BEDLOAD DATABASE AND PREDICTION PERFORMANCE

Rollin H. Hotchkiss, Ph.D., P.E., D.WRE, F.ASCE., Professor, Dept. of Civ. & Env. Eng., 368 Clyde Building, Brigham Young University, Provo, UT 84602, Phone: (801) 422-6234, Email: rhh@byu.edu

Darren D. Hinton, P.E., Ph.D., Northwest Hydraulic Consultants, 835 S. 192nd Street, Bldg C, Ste 1300, Seatac, WA 98148, Phone: (206) 241-6000, Email: DHinton@nhcweb.com

Abstract: This topic will be of interest for two reasons: (1) we make available to all interested parties thousands of high-quality bedload transport measurements that can be used in research and applications, and (2) we tested two empirical bedload transport equations using data from the database. We compiled the most comprehensive database to date containing high quality and well-documented bedload sediment transport measurements. We used a subset of the database to test the performance of the Barry et. al 2004 formula and Rosgen's Pagosa Good/Fair (FlowSed) formula. Each method used a single measurement at or near bankfull to calibrate the formula. The ability of each method to predict bedload transport was determined using the Root Mean Square Error of the logarithms of predicted and measured values of bedload. The Pagosa curve provided the greatest accuracy. The varying exponent of the Barry formula approximated the static exponent of the Pagosa formula. By improving bedload transport prediction, stream restoration professionals will have greater confidence in the competency of restored streams and reduce the potential for aggradation or degradation through improved channel design.

INTRODUCTION

Bedload transport formulae for gravel bed streams are used for stream restoration and urban stream design, sediment budget calculations, fish habitat assessment, and mitigating downstream effects of dams [Wilcock et al., 2009]. Unfortunately, despite widespread use, these formulae fail to consistently and accurately predict bedload transport across a wide range of natural conditions [Gomez and Church, 1989; Wong and Parker, 2006]. Due partly to inaccuracies and uncertainties, field measurements are often collected to calibrate formulae. However, bedload sampling is both expensive and difficult, which leads some practitioners to simply apply bedload formulae without calibration [Doyle et al., 2007]. While calibration of bedload formulae is known to improve accuracy [Wilcock, 2001], previous studies have not compared the relative performance of calibrated formulae. Additionally, previous studies have only focused on semi-empirical formulae, which are based on theoretical considerations and then adjusted using flume or field data.

Therefore, the objective of this research was to evaluate and compare the performance of two calibrated bedload transport formulae. Both of the selected formulae were empirical, essentially created by fitting a best-fit curve to large quantities of data. This research employed more measurements than previous comparison studies and used one field measurement near bankfull discharge for calibration. This analysis evaluates the advantage of calibrating a formula with a single measurement. It also evaluates the predictive performance of two formulae not previously examined.

LITERATURE REVIEW

The comparison of bedload transport formulae is not a new idea. Numerous comparison studies of total sediment load (including suspended load and bedload) have been conducted. While many studies

studies favor sand bed channels, some also include elements pertinent to coarse bed channels [Karamisheva et al., 2006; Molinas and Wu, 2001; Pacheco-Ceballos, 1989; Wu et al., 2000]. For example, Yang and Huang [2001] used a large flume data to test a series of formulae that included mostly total load equations with a few interspersed bedload transport equations. They also referenced an additional twelve total load comparison studies largely dealing with total load formulae and sand bed channels.

McLean [1980] reported that very little effort had been made to test bedload predictive formulae on gravel bed streams up until that time. Since that time, a number of comparisons of bedload transport formulae have been conducted. McLean used field data from five rivers (Vedder River near Yarrow, Canada; Elbow River near Bragg Creek, Canada; North Saskatchewan River at Nordegg, Canada; Snake River near Anatone, WA; and Clearwater River near Spalding, FL) to compare bedload predictive formulae. Gomez and Church [1989] used 358 measurements, 90 of which came from flume experiments and the rest from field sampling, to test twelve predictive equations on gravel bed streams. Reid et al. [1996] used data from Nahal Yatir, an ephemeral stream located within the Negev Desert, Israel, to perform a comparison study of six equations. Almadeij & Diplas [2003] used 174 measurements from three gravel-bed streams to test four equations. Bravo-Espinosa et al. [2003] used 1,020 measurements from 22 gravel-bed streams to test seven equations. Martin [2003] used data from the Vedder River in Canada to test four formulae. Barry et al. [2004] used 2,104 measurements from 24 gravel bed rivers in Idaho to test eight different variations of four bed load transport equations. In addition to the equations evaluated in this study, they proposed a new empirical formula calibrated using sub-basin characteristics. Duan et al. [2006] using three formulae tested 14 bedload samples on the Las Vegas Wash, a desert, gravel-bed stream in Las Vegas that conveys effluent wastewater and drainage.

In summary, although there have been many tests evaluating bedload formulae, this present study is warranted for several reasons. First, there are still a significant number of formulae that have not been tested; this study includes two such equations which, uniquely, are empirical. Second, testing of bedload equations has been performed often in the past using increasing numbers of observations with each iteration. The present study improves on past efforts in that it uses a sub-set of a database with more than 8,000 high-quality observations from 160 field sampling datasets (Hinton, 2012).

BEDLOAD TRANSPORT FORMULAE

This study compared the Barry and Pagos bedload transport formulae as summarized in Table 1. The Barry formulae was selected because, first, it is an empirical formula and, second, because of a reference outlining the calibration process [Barry et al., 2004]. The Pagosa formula was selected because it is perhaps the most well-known empirical bedload predictive formula [Lave, 2008; Rosgen et al., 2006; Simon et al., 2007; Simon et al., 2005]. Both formulae used the same sampling methodology for data collection. The following section describes each formula in greater detail.

Table 1 Summary of selected bedload transport formulae

Formula Name	D_{50} Range for Formula Development	Collection Location	Collection Method	Stream Slope
Barry	23 mm – 204 mm	Idaho Streams	Helley-Smith	0.0005 < S < 0.0718
Pagosa	~76 mm[1]	Colorado Streams	Helley-Smith	0.0117

Barry et al. [2004] developed an empirical power relationship between flow and bedload transport derived from Snake River Adjudication data. The Barry et al. general power formula (Barry) was derived for channels with coarse-grained surfaces and takes the form (refer to Table 2 for formula notation):

$$q_b = 257\, A^{-3.41} Q^{(-2.45q^* + 3.56)} \qquad (1)$$

$$q^* = \left(\frac{\tau_{Q_2} - \tau_{D_{50s}}}{\tau_{Q_2} - \tau_{D_{50ss}}}\right)^{\frac{3}{2}} \qquad (2)$$

The Barry formula is essentially a rating curve in which the coefficient is related to the tributary drainage area and the exponent is related to the channel armoring of the site relative to its transport capacity and sediment supply. As such, it may be considered an “off-the-shelf” formula that does not require direct calibration. However, the drainage area coefficient may be calibrated to match measured bedload data. The exponent is not adjusted and is calculated using the average cross-sectional shear stress at bankfull with the critical shear stress required to mobilize the surface and subsurface layers.

Barry et al. [2004] reported there were three streams in their study for which the exponent could not be calculated. This is due to a weakness in how the relative armoring coefficient is calculated. If the total cross-sectional average shear stress at the 2-year return discharge is less than the critical shear stress required to mobilize the D_{50} of either the surface or subsurface, the exponent becomes undefined and can no longer be calculated. It should also be noted that this formula is unable to predict sediment transport by sediment size class or the effects of changing velocity and shear stress.

The Pagosa Good/Fair and Poor (Pagosa) methods were developed by David Rosgen with Helley-Smith data collected from six streams near Pagosa Springs in Colorado [Rosgen et al., 2006]. The data were non-dimensionalized using a measurement of discharge and bedload transport at bankfull and then fit with a power relationship for each stability class [Rosgen et al., 2006]. The two power fit relationships are (refer to Table 2 for formula notation):

$$G_* = -0.0113 + 1.0139 Q_*^{2.1929} \qquad \text{[Good/Fair]} \qquad (3)$$

$$G_* = 0.07176 + 1.0217 Q_*^{2.3772} \qquad \text{[Poor]} \qquad (4)$$

The Good/Fair curve represented three streams exhibiting good/fair stabilities while the Poor curve represented three streams with significant degradation or aggradation. Only the Good/Fair curve is used in this analysis. A disadvantage of the Pagosa formula is that it must always be calibrated using field measurements at bankfull discharge that are difficult to obtain or may not occur during the study period. It also is unable to directly predict sediment transport by sediment size class or the effects of changing velocity and shear stress.

Table 2 Formula notation

Notation	Description	Units
A	drainage area	km^2
G*	bedload transport term equal to the ratio of the given transport rate with the transport rate at bankfull	-
Q	discharge	m^3/s
q_b	unit bedload transport rate	kg/s/m
Q_b	bedload transport rate	kg/s
q*	relative armoring term	-
Q*	discharge term equal to the ratio of the given discharge with bankfull discharge	-
$\tau_{D_{50s}}$	critical shear stress required to mobilize the surface layer	N/m^2
$\tau_{D_{50ss}}$	critical shear stress for the subsurface layer	N/m^2

STUDY METHODOLOGY

The study first commenced with collecting the necessary data. Prior to the bedload comparison effort, a bedload database of more than 8,000 bedload field measurements was compiled as described in Hinton [2012]. Quality bedload measurements from around the world were gathered from sources including published journal articles, direct physical measurements of bedload by the authors, and other researchers' unpublished data. Following data selection, the formulae were calibrated and then statistically analyzed. These three phases are described in more detail in the following paragraphs.

Data selection

Data were selected based on appropriateness and availability of information required to solve the formulae. Sites that produced negative or unrealistic exponents for the Barry formula were not selected. All bedload data selected for the study were collected with Helley-Smith pressure differential samplers.

Nearly 2,300 distinct bedload measurements obtained from 23 sites were included in this comparison. The data represent varying geologic compositions and drainage areas ranging from 3 to 360 square kilometers. Because very few sites included measurements of the bottom channel width, the top width was used instead. Some sites reported bankfull discharge derived from field-based parameters while others approximated bankfull using the 1.5-year discharge calculated using a Log-Pearson Type III analysis of historical stream gage data.

The sites included in this study were coarse bed channels with surface median diameters ranging from 10 to 160 mm. Surface grain size distributions were measured using standard pebble count methodology while subsurface grain size distributions were measured by collecting bulk core

samples on site and then analyzing the composition in the laboratory. Water surface slopes ranged from 0.001 to 0.055. Additional information regarding the sites can be found in the references provided in Table .

Table 3 General information for study sites

Site #	Data Set	State	Number of Samples	Drainage Area (km^2)	Source
1	East St. Louis Creek	CO	109	8	*St. Louis Creek Dataset*[1,2]
2	Fool Creek	CO	95	3	
3	St. Louis Creek Site 1	CO	98	56	
4	St. Louis Creek Site 2	CO	117	54	
5	St. Louis Creek Site 3	CO	107	54	
6	St. Louis Creek Site 4	CO	208	34	
7	St. Louis Creek Site 4A	CO	185	34	
8	St. Louis Creek Site 5	CO	93	21	
9	Little Granite Creek	WY	69	55	*Little Granite Creek Dataset*[2,3]
10	Fivemile Creek	OR	12	91	*Klamath Dataset*[4]
11	South Fork Sprague River	OR	11	161	
12	Sycan River above Marsh	OR	17	256	
13	Annie Creek	OR	20	73	
14	Big Wood River near Ketchum	ID	92	356	*Idaho Dataset*[5,6]
15	Little Slate Creek	ID	134	162	
16	Lolo Creek Data	ID	82	106	
17	Main Fork Red River	ID	174	129	
18	Rapid River	ID	166	280	
19	South Fork Red River	ID	170	99	
20	Trapper Creek	ID	156	21	
21	Fall Creek	CO	81	12	*Rosgen Dataset*[7]
22	Wolf Creek at Bridge	CO	72	47	

[1] *[S E Ryan et al., 2002]*
[2] *Personal Communication. Sandra Ryan-Burkett. 22 Nov. 2010.*
[3] *[S E Ryan and Emmett, 2002]*
[4] *Personal Communication. Walt Lucas. 8 Jun. 2011*
[5] *[Barry et al., 2004]*
[6] *Online content: http://www.fs.fed.us/rm/boise/research/watershed/BAT/index.shtml Access: 21 Oct 2010.*
[7] *Personal Communication. David Rosgen. 13 Jan. 2012.*

Formulae Calibration

Using the methods listed earlier within the Bedload Transport Formulae section, two formulae calibrated with one bedload measurement were compared. The calibration point was used to match predicted values to measured values by adjusting the leading coefficient of the Barry power relationship. The predicted rates were then compared with the actual measurements of transport rate. The Idaho data was used to derive the Barry formulae; however, the calibration process adjusted the coefficient from its standard “off-the-shelf” form.

Statistical Analyses

The root means square error (RMSE) has previously been used [Gomez and Church, 1989] as a statistical comparison between predicted and measured values of bedload transport. The root mean square error can be computed according to Equation 5:

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

where:

x_p = predicted bedload transport (kg/s)
x_m = measured bedload transport (kg/s)
n = number of samples

Because the RMSE accounts for the differences between predicted and measured values, errors associated with higher discharges will be emphasized. In other words, the same percent difference will produce much higher errors for high discharges than for low discharges. To remove this bias, a log transformation was applied to the predicted and measured values by adding 1 to each value and then calculating the base-10 logarithm. The RMSE was then calculated for the transformed values. The transformation and resulting RMSE equation is summarized in Equation 6, referred to as the root mean square error of the logarithmic values (RMSEL).

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

RESULTS AND ANALYSIS

The RMSEL values comparing the logarithms of the predicted and measured rates are reported in Table 4 which include errors for each individual stream. Also included in Table 4 was the exponent calculated for the Barry formula. Figure Figure 1 shows the predicted versus measured transport rate and includes a 1:1 relationship line for comparison. If the predicted values perfectly matched the measured values, they would match the 1:1 relationship line. Both the Barry and Pagosa formulae shown in Figure Figure 1 approximate a 1:1 correlation between measured and predicted values.

The Pagosa formula was most successful at predicting bedload transport with RMSEL values ranging from 0.002 to 0.114. The Barry provided slightly less accurate results with RMSEL values ranging from 0.002 to 0.228. However, both results were comparable as shown in Figure 1. During the data selection process it became evident that the Pagosa formula was easier to apply to various sites because the exponent of the Barry formula becomes undefined if the critical shear stress calculated for the surface and subsurface D_{50} grain size is greater than the average shear stress at the predicted bankfull discharge. On the other hand, it was noted that for very small measured bedload rates the Pagosa formula occasionally erroneously predicted negative transport rates.

As was mentioned previously, the exponent for the Barry formula was calculated using bankfull characteristic and gradations of the channel surface and subsurface. In this analysis, the calculated exponent ranged from 1.24 to 3.53 with a weighted average of 2.47. A rating curve

relating bedload transport to discharge for any given site has been shown to vary between 2 and 5 for Helley-Smith sampling data [Pitlick et al., 2004].

In comparison, the Pagosa formula exponent remains at a static value of 2.19. The Pagosa formula differs from typical rating curves as it relates bedload transport rate to the percent of bankfull discharge, not discharge itself.

Table 4 Bedload transport formulae root mean square error of the logarithms

Data Set	Number of Samples	RMSE (log)		Barry Calculated Exponent
		Barry	Pagosa	
East St. Louis Creek	109	0.005	0.005	1.53
Fool Creek	95	0.002	0.002	1.61
St. Louis Creek Site 1	98	0.026	0.023	2.72
St. Louis Creek Site 2	117	0.024	0.023	2.99
St. Louis Creek Site 3	107	0.023	0.024	2.79
St. Louis Creek Site 4	208	0.014	0.014	2.92
St. Louis Creek Site 4A	185	0.013	0.013	2.78
St. Louis Creek Site 5	93	0.009	0.009	2.30
Little Granite Creek	69	0.031	0.046	2.59
Fivemile Creek	12	0.006	0.005	2.19
South Fork Sprague River	11	0.043	0.002	3.44
Sycan River above Marsh	17	0.077	0.035	2.83
Annie Creek	20	0.056	0.066	1.92
Big Wood River near Ketchum	92	0.099	0.114	3.53
Little Slate Creek	134	0.022	0.015	1.99
Lolo Creek Data	82	0.026	0.007	2.03
Main Fork Red River	174	0.126	0.016	2.99
Rapid River	166	0.228	0.073	2.55
South Fork Red River	170	0.025	0.011	2.60
Trapper Creek	156	0.009	0.009	1.77
Fall Creek	81	0.005	0.005	2.37
Wolf Creek at Bridge	72	0.025	0.022	1.24
All Data	2,268	0.045	0.023	2.47

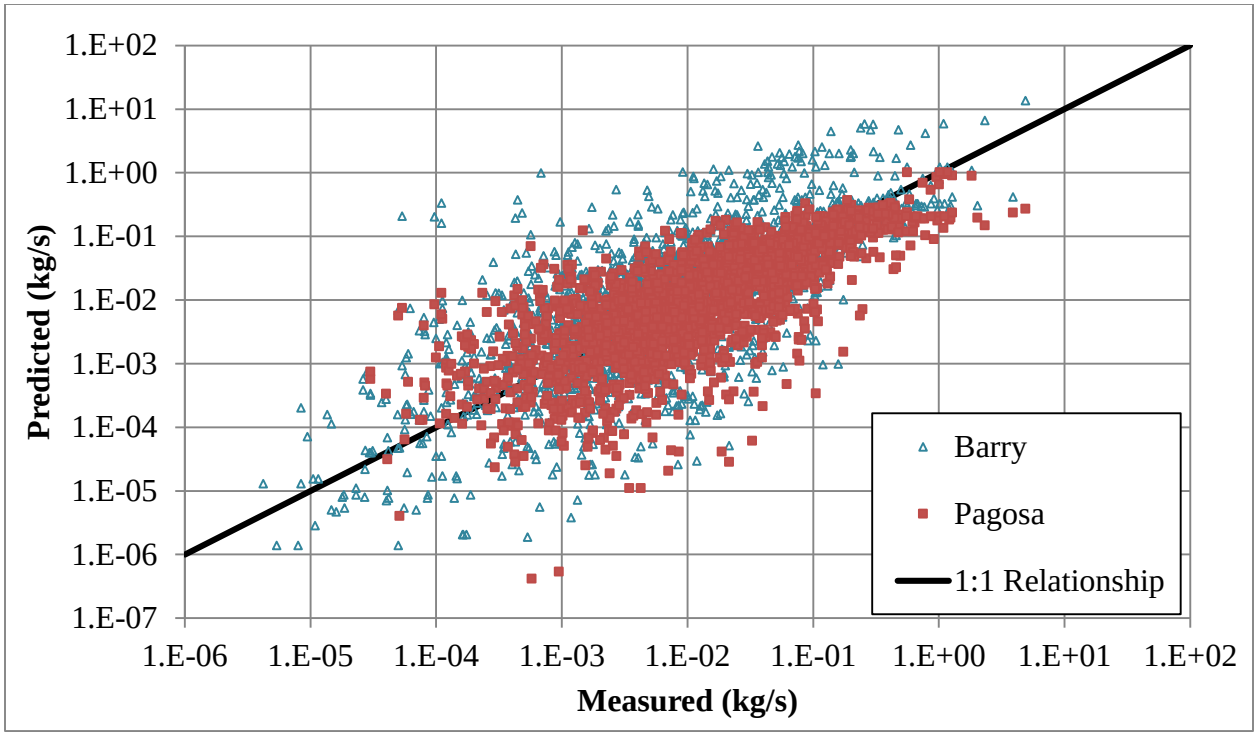

Figure 1 Barry and Pagosa predicted versus measured bedload transport values

CONCLUSION AND RECOMMENDATIONS

Two bedload transport prediction formulae were compared using nearly 2,300 Helley-Smith measurements from 22 different streams in the western United States using calculated RMSEL values. The sites included in this study had water surface slopes, median diameters, and drainage areas between 0.001 and 0.055, 10 and 160 mm, and 3 and 360 km^2, respectively. The performance of these formulae in this study have not previously been compared. Of the formulae compared, the Pagosa Good/Fair equation was the best predictor of bedload transport rates.

The exponent calculated for the Barry formula for the 22 sites varied between 1.2 and 3.5; however, the average value for all data was 2.5. This is compared to the 2.2 exponent of the Pagosa formula.

REFERENCES

Almedeij, J. H., and P. Diplas (2003), "Bedload transport in gravel-bed streams with unimodal sediment," *Journal of Hydraulic Engineering*, *129*(11), 896-904.

Barry, J. J., J. M. Buffington, and J. G. King (2004), "A general power equation for predicting bedload transport rates in gravel bed rivers," *Water Resources Research*, *40*(10), W10401.

Bravo-Espinosa, M., W. Osterkamp, and V. L. Lopes (2003), "Bedload transport in alluvial channels," *Journal of Hydraulic Engineering*, *129*, 783.

Doyle, M. W., D. Shields, K. F. Boyd, P. B. Skidmore, and D. W. Dominick (2007), "Channel-forming discharge selection in river restoration design," *Journal of Hydraulic Engineering*, *133*, 831.

Duan, J. G., L. Chen, and S. Scott (2006), "Application of surface-based bedload transport equations to a desert gravel-bed stream," *Journal of Hydraulic Research*, *44*(5), 624-630.

Gomez, B., and M. Church (1989), "An assessment of bedload sediment transport formulae for gravel bed rivers," *Water Resources Research*, *25*(6), 1161-1186.

Hinton, D. (2012). Complexity of Bedload Transport in Gravel Bed Streams: Data Collection, Prediction, and Analysis. Dissertation, Brigham Young University, Provo, Utah.

Karamisheva, R. D., J. F. Lyness, W. R. C. Myers, and J. O'Sullivan (2006), "Sediment discharge prediction in meandering compound channels," *Journal of Hydraulic Research*, *44*(5), 603-613.

Lave, R. A. (2008), The Rosgen Wars and the Shifting Political Economy of Expertise, Dissertation thesis, 251 pp, University of California, Berkeley, Berkeley, California.

Martin, Y. (2003), "Evaluation of bedload transport formulae using field evidence from the Vedder River, British Columbia," *Geomorphology*, *53*(1), 75-95.

McLean, D. G. (1980), Flood Control and Sediment Transport Study of the Vedder River, Thesis, University of British Columbia, Vancouver.

Molinas, A., and B. Wu (2001), "Transport of sediment in large sand-bed rivers," *Journal of Hydraulic Research*, *39*(2), 135-146.

Pacheco-Ceballos, R. (1989), "Transport of sediments: analytical solution," *Journal of Hydraulic Research*, *27*(4), 501-518.

Pitlick, J., Y. Cui, P. R. Wilcock, and R. M. R. Station (2009), *Manual for Computing Bedload Transport Using BAGS (Bedload Assessment for Gravel-bed Streams) Software*, United States Dept. of Agriculture, Forest Service, Rocky Mountain Research Station.

Reid, I., D. M. Powell, and J. B. Laronne (1996), "Prediction of bed-load transport by desert flash floods," *Journal of Hydraulic Engineering*, *122*(3), 170-173.

Rosgen, D. L., H. L. Silvey, and D. Frantila (2006), *Watershed Assessment of River Stability and Sediment Supply (WARSSS)*, Wildland Hydrology.

Ryan, S. E., and W. W. Emmett (2002), *The Nature of Flow and Sediment Movement in Little Granite Creek Near Bondurant, Wyoming*, US Department of Agriculture, Forest Service, Rocky Mountain Research Station.

Ryan, S. E., L. S. Porth, and C. Troendle (2002), "Defining phases of bedload transport using piecewise regression," *Earth Surface Processes and Landforms*, *27*(9), 971-990.

Simon, A., M. Doyle, M. Kondolf, F. Shields Jr, B. Rhoads, and M. McPhillips (2007), "Critical evaluation of how the Rosgen Classification and associated “Natural Channel Design” Methods fail to integrate and quantify fluvial processes and channel response," *Journal of the American Water Resources Association*, *43*(5), 1117-1131.

Simon, A., M. Doyle, M. Kondolf, F. Shields Jr, B. Rhoads, G. Grant, F. Fitzpatrick, K. Juracek, M. McPhillips, and J. MacBroom (2005), "How well do the Rosgen Classification and associated "Natural Channel Design" Methods integrate and quantify fluvial processes and channel response," *Proc. American Society of Civil Engineers, May*, 15-19.

Wilcock, P. R. (2001), "Toward a practical method for estimating sediment transport rates in gravel bed rivers," *Earth Surface Processes and Landforms*, *26*(13), 1395-1408.

Wilcock, P. R., J. Pitlick, Y. Cui, and R. M. R. Station (2009), *Sediment Transport Primer: Estimating Bed-Material Transport in Gravel-Bed Rivers*, US Dept. of Agriculture, Forest Service, Rocky Mountain Research Station.

Wong, M., and G. Parker (2006), "Reanalysis and correction of bedload relation of Meyer-Peter Muller using their own database," *Journal of Hydraulic Engineering*, *132*, 1159.

Wu, W., S. WANG, and Y. Jia (2000), "Nonuniform sediment transport in alluvial rivers," *Journal of Hydraulic Research*, *38*(6), 427.

Yang, C. T., and C. Huang (2001), "Applicability of sediment transport formulas," *International Journal of Sediment Research*, *16*(3), 335-353.