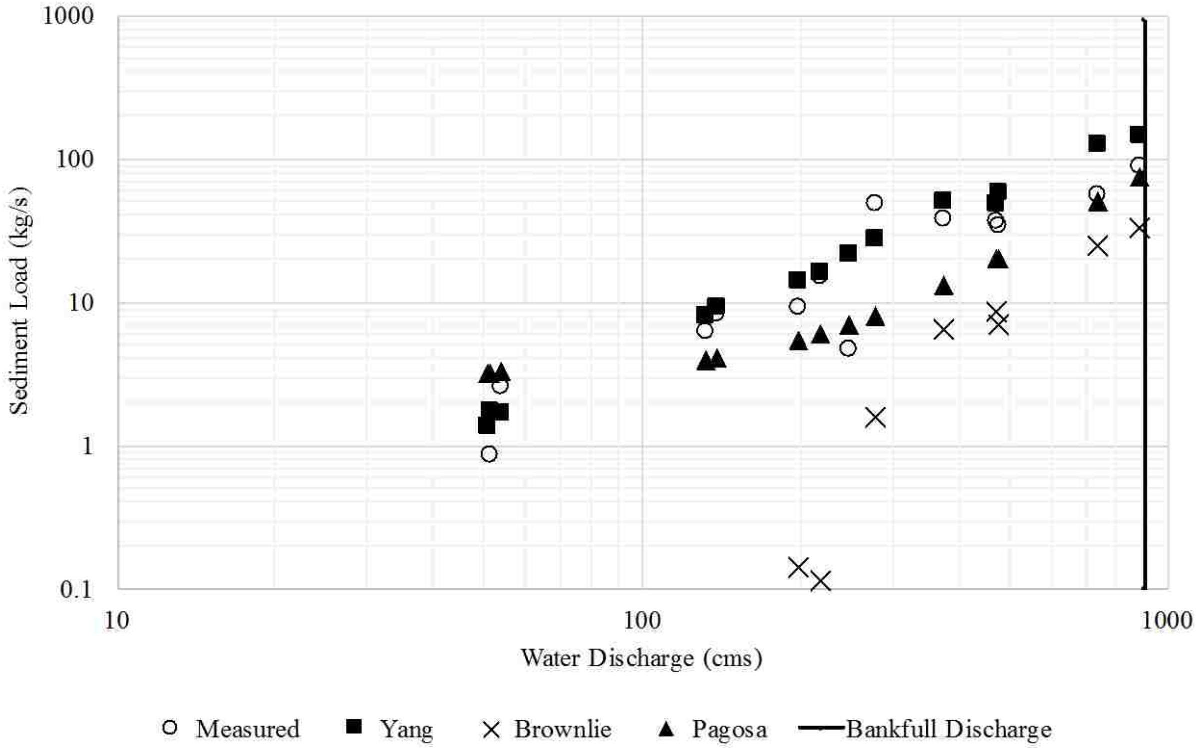

Figure 28: Sediment Rating Curves for the Chippewa River at Durand in Wisconsin

Table 24: RMSEL Values for the ChippewaRiver at Durand in Wisconsin

Equation	RMSEL
Yang	0.232
Brownlie	0.768
Pagosa	0.311

USGS Regression Equations for Colorado

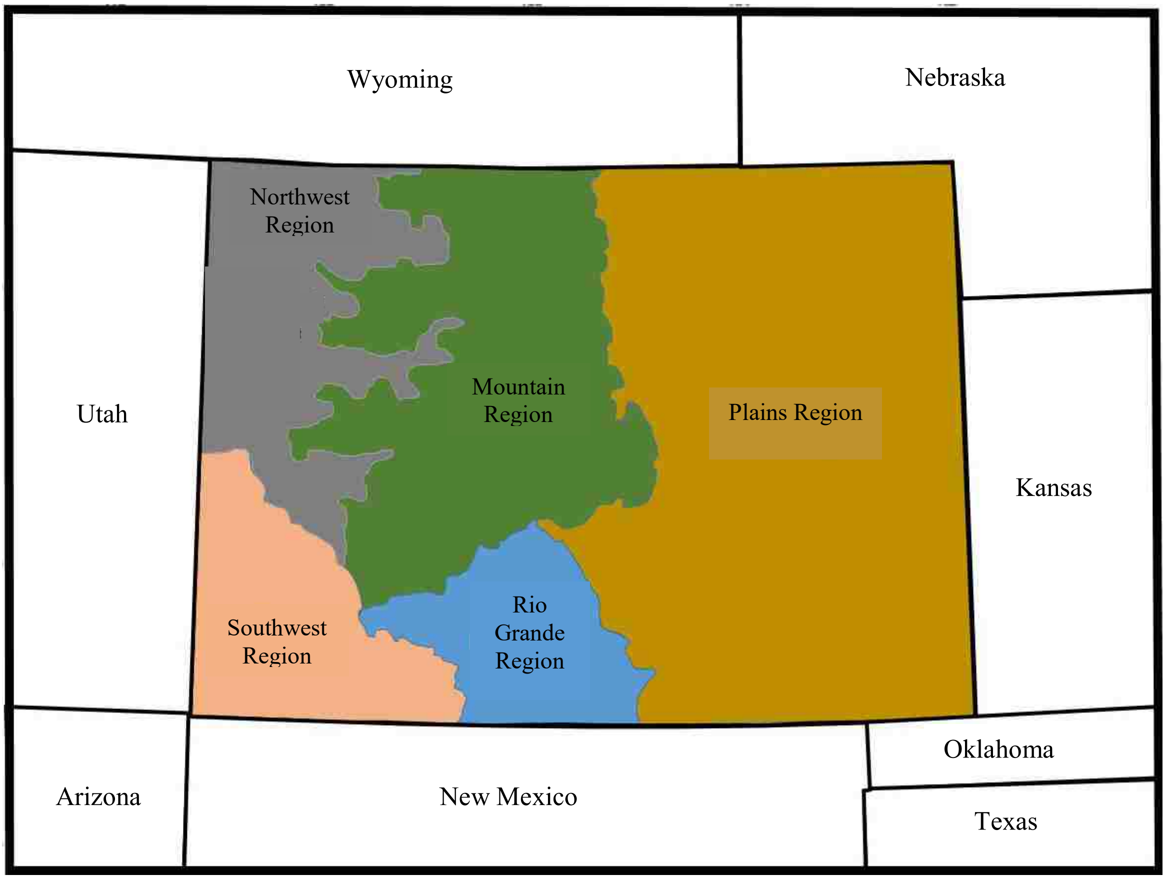

Figure 29: USGS Regions for Colorado Regression Equations

The USGS Regression equations for the Mountain Hydrologic Region of Colorado are:

$$Q_{10} = 10^{-2.64} A^{0.89} P^{2.22} \quad (13)$$

$$Q_{25} = 10^{-2.86} A^{0.96} P^{1.92} \quad (14)$$

$$Q_{50} = 10^{-2.69} A^{0.98} P^{1.49} \quad (15)$$

$$Q_{75} = 10^{-2.85} A^{1.01} P^{1.40} \quad (16)$$

$$Q_{90} = 10^{-3.46} A^{1.10} P^{1.59} \quad (17)$$

Where

A = drainage area [mi^2]

P = mean annual precipitation [in]

The USGS Regression equations for the Northwest Hydrologic Region of Colorado are:

$$Q_{10} = 10^{-6.03} A^{1.03} P^{4.23} \tag{18}$$

$$Q_{25} = 10^{-5.86} A^{1.05} P^{3.72} \tag{19}$$

$$Q_{50} = 10^{-6.07} A^{1.05} P^{3.61} \tag{20}$$

$$Q_{75} = 10^{-6.91} A^{1.07} P^{3.98} \tag{21}$$

$$Q_{90} = 10^{-8.32} A^{1.06} P^{4.80} \tag{22}$$

The USGS Regression equations for the Rio Grande Hydrologic Region of Colorado are:

$$Q_{10} = 10^{-32.35} A^{1.13} E^{8.04} \tag{23}$$

$$Q_{25} = 10^{-41.33} A^{1.07} E^{10.18} \tag{24}$$

$$Q_{50} = 10^{-38.61} A^{0.96} E^{9.46} \tag{25}$$

$$Q_{75} = 10^{-42.09} A^{0.90} E^{10.30} \tag{26}$$

$$Q_{90} = 10^{-50.71} A^{0.89} E^{12.42} \tag{27}$$

Where

E = mean elevation of watershed [ft]

APPENDIX B

The following is a study that was conducted regarding the exponent value of the Pagosa Good/Fair equations for bedload transport.

Introduction

Sediment rating curves show the relationship between discharge in a river and the amount of sediment that is transported. These curves can be used to predict a number of characteristics associated with sediment transport, including erosion within a river and water quality. To determine the amount of sediment that is transported by a given discharge, various equations have been developed. Many of the equations used to create sediment rating curves incorporate a number of morphological characteristics of the river such as the bed slope, the hydraulic radius, and a representative particle diameter of the sediment that is transported.

When a sediment rating curve is created, the exponent of the associated power function that describes the relationship between the river discharge and amount of sediment that is transported varies from river to river. Despite this fact, the Pagosa Good/Fair equation developed by Dr. David Rosgen of Wildland Hydrology (Equation 28) uses a constant exponent of 2.1929 and is said to be a general equation that can be used to develop sediment rating curves for gravel-bed rivers. The purpose of this research, therefore, was to produce a number of sediment rating curves for gravel-bed rivers to compare the corresponding exponents of the power functions to the constant exponent used in the Pagosa Good/Fair equation.

$$G_* = -0.0113 + 1.0139Q_*^{2.1929} \quad (28)$$

Where

G_* = bedload transport term equal to the ratio of the given transport rate with the transport rate at bankfull (dimensionless)

Q_* = discharge term equal to the ratio of the given discharge with bankfull discharge (dimensionless)

Literature Review

The idea that the exponent value in the power function of sediment rating curves varies by river is evident in a number of sediment transport equations. Barry, Buffington, and King (2004) developed a sediment transport equation in the form of a power function. They suggest an empirical exponent value that is determined by the shear stress for the 2-year return discharge, the shear stress required to mobilize the surface layer, and the shear stress required to mobilize the subsurface layer. Thus, the exponent of their power function is based upon characteristics of the stream and is unique for each stream.

Parker (1990) developed a sediment transport equation that is broken up into sediment size classes and incorporates a hiding function similar to that developed by Einstein. Based upon the size class and the hiding function value, the exponent values in the Parker equation changes. Thus, like the Barry equation, in the Parker equation the exponent of the power function is unique for each situation.

Methodology

To produce sediment rating curves whose exponents could be compared to the constant exponent in the Pagosa Good/Fair equation, six different sites (Little Granite Creek, Big Wood

River, Little Slate Creek, Lolo Creek, Rapid River, and Trapper Creek) were selected from the sediment transport database on the Brigham Young University World Water website (Hinton, Hotchkiss, Ames, 2016). For each site, a sediment rating curve was created in log-log scale using both measured transport data from the database and calculated transport data using the Pagosa Good/Fair equation with sediment transport (kg/s) on the ordinate and discharge (cms) on the abscissa. A best-fit power trendline for the measured data was added to each of the graphs and the exponents were compared to the exponent in the Pagosa Good/Fair equation.

Results

Sediment rating curves were created for each of the six sites chosen from the database. Lolo Creek had the lowest exponent value of 1.4145 and Big Wood River had the highest exponent value of 3.5866 as shown in Figure 30 and Figure 31, respectively. The remaining four sediment rating curves for Little Granite Creek, Little Slate Creek, Rapid River, and Trapper Creek can be found in the appendix. A list of all six sites and their corresponding exponent values is displayed in Table 25.

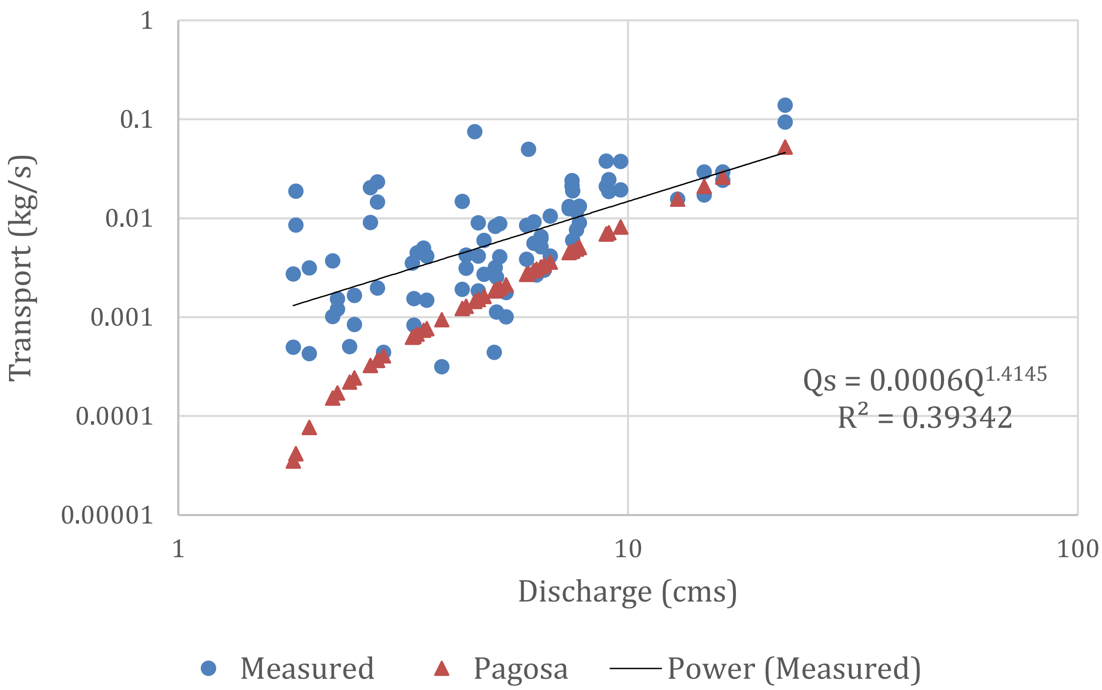

Figure 30: Sediment Rating Curve for Lolo Creek

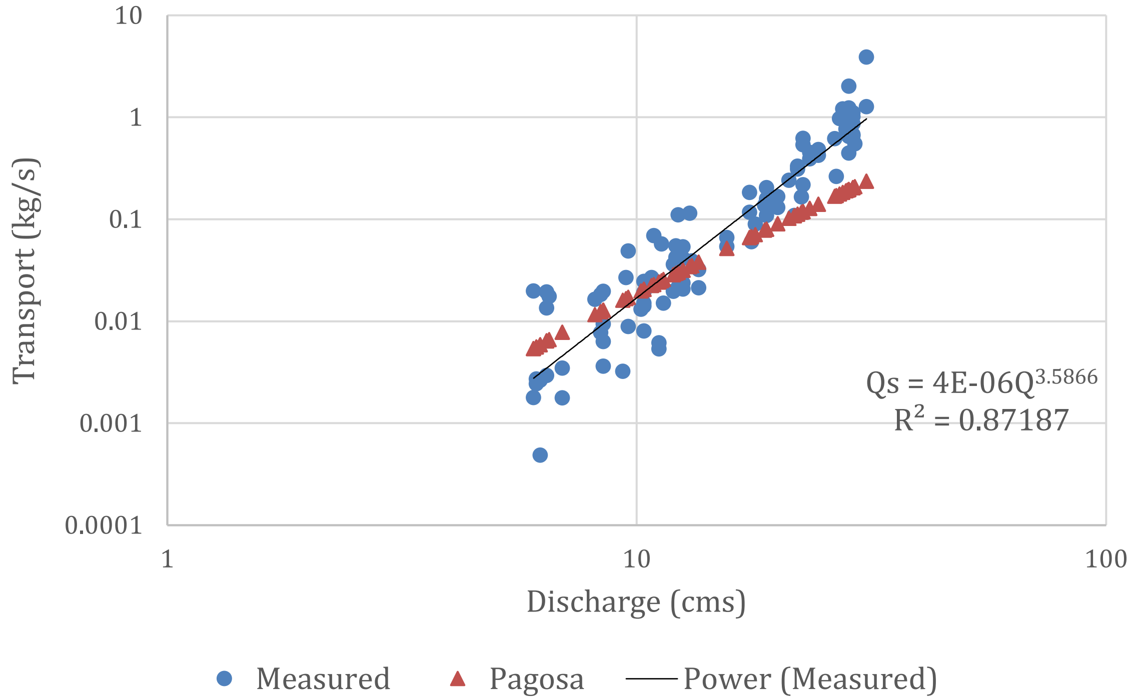

Figure 31: Sediment Rating Curve for the Big Wood River

Table 25: Sediment Rating Curve Exponents

Site	Exponent
Little Granite Creek	2.8638
Big Wood River	3.5866
Little Slate Creek	1.6093
Lolo Creek	1.4145
Rapid River	2.1586
Trapper Creek	1.6998

Discussion of Results

The sediment rating curves produced power functions with exponent values ranging from 1.4145 to 3.5866 (see Table 25). Each of the exponent values was unique for the specific river to which it corresponded. A unique exponent value for each site is expected as each site exhibits morphological characteristics that differ from the others. For this reason, many sediment transport equations use a unique exponent value for each site. However, the Pagosa Good/Fair equation uses a general exponent value of 2.1929 for all gravel-bed rivers.

Although the exponent values in this research were different for each of the six sites, a linear average of the six exponent values produced a value of 2.2221. This linear average value of 2.2221 closely matches the exponent value in the Pagosa Good/Fair equation, suggesting that the Pagosa Good/Fair equation is an averaged equation. In other words, on average, the Pagosa Good/Fair equation produces a sediment rating curve that matches a sediment rating curve produced from measured data.

Conclusion

Sediment rating curves were created for six different sites using data from the sediment transport database on the Brigham Young University World Water website. Best-fit trendlines for the measured data were added to the graphs to produce power functions whose exponent values could be compared to the exponent value of 2.1929 in the Pagosa Good/Fair equation. Each of the six sites had different exponent values ranging from 1.4145 to 3.5866, which supports the idea that sediment rating curves are unique for the site they describe. However, when the exponent values for the six sites were averaged, it produced an exponent value of 2.2221, which closely matches the value used in the Pagosa Good/Fair equation. The averaged exponent value resembling the exponent value in the Pagosa Good/Fair equation suggests that the Pagosa Good/Fair equation is an averaged equation that will, on average, produce a sediment rating curve that matches a sediment rating curve produced from measured data.

References

Barry, J. J., Buffington, J. M., and King, J. G. (2004). "A general power equation for predicting bed load transport rates in gravel bed rivers." *Water Resources Research*, 40 (10), 1-22.

Hinton, D., Hotchkiss, R., Ames, D. P. (2016), "Sediment Transport Database HydroServer." http://worldwater.byu.edu/app/index.php/sediment, Accessed on 03/18/2016.

Parker, G. (1990). "Surface-based bedload transport relation for gravel rivers." *Journal of Hydraulic Research JHYRAF*, *28*(4), 417-436.

Appendix

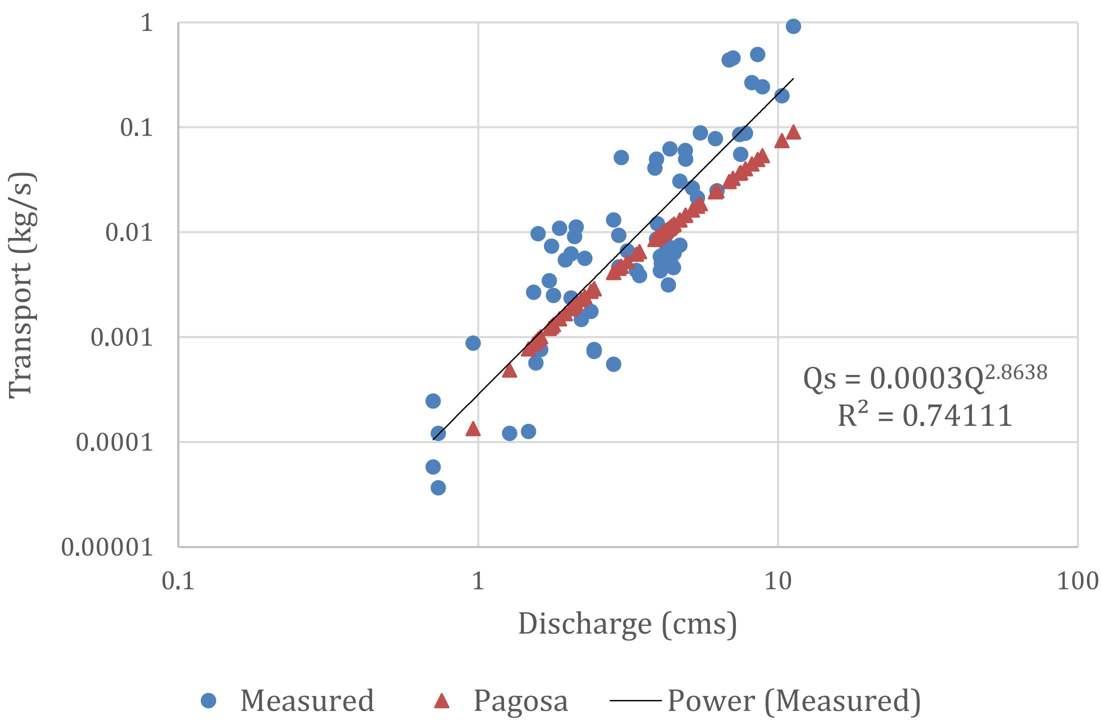

Figure 32: Sediment Rating Curve for Little Granite Creek

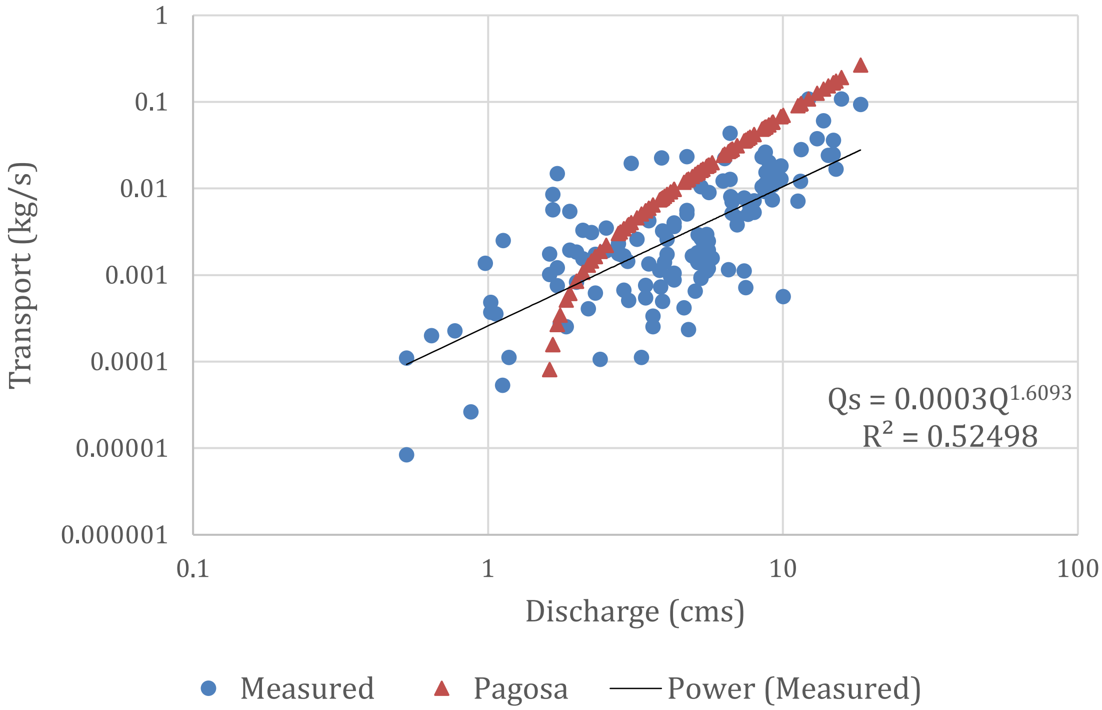

Figure 33: Sediment Rating Curve for Little Slate Creek

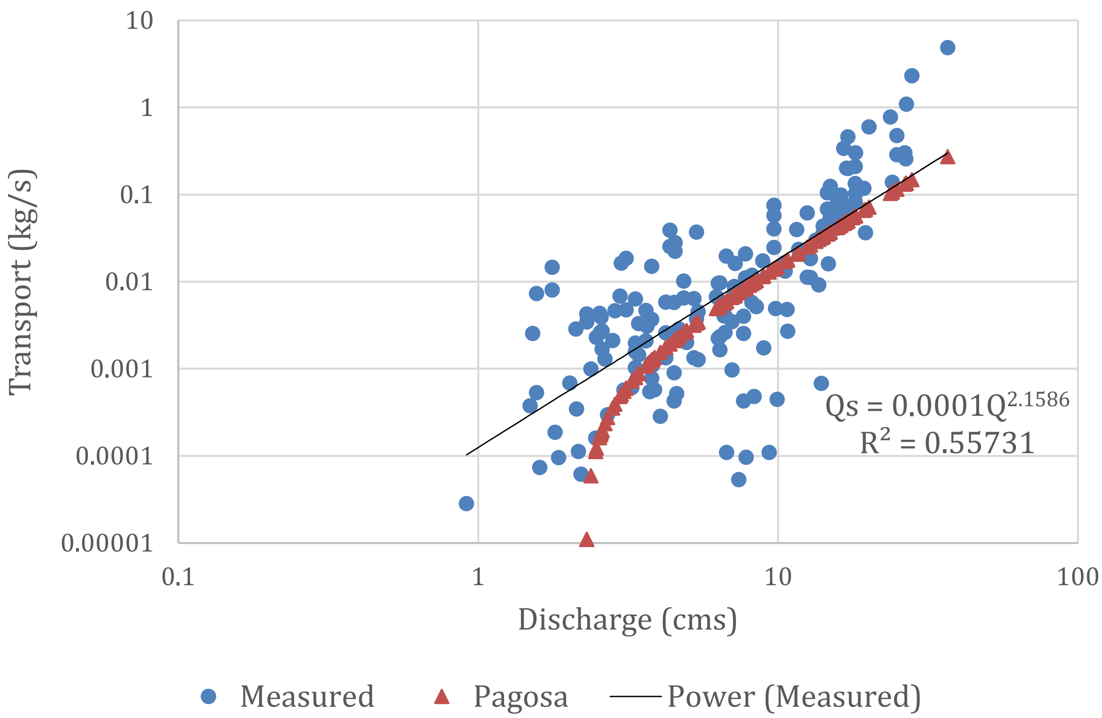

Figure 34: Sediment Rating Curve for the Rapid River

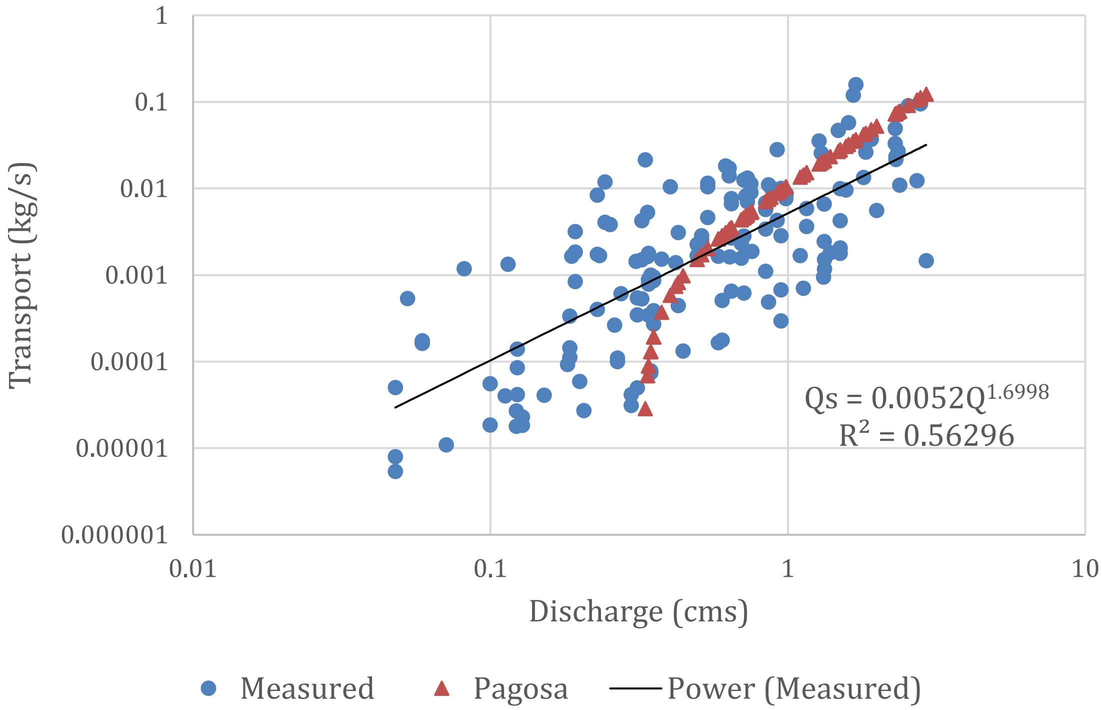

Figure 35: Sediment Rating Curve for Trapper Creek