Complexity of Bedload Transport in Gravel Bed Streams:

Data Collection, Prediction, and Analysis

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A dissertation submitted to the faculty of
Brigham Young University
in partial fulfillment of the requirements for the degree of

Doctor of Philosophy

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December 2012

ABSTRACT

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Bedload transport has long been known for its complexity. Despite decades of research, significant gaps of understanding exist in the ability to assess and predict bedload movement. This work introduces a comprehensive bedload database that is a compilation of 40 years of field samples; compares prediction formulae using a subset of the database; evaluates the influence of the armor layer on stream response to sediment input, presents a mathematically manipulation of the empirical Pagosa Good/Fair formula for bedload transport into a format similar to the semi-empirical Parker Surface-Based 1990 formula; and addresses the complications of bedload transport by collecting bedload samples on a stream in Central Utah.

A comprehensive review of available bedload data resulted in a publicly available database with more than 8,000 individual bedload samples on gravel bed streams. Each measurement included detailed information regarding channel, site, and hydraulic characteristics. A subset of this database was used to compare four calibrated (a single bedload measurement near bankfull discharge is used to improve prediction accuracy) and two un-calibrated bedload prediction formulae. The four calibrated formulae include three semi-empirical (a theoretical treatment adjusted to fit bedload measurements) and one empirical (solely based on regression of bedload measurements) formula; the two un-calibrated formulae are both semi-empirical. Of the formulae compared, the empirical Pagosa Good/Fair formula (a calibrated formula) provided the most accurate prediction results with an overall root mean square error of 6.4%, an improvement of several orders of magnitude over the un-calibrated formulae. The Pagosa Good/Fair formula is cast in a form similar to the Parker 1990 formula, suggesting that criticisms stating that the empirical Pagosa method lacks a theoretical basis are unfounded.

The hypothesis of equal mobility that states the gradation of the average annual gravel bedload yield for a given stream matches the particle size distribution of the subsurface material is evaluated with relation to the armor layer. Equal mobility is found to correlate to armor layer such that lower armor ratios indicate a greater tendency to uphold the equal mobility hypothesis and increasing armor ratio values tending to move toward supply limited conditions. This correlation provides an upper limit for lightly armored streams.

Bedload sampling efforts described in this work compare the Helley-Smith sampler with the net trap sampler and duplicate previous observations that bedload transport collected using net traps increase more rapidly with discharge than for data collected using Helley-Smith samplers. An alternative, relatively low-cost method for collecting bedload during relatively high discharges on highly urbanized streams is also proposed.

Keywords: bedload, sampling, database, bedload prediction, armor layer

ACKNOWLEDGEMENTS

This work represents the expertise, support, and assistance of so many sources. First off, I would like to express my gratitude to those serving as committee members. In particular I need to acknowledge the mentoring and guidance of my two graduate advisors: Blake P. Tullis (USU) and Rollin H. Hotchkiss (BYU). Their advice has been most helpful as a graduate student and as a professional engineer.

I acknowledge the sacrifice and sustaining influence of my wife Accalia. None of this would have happened or been possible without her. I know of her struggles and trials brought on by my research and schooling, many of which far exceeded the challenges I experienced. I acknowledge the sacrifice of my three sons who, despite my best efforts, have had to deal with a distracted and often-absent father. My parents and parents-in-law have also been extremely supportive during this process.

Finally, I acknowledge the divine influence that initiated and coordinated this work. Sparks of intelligence and direction would come in my most desperate hours and during times when my mental capacity was functioning at its lowest level. For some reason, unknown to me, His providence has carried me and completed this work, for which I will ever be grateful.

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1 INTRODUCTION

1.1 Overview

The process by which a river moves entrained sediment by saltating, tumbling, or skipping along the bed surface, referred to as bedload transport [Emmett, 1984; Leopold and Emmett, 1976], is a key characteristic for long term channel stability and health. For instance, bedload transport is directly linked to bank erosion and scour that can threaten nearby roads and bridges. Additionally, bedload movement can complicate stream restoration [Wilcock, 2001], fish spawning [Milhous, 1973; Wilcock and DeTemple, 2005], culvert and channel design, and environmental response to deforestation, such as wildfires [Wilcock et al., 2009]. These and other issues require consistent and accurate methods to predict sediment transport.

Despite over 100 years of research, estimating bedload transport remains difficult at best [Gomez and Church, 1989a]. Much of what we know about sediment transport stems from flume studies, where the basic physical processes have been isolated and documented. However, complexities in nature complicate the basic physics of sediment movement and present details too numerous and diverse to be modeled completely with current methods [Lisle and Madej, 1992].

Several specific factors complicate predicting bedload transport in gravel bed streams. First, quality data are often scarce [King *et al.*, 2004]. To compound the issue, much of the existing data are scattered among academic journals, online databases, and researchers' filing cabinets. Second, predictive formulae, often based on historical bedload data, have failed to gain universal acceptance because of inaccuracy and inconsistency when applied to the wide range of natural conditions found in rivers and streams [Gomez and Church, 1989a; Martin, 2003; Wilcock *et al.*, 2009]. Third, the interchange between sediment input and the channel's surface layer is complicated and not well understood [Almedeij and Diplas, 2003; Lisle, 1995; Parker, 1990; Parker and Klingeman, 1982]. The storing and evacuation of sediment in granular interstices and voids of gravel-bed streams is difficult to model mathematically. Finally, bedload sampling is frequently difficult and dangerous [King et al., 2004]. Significant sediment movement often occurs only at higher discharges at or exceeding flood stage [Wilcock, 2001].

This work begins with the compilation of a bedload transport database. Quality data were located by (1) contacting stream restoration practitioners and researchers who have measured bedload transport in the field and (2) conducting a literature review of published bedload transport data. The resulting data were compiled into a single location with a standard format and a consistent set of units. A subset of this database was then used to compare five bedload predictive formulae. This comparison evaluates the accuracy of a calibrated predictive sediment transport relationship (a single, near bankfull sediment transport data point is used to calibrate the relationship) with non-calibrated methods; the accuracy of empirical and semi-empirical formulae is also evaluated.

Several of the predictive formulae used in the bedload comparison study are based on equal mobility. The equal mobility hypothesis, which relates sediment input to the composition of the channel bed material, is compared to the armor layer composition. Using measurements from the database described previously, a relationship between an equal mobility parameter and the armor ratio is evaluated.

The similarities between empirical and semi-empirical bedload transport formulae are evaluated by the development of a mathematical manipulation between two of the formulae included in the comparison study. The empirical Pagosa Good/Fair Formula is cast in the same form of the semi-empirical Parker Surface-Based 1990 Formula.

Finally, the appendix includes an account of bedload sampling on Hobble Creek in Utah. The sampling methods used are described and a new method for sampling during high discharges in urbanized settings is presented. Data collected on Hobble Creek have been included in the bedload database and were compared with predictions from one of the formulae used in the comparison study described previously.

1.2 Organization

This dissertation is organized into three chapters and one appendix. Each of the above issues will be described completely in a chapter including an introduction, literature review, methods, results, and conclusion. Each individual chapter will be submitted independently for publication in an archived journal. To summarize, Chapter Two will discuss the compilation of the new publicly available bedload database. Chapter Three will compare the performance of several common bedload predictive formulae. Chapter Four will relate the armor layer to sediment input in the form of an equal mobility hypothesis. Chapter Five will describe the mathematical manipulation of the Pagosa formula. The Appendix discusses bedload sampling efforts on a stream during flood stage.

The following represents a summary of the five key contributions from this program.

1.3 Contributions

There are five specific contributions to science as a result of this work:

1. An extensive effort compiling and gathering existing published and unpublished bedload data produced 180 data sets and more than 8,300 separate measurements. Unique to this database is its easy-to-use format and the inclusion of previously unpublished data (approximately 30% of total). Additionally, it provides a guide for what field measurements are needed when sampling bedload. While other databases exist, none are as comprehensive as this one. This database includes unique sections for geomorphology and bankfull geometry. All data have been double-checked and a value code has been added to illustrate completeness and quality. The database is available on a public ftp site.
2. For the first time, a comparison of calibrated bedload formulae is conducted. Although there have been several studies comparing bedload predictions, none have used data at or near bankfull to calibrate the selected equations. The comparison finds that the Pagosa Good/Fair formula is the most successful in predicting bedload transport for gravel bed streams over a wide range of slope and hydraulic conditions.
3. Based on a direct correlation between the armoring and the hypothesis of equal mobility, a new metric for categorizing lightly armored channels is presented for gravel-bed sediment transport studies.
4. For the first time, a unique mathematical manipulation demonstrates that the semi-empirical physically-based Parker 1990 Surface-based Formula is mathematically equivalent to the empirical Pagosa Good/Fair Formula. This shows that physics-based

processes inducing bedload movement are indeed represented in the regression-based Pagosa Good/Fair formula.

5. A new sampling technique, a portable net trap, is described and used to collect bedload measurements. A portable net trap provides a low-cost alternative to sampling bedload during floods exceeding bankfull and/or for high-velocity conditions. Data from portable net traps also provide supporting evidence for claims that the Helley-Smith pressure differential sampler over-predicts transport at low flows and under-predicts at high flows relative to the net trap sampler. Potential reasons for the differences between the two samplers are more clearly understood when considering the performance of this work's portable net trap. This comparison has not been done at the magnitude of discharges encountered during this study.

2 COMPREHENSIVE AND QUALITY-CONTROLLED BEDLOAD TRANSPORT DATABASE

2.1 Introduction

Accurately characterizing and predicting bedload transport in coarse-bed streams has challenged researchers for over a century. Bedload studies conducted in flumes have afforded valuable insights into the basic physical processes influencing transport. However, those processes are masked or disrupted in the field by the complexities of natural fluvial systems. Additional difficulties in the field are caused by temporal and spatial variations in bedload transport [Holmes Jr, 2010; S Ryan and Porth, 1999a] and differences in geographic location and discharge histories.

Access to bedload observations and sampling in the field is necessary to expand the current understanding of sediment transport in coarse-bed streams. Due to the difficulty and expense in collecting reliable field data [King et al., 2004], however, past research has focused on a few quality data sets such as Oak Creek, OR [Milhous, 1973] and East Fork River, WY [Leopold & Emmett, 1976]. There is a great need for additional quality field bedload data [Barry, 2007; Gomez and Church, 1989b] which could be used to assist in the research and analysis of bedload phenomena.

Many quality bedload data are difficult to access or inaccessible as they are scattered throughout various current and outdated scientific journals, posted on government websites, or locked in filing cabinets. Articles referencing bedload measurements made in the field rarely include the raw data in tabular format, preferring instead to display the data graphically. Some researchers have made compiled data available as an appendix in their thesis or dissertation [Almedeij, 2002; Smith, 1990], but the data are limited to the scope of their research and would have to be transcribed to use the data.

The purpose of this paper is to describe a new publicly available database of high quality bedload measurements and associated stream characteristics compiled in this study. The resulting database is larger in scope than any previous effort; includes some previously unpublished data; and is available online in a digital, easy-to-use format.

2.2 Previous Efforts

Perhaps the largest collection of bedload data from one region is the Boise River Adjudication database which can be accessed online [King et al., 2004]. It includes files for 33 separate streams or rivers in Idaho. The files include stream flow, bedload discharge, channel geometry, and bed material information for each site. This database is limited to those streams sampled during the Snake River Adjudication.

Another effort is the Bedload Research International Cooperative (BRIC) which was organized as a collaborative effort to share bedload data among professionals and researchers across the globe. Unfortunately, the BRIC website is not yet operational. The BRIC, when fully functional, intends to provide an accessible location for others to share and contribute new bedload data [Laronne and Gray, 2003]. However, no mechanism has been proposed to transfer existing or historic bedload measurements to the BRIC. Even with a functional BRIC website, a void exists for access to previously collected bedload measurements.

2.3 Database Description

By contacting individual researchers and searching through journal databases (see attached references), a comprehensive and quality-controlled bedload transport database of available data has been compiled in this study. Presented in spreadsheet format, it is simple to use and publicly accessible on an ftp site. It includes more than 8,000 bedload transport measurements for gravel bed streams over a wide range of discharges and geographic locations. Another unique aspect of this database is the inclusion of significant number of unpublished data (Rosgen 2011 & 2012, Pers. Comm.)

After the database was carefully compiled and converted to a consistent set of units, all data were reviewed for quality assurance purposes. The entered data were first compared with the original data to ensure their integrity. Then, looking at various factors, a completeness and value code were assigned to each dataset. For simplicity, the database consists of a single worksheet within a spreadsheet document. The metadata for each data set are included in a header row above the measurements collected at that site. Each row under the header is associated with a single bedload measurement while the columns describe features of the sample. Columns within the database are grouped generally into the following sections: sample description, discharge and transport data, hydraulic and channel characteristics, surface and subsurface particle size distributions (PSD), bankfull characteristics, and stream classification. These sections and the columns falling within them are summarized in Table 2.1 and then described in greater detail in the following discussion.

Table 2.1: Summary of sections and columns in database

Section	Column	Description
Sample Description	Name	Stream or river name
	Region or State	State, territory or region of sampling site, latitude/longitude
	Percent Complete	Identifies the percentage of key columns that contain data
	Value Code	Represents the completeness, size, and legitimacy of dataset
	Number of Samples	Total number of samples collected at that site
	Drainage Area	Area of contributing watershed
	Sampling Method	Sample collection method (e.g. net traps, Helley-Smith)
	Number of Intervals	Number of intervals taken at the cross section per sample
	Sampling Duration	Duration of sampling interval (i.e. 1 minute at each of the 20 intervals at the cross section)
	Number of passes	Passes made at cross section (e.g. 2 passes of 20 intervals each)
	Total Sampling Duration	Total lapsed time during collection
Discharge and Transport Data	Date Collected	Sample date
	Channel Discharge	Average discharge for sampling duration
	Total Bedload Transport	Rate of bedload transport measured
	Particle Size Distribution	11 columns representing bin sizes (0.25 mm to 64 mm)
	Largest Grain Size Moved	Largest particle collected – measuring b-axis
	Bedload D_{50}	Median particle size of bedload sample
Channel and Hydraulic Characteristics	Average Slope	Water surface slope reported for the sampling reach
	Top Width	Measured top width of water surface at sampling time
	Average Depth	Average depth associated with sample
	Mean Cross Sectional Area	Flow area measured or calculated at given discharge
	Average Velocity	Discharge divided by flow area
	Channel Geometry	X-Y point array representing cross section geometry
Surface and Subsurface Particle Size Distributions (PSD)	Subsurface D_{50}	Median particle size for subsurface (mm)
	Subsurface PSD	11 columns representing bin sizes (256 – 0.25 mm)
	Surface D_{50}	Median particle size for surface (mm)
	Surface PSD	13 columns representing bin sizes (1,028 – 0.25 mm)
	Armor Ratio	Ratio of surface D_{50} to subsurface D_{50}
	Measurement Technique	How the PSD was measured (bulk core, pebble count, etc.)
Bankfull Characteristics	1.5-yr Flood	Discharge with 1.5-year recurrence interval
	Bankfull Discharge	Discharge just filling the banks of the cross section
	Bankfull Width	Top width of water surface for given bankfull discharge
	Bankfull Depth	Average depth associated with bankfull discharge
	Bankfull Area	Measured or calculated bankfull discharge area
	Width/Depth Ratio	Ratio of bankfull width to depth
Stream Classification	M&B Morphology	Montgomery & Buffington Morphology Classification
	Stream Order	Stream order classification (1 – 7)
	Max Depth	Maximum depth measured at cross section
	Width Flood-Prone Area	Active floodplain width
	Entrenchment Ratio	Degree of channel entrenchment (using Rosgen definition)
	Valley Slope	Overall valley slope within which the site is located
	Sinuosity k	Ratio of channel slope to valley slope
	Rosgen Classification	Stream classification from A to G
	Rosgen Stream Stability	Good/fair or poor
Source	Misc. Notes	Appropriate comments not covered elsewhere
	Source	Reference to the sample source

2.3.1 Sample Description Section

Each sample includes its name and location. Data are primarily from the Western United States, with a few additional sites from other parts of North America and Europe. Table 2.2 lists the number of datasets from each state or locality.

Table 2.2: Number of datasets and observations by state or region

Location	Number of Data Sets	Number of Observations
Outside of United States	5	524
California	3	240
Colorado	114	2,771
Idaho	35	3,495
Mississippi	1	358
Oregon	9	279
Utah	2	88
Wyoming	14	679
Total	**183**	**8,434**

The "Percent Complete" column reports the completeness of the given dataset based on following 20 primary reporting columns:

1. Drainage area
2. Sampling method
3. Date collected
4. Channel discharge
5. Total bedload transport
6. Bedload particle size distribution (PSD)
7. Bedload median diameter (D_{50})
8. Average slope
9. Top width

10. Average depth

11. Channel geometry

12. Subsurface D_{50}

13. Subsurface PSD

14. Surface D_{50}

15. Surface PSD

16. Bankfull discharge or 1.5-yr Flood

17. Bankfull width

18. Bankfull depth

19. Montgomery and Buffington Morphology Classification

20. Rosgen Classification

Percent complete is the percentage of the key 20 columns for which data were available or for which data could be derived. Each column for which data were available was calculated as five percent of the total. For example, a site with 10 completed columns was assigned a "percent complete" value of 50 percent. If 18 columns had data, the value was 90 percent.

Care was taken to only include quality data. Data published in scientific journals were assumed to have been adequately scrutinized. Unpublished data were collected from sources that were either referenced in the literature or were recommended by other established researchers. An additional parameter was included to compare the relative value of a given dataset or stream with another. The value or quality of the dataset was objectively determined using the value computed in the "Percent Complete" column, the total number of bedload samples, and the number of associated references. The value of a dataset is larger if it provides more supporting field information and if it has more bedload samples than another dataset. Additionally, it was assumed that another reflection of dataset quality was how often it was referenced in the literature. Weighting coefficients were added according to the relative importance of the three parameters used to calculate the value code as shown in Table 2.3. The final value code was calculated as the product of the three parameters. For example, if a dataset was 60 percent complete (1.2), had 40 samples (0.5), and was referenced in the literature two times (1.66), the value code would be 1.0. It should be noted that this value code does not guarantee data quality but is solely intended as a guide.

Table 2.3: Weighting coefficients for value code

Parameter	**Maximum Weighting Coefficient**	**How Applied**
Percent Complete	2.00	Multiplied by percent complete
Number of Samples	1.25	Weighting coefficient was incremental by 10s up to 100 samples. (e.g. 40 samples assigned 0.50; 50 samples assigned 0.63; 100 samples or more received 1.25)
Literature References	2.00	0 references: 1.00 1 reference: 1.33 2 references: 1.66 3 or more reference: 2.00
Total	**5.00**	

Additional information regarding sampling methodology was also reported in this section. Primary sampling methods include the pressure differential sampler (i.e. Helley-Smith, BL-84, etc.) and net traps although other methods were also included. These columns were created specifically to report data for pressure differential samplers; data for other sampling methods were fit into the columns that best fit the procedure.

2.3.2 Discharge and Transport Data Section

As the main crux of the database, this section includes the water discharge and bedload transport rate. A date column for each sample was also included. Figure 2.1 shows the percent of total measurements associated with each year ranging from 1969 to the present.

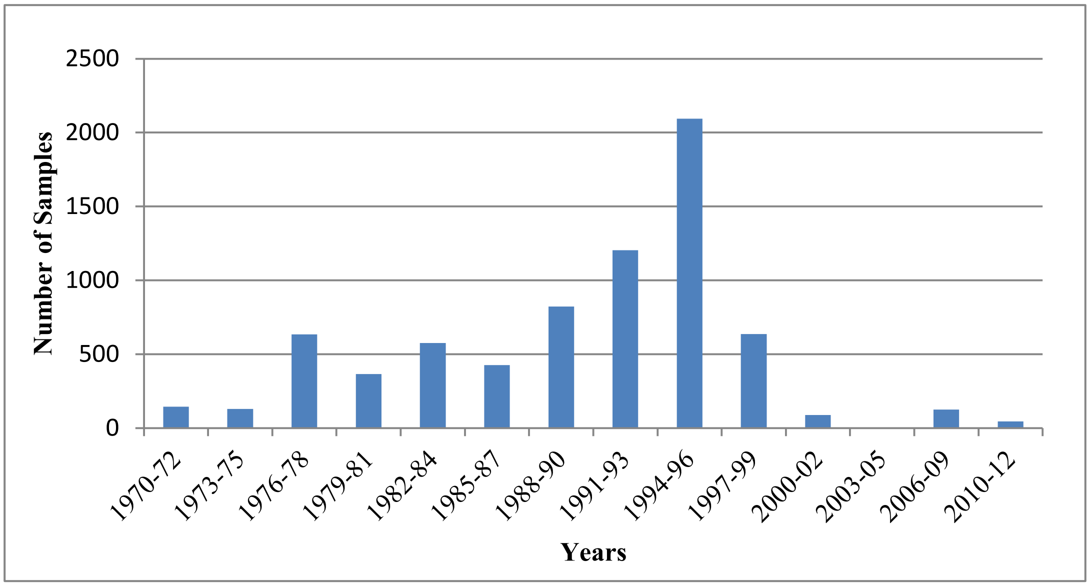

Figure 2.1: Number of samples per year for data included in database.

Where possible, the particle size distribution (PSD) of the bedload including the median diameter and largest grain size moved was included. The PSD was divided into bins of 0.25, 0.5, 1, 2, 4, 8, 16, 32, and 64 mm. Each bin lists the percentage of the total bedload retained on the sieve by weight. The bin range was adequate for the bedload PSDs included in the database.

2.3.3 Channel and Hydraulic Characteristics Section

General channel and hydraulic characteristics such as water surface slope, water surface top width, average depth, and geometry are included. The average depth was taken as the cross-sectional area divided by the top width. If the mean cross-sectional area or mean velocity were reported, those values were used in lieu of calculated values.

In order to include the channel geometry within a single cell, the x and y coordinates defining the cross section were paired together and listed in consecutive order from left to right with each x-y pair contained in brackets (i.e.[x_1,y_1], [x_2, y_2], and so forth). If more than one cross section was available, they were also included in the database.

2.3.4 Surface and Subsurface Particle Size Distributions

When available, the surface PSDs were listed in 13 bins corresponding to 0.25-, 0.5-, 1.0, 2.0, 4.0, 8.0, 16-, 32-, 64-, 128-, 256-, 512-, and 1,024-mm sizes. The subsurface PSDs were listed in 11 bins corresponding to 0.25-, 0.5-, 1.0, 2.0, 4.0, 8.0, 16-, 32-, 64-, 128-, 256-mm sizes. Each bin lists the percent finer by weight. If more than one sample was gathered, then one of two things was done. The first scenario, where the dataset was referenced in a published article, then the available samples gathered using similar methods were averaged together to match the published values. For example, if five pebble counts and three bulk core samples of the surface were reported, the pebble counts were averaged together into one value and the bulk core samples averaged into another. For the second scenario, where the dataset was not referenced in a published article, all collected surface and subsurface sample PSDs were reported separately.

The D_{50} for both the surface and subsurface layers are also included when available. Often, only the D_{50} was reported with no corresponding PSD. Using the D_{50} reported for the surface and subsurface layers, an armor ratio was calculated based on the ratio of the two D_{50} values.

2.3.5 Bankfull Characteristics Section

In stream restoration or bedload transport analysis, the channel-forming discharge is of principal interest [Barry et al., 2008; Doyle et al., 2007]. The bankfull discharge, or that discharge that fills the channel to the brink of its floodplain [Williams, 1978], is often proposed as the channel-forming discharge and is listed often in the literature. Because the bankfull discharge is often associated with a recurrence interval of between 1 and 2 years [Doyle et al., 2007], researchers will often report the 1.5-year discharge in lieu of the bankfull discharge where there is an absence of field indicators.

There is some disagreement as to whether bankfull, 1.5-year, or another (i.e., effective) discharge should be linked to the channel-forming discharge [Crowder and Knapp, 2005; Doyle et al., 2007; Simon et al., 2004; Williams, 1978]. This database seeks to circumvent this issue by reporting both the 1.5-year and bankfull discharges when available. In some cases, both values were listed by the researcher and were included in the database.

Associated with the bankfull discharge are a number of descriptors, some reported and others calculated. These descriptors include the width, depth, area, width-to-depth ratio, and maximum depth associated with the channel-forming discharge. If two values of discharge were reported (i.e. bankfull and 1.5-year), then a note was added to state which discharge was associated to the descriptors.

2.3.6 Stream Classifications

Two systems of stream classification are included in the database: the Montgomery-Buffington Stream Morphology System [Montgomery and Buffington, 1997] and the Rosgen Classification System [Rosgen et al., 2006]. Various parameters important to the classification process were included in the database. These parameters include stream order, maximum depth, width of the flood-prone zone, entrenchment ratio, valley slope, and sinuosity.

2.3.7 Source

The last column in the database cites the data source. Those using this database are encouraged to first refer to the source of the data, if available, before using the raw data for research. A weakness of preparing the bedload data in this format is that the observations associated with the data are often lost. Observations such as surface imbrication, sediment sorting, stability of the channel, upstream disturbances, whether the discharge is on the rising or falling limb of the hydrograph, and other stream conditions are all important in understanding the natural processes affecting bedload transport. Because of the endless observations that could be made on any given stream, it is impractical to include observations within this database. It is the responsibility, then, of the database user to be familiar with the published works associated with and describing sampling efforts for a given dataset and to then identify any observations made in the field by the original researcher. The user must ensure that the data from this database are being used appropriately.

2.4 Data Availability

To allow public access to this database, the spreadsheet has been posted to an ftp site located at the following URL: ftp://bedload.byu.edu. This link will allow any user to download the current version of the database for personal use. A date indicating the last revision to the database is also included. It is anticipated that this database will move to a more dynamic mode that will allow others to contribute such that the database can grow as new data become available.

2.5 Summary and Conclusions

The more high quality bedload data become available to interested parties, the better bedload transport will come to be understood. This database spans a wider range of flow conditions and transport scenarios than previously available, includes more data than currently accessible anywhere else, and includes a significant amount of unpublished data (more than 30 percent of the database). All of the data have been converted to a consistent set of units and a standard format and is available in digital format for others to access. The goal of this database is that it will be used as a tool to understand transport processes and improve bedload transport predictions.

2.6 Acknowledgments

This research was jointly funded by the U.S.D.A. Forest Service Rocky Mountain Research Station and the U.S. Fish and Wildlife Service. We are grateful to numerous researchers who contributed to this work. We appreciate the thoughtful insight and direction from an advisory committee consisting of John Buffington, Yantao Cui, Marwan Hassan, Gary Parker, and Tim Randle. Peter Wilcock's advice and encouragement was also enormously helpful. Finally, we are indebted to David Rosgen, who invited us to his office and made his records available for inclusion in the database.

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Online Resources:

Boise River Adjudication Bedload Database Available at: http://www.fs.fed.us/rm/boise/research/watershed/BAT/Boise%20River.htm

Data for Goodwin Creek, Nahal Yatir, Jacoby Creek, Elbow River, Snake River, and Clearwater River available at: ftp://earth.agu.org/apend/wr/2009wr008007/2009wr008007-ds03.txt

3 A COMPARISON OF CALIBRATED EMPIRICAL AND SEMI-EMPIRICAL METHODS FOR BEDLOAD TRANSPORT RATE PREDICTION

3.1 Introduction

Bedload transport formulae for gravel bed streams are used for stream restoration design, calculating sediment budgets, urban stream design, fish habitat assessment, and the mitigation of downstream effects of dams [Wilcock et al., 2009]. Despite their widespread use, these formulae unfortunately fail to consistently and accurately predict transport across the wide range of natural conditions [Gomez and Church, 1989b; Wong and Parker, 2006]. Because of the uncertainty associated with bedload formulae, bedload transport measurements collected in the field are often used to calibrate or act as a surrogate for a formula. However, bedload sampling is costly and difficult, leading some practitioners to simply use bedload formulae without calibration [Doyle et al., 2007]. While using field measurements to calibrate bedload formulae is known to improve accuracy [Wilcock, 2001], previous comparison studies have not evaluated the relative performance between calibrated formulae. Additionally, previous studies have focused on semi-empirical formulae, which are based on theoretical considerations and then adjusted using flume or field data.

The purpose of this study is to evaluate the performance of three calibrated and one un-calibrated semi-empirical bedload predictive formulae with one calibrated empirical formula. It does so using more measurements than any previous comparison study and calibrates each formula using one field measurement near bankfull discharge. This analysis assesses the benefit of incorporating a single measurement in the calibration of a formula and provides guidance in the selection of an appropriate bedload formula.

3.2 Literature Review

The comparison of bedload transport formulae is not a new idea. Numerous total sediment load (including suspended load and bedload) comparison studies have been conducted. These studies have tended to favor sand bed channels but often 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 relatively large dataset of primarily flume data to test a series of formulae that include mostly total load equations with a few interspersed bedload transport equations. They then list 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. He used field data from five rivers (Vedder River near Yarrow, Elbow River near Bragg Creek, North Saskatchewan River at Nordegg, Snake River near Anatone, and Clearwater River near Spalding) to compare the Meyer-Peter Muller (MPM) formula, used in this study, with two others. The MPM formula over-estimated transport and produced significant erroneous zero-transport predictions.

Gomez and Church [1989b] observed that there were more bedload equations than reliable datasets for comparison for coarse bed streams. They used 358 measurements, 90 of which came from flume experiments and the rest from field sampling, to test twelve equations including the MPM formula on gravel bed streams. None of the formulae, including the MPM, provided satisfactory results. In fact most of the formulae over predicted bedload transport and none were recommended for use in predicting bedload transport. They indicated that bias between measured and calculated values could be minimized by shifting the formula if the trend of the formula matches the data, essentially proposing formula calibration.

Reid et al. [1996] used data from Nahal Yatir, an ephemeral stream located within the Negev Desert, Israel to perform a comparison study. Their work is unique because the bedload represents a gravel-bed stream with no armor layer due to the high amounts of available sediment, also referred to as transport-limited. They tested six equations including the MPM and Parker Surface-based 1990 formula (Parker 1990) and reported the MPM and Parker 1990 formulae provided satisfactory results. The MPM formula performed the best, but it was sensitive to the representative diameter used. The best results for the MPM were reported when using a weighted diameter formulated as $D_m = \sum_{i=1}^{n} f_i D_i$, where f_i is the proportion of the ith size fraction and D_i is the mean grain size for that fraction. Using the D_{50} in lieu of D_m as the effective diameter for the MPM resulted in moving the Parker 1990 formula to the best predictor in their work.

Three bedload comparison studies were published in 2003. Almadeij & Diplas [2003] tested 174 measurements from three gravel-bed streams. They tested 4 equations, one of which was the MPM. None of the tested equations performed overly well, sometimes over or under predicting the transport by one or two orders of magnitude. Bravo-Espinosa et al. [2003] used 1,020 measurements from 22 gravel-bed streams to test seven equations, one of which was the MPM. Although it was not the best predictor, the MPM formula did relatively well at predicting sediment transport in transport limited situations. Martin [2003] used data from the Vedder River and tested four formulae, one of which was the MPM. She reported that all four formulae tended to under predict bedload transport and that the MPM often inaccurately predicted zero transport.

Barry et al. [2004] used 2,104 measurements from 24 gravel bed rivers in Idaho to test eight different formulations of four bed load transport equations including two versions of the MPM formula. In their study, formulae with thresholds (such as the MPM) performed poorly and often erroneously predicted zero transport. Site specific hiding functions did not guarantee better results than "off-the-shelf" functions either.

Duan et al. [2006] collected bedload samples on Las Vegas Wash, a desert, gravel-bed stream in Las Vegas that conveys wastewater effluent and drainage. They then tested fractional transport rates using three formulae including the Parker 1990. Duan et al reported the Parker 1990 formula performed satisfactorily and was best overall at predicting the measured values, although it tended to underestimate transport.

3.3 Bedload Transport Formulae

The five different bedload transport formulae compared in this study are summarized in Table 3.1 and then described in more detail in the following sections. The MPM was selected because of its frequent use in the literature. The Parker 1990 was selected because of its frequent use in the literature and because of a calibration procedure reported for the Parker-Klingeman 1982 Subsurface-Based formula [Bakke et al., 1999; Parker and Klingeman, 1982]. The Parker 1990 formula is the surface-based derivation of the 1982 formula and was more compatible with the other selected formulae in that it uses the surface particle size distribution instead of the subsurface. It was used as a bridge between the calibrated and un-calibrated equations. The Wilcock and Barry formulae were selected because of references outlining the intended calibration process for each [Barry et al., 2004; Wilcock, 2001]. The Pagosa formula was selected because it is perhaps the most well-known empirical formula [Lave, 2008; Rosgen et al., 2006; Simon et al., 2007; Simon et al., 2005].

Table 3.1: Summary of selected bedload transport formulae

Formula Name	Calibrated	D_{50} Range for Formula Development	Where Collected	How Collected	Slope
MPM	No	0.4 – 29 mm[1]	Laboratory	Flume	< 0.02[2]
Parker 1990	No	63 mm	Oak Cr., OR	Vortex sampler	0.008 < S < 0.01
Parker 1990	Yes	63 mm	Oak Cr., OR	Vortex Sampler	0.008 < S < 0.01
Wilcock	Yes	N/A	N/A	Parker 1979, Parker 1990, Flume[2]	N/A
Barry	Yes	23 mm – 204 mm	Misc. Idaho Streams	Helley-Smith	0.0005 < S < 0.0718
Pagosa	Yes	~76 mm	Southwest Colorado	Helley-Smith	0.0117

[1]Arithmetic mean diameter of the sediment
[2]Its range of applicability was extended to steeper channels by subsequent researchers [Wong and Parker, 2006]
[3][Paintal, 1971; Proffitt and Sutherland, 1983]

3.3.1 Meyer-Peter Muller (MPM)

The MPM [Wong and Parker, 2006] was developed in 1948 using flume data. It is included in this study because of its frequent use in practice and research [Almedeij, 2003; Almedeij and Diplas, 2003; Barry *et al.*, 2004; Bravo-Espinosa *et al.*, 2003; Gomez and Church, 1989b; Martin, 2003; Reid *et al.*, 1996]. The MPM originally included a sidewall and bed roughness correction but it was found that the bed roughness correction was unnecessary and the sidewall correction needed to be revised to include more recent research on skin friction and effective roughness [Wong and Parker, 2006]. Its corrected form is:

$$q = \left(\sqrt{Rg}D_{50}^{1.5}\right) 3.97 \left(\tau_b^* - 0.0495\right)^{1.5} \quad (3.1)$$

$$\tau_b^* = \frac{HS}{RD_{50}} \quad (3.2)$$

where q is the predicted unit bedload transport rate (m^3/s/m), R is the submerged specific gravity of sediment, g is the acceleration due to gravity (m/s^2), D_{50} is the median diameter of the surface layer (m), τ^*_b is the dimensionless Shields stress for the bed region of wide channels, H is flow depth (m), and S is slope of the energy grade line (m/m). It should not be used where a high proportion of the bed material is carried in suspension [Gomez and Church, 1989b]. The formula was originally intended for uniformly sorted sediment with slopes less than two percent. Additional research has extended its applicability to channels steeper than two percent [Wong and Parker, 2006].

3.3.2 Parker Surface-Based 1990 (Parker 1990)

The Parker Surface-Based 1990 formula (Parker 1990) consists of three functions that represent successive levels of transport intensity [Pitlick et al., 2009] that take the form:

$$W_i^* = \begin{cases} 11.9\left(1 - \frac{0.853}{\varphi}\right)^{4.5} & for\ \varphi_{50} > 1.59 \\ 0.00218e^{[14.2(\varphi-1)-9.28(\varphi-1)^2]} & for\ 1.0 \leq \varphi_{50} \leq 1.59 \\ 0.00218\varphi^{14.2} & for\ \varphi_{50} < 1.0 \end{cases} \quad (3.3)$$

$$\varphi_{50} = \frac{\tau}{0.0876(\rho g R D_{50})} \quad (3.4)$$

$$\varphi = \omega\varphi_{sg}\left(\frac{D_i}{D_{sg}}\right)^{-0.0951} \quad (3.5)$$

$$\omega = 1 + \frac{\sigma_\varphi}{\sigma_{\varphi o}}(\omega_o - 1) \quad (3.6)$$

$$\varphi_{sg} = \frac{\tau_{sg}^*}{\tau_{rsg}^*} \quad (3.7)$$

$$\tau_{sg}^* = \frac{u_*^2}{(s-1)gD_{sg}} \quad (3.8)$$

$$Q_{b_i} = \frac{W_i^* F_i B u_*^3 \rho_s}{(s-1)g} \quad (3.9)$$

where W_i^* is the dimensionless bedload parameter for each size class of the surface layer gradation, τ is the average cross sectional shear stress (N/m2), 0.0876 is the reference Shields stress, ρ is the density of water, g is the gravitational coefficient (m/s2), R is the submerged specific gravity, D_{50} is the median diameter of the surface (m), φ is a parameter formulated from the nested hiding and sorting functions (φ and ω), D_i is the representative diameter for a given size class, D_{sg} is surface geometric mean diameter, σ_{φ} is the arithmetic standard deviation of the surface distribution on the psi scale [Wilcock et al., 2009], $\sigma_{\varphi o}$ and ω_o are determined graphically from Figure 5 of Parker [1990], $\tau^*_{r_{sg}}$ is the reference Shields stress that is assumed to be 0.0386, u^* is the shear velocity, s is the un-submerged specific gravity of the sediment, Q_{b_i} is the bedload transport rate (kg/s) within a given sediment size class, F_i is the fraction of the surface gradation within a given size class, B is the channel width (m), and ρ_s is the sediment density (kg/m3).

This formula was modified from a subsurface-based bedload equation [Parker and Klingeman, 1982] derived from Oak Creek data. The formula includes a hiding and sorting function and excludes material less than 2 mm in diameter [Parker, 1990]. This formula has the same limitations as the 1982 subsurface-based version: it should only be used on medium or small gravel-bed streams with moderate slopes and only a small percentage of through-put load [Gomez and Church, 1989b; Parker and Klingeman, 1982]. By adjusting the reference Shields stress, the equation can be calibrated to fit field measurements [Bakke et al., 1999; Pitlick et al., 2009].

3.3.3 Wilcock Two-Fraction 2001 (Wilcock)

The Wilcock Two-Fraction 2001 formula (Wilcock) develops separate predictions for sand and gravel portions of bedload that are added together for a total bedload transport rate. The relationships included in this method stem from modifications to several other methods. Wilcock [2001] stresses the composition of the formula, though, is less important than calibrating the formula, which is done by adjusting the reference shear stress to match bedload measurements (described later). A unique aspect of this approach is that a representative grain size for the two fractions is not needed, only the percentage of sand in the surface layer. The formula takes the form:

$$W_g^* = \begin{cases} 11.2\left(1 - 0.846\frac{\tau_{r_g}}{\tau}\right)^{4.5} & for\ \tau > \tau_{r_g} \\ 0.0025\left(\frac{\tau}{\tau_{r_g}}\right)^{14.2} & for\ \tau < \tau_{r_g} \end{cases} \tag{3.10}$$

$$W_s^* = 11.2\left(1 - 0.846\sqrt{\frac{\tau_{r_s}}{\tau}}\right)^{4.5} \tag{3.11}$$

$$Q_{b_g} = \frac{W_g^* f_g \rho_s B u_*^3}{(s-1)g} \tag{3.12}$$

$$Q_{b_s} = \frac{W_s^* f_s \rho_s B u_*^3}{(s-1)g} \tag{3.13}$$

$$Q_b = Q_{b_g} + Q_{b_s} \tag{3.14}$$

where W_g^* and W_s^* are the dimensionless bedload transport parameters of the gravel and sand portions, respectively, of the total bedload rate; τ_{r_g} and τ_{r_s} are the reference shear stresses for gravel and sand (N/m^2), respectively, determined using a least squares regression of bedload measurements; τ is the average cross sectional shear stress (N/m^2); f_g and f_s are the surface fractions of gravel and sand, respectively; ρ_s is the density of sediment; B is the channel width; u_* is the shear velocity; s is the specific gravity of the sediment; g is the acceleration due to gravity; Q_b is the total bedload transport rate (kg/s); and Q_{b_g} and Q_{b_s} are the gravel and sand portions of the bedload transport rate, respectively. Here the reference shear stress is that stress necessary to make the dimensionless bedload parameter W^* equal to 0.002.

The equation is set up so that the reference shear stress is adjusted to match actual bedload samples [Pitlick et al., 2009; Wilcock, 2001]. Wilcock recommends at least one but preferably three samples to reconcile the competing demands of cost and accuracy when predicting bedload transport. With two or more measurements, the adjustment to the reference shear stress (gravel and sand) is done using a least square regression of the bedload samples. With one measurement, as done in this study, the reference shear stress is iteratively adjusted until the predicted values of bedload transport line up with the actual measurement. The formula requires very accurate measurements of small transport and recommends the use of pit or net traps. It should not be used for widely sorted sediment or when predicting channel armoring.

3.3.4 Barry et al. 2004 (Barry)

Barry et al. [2004] developed an empirical power relationship between flow and bedload transport derived from Snake River Adjudication data. The relationship is derived for channels with coarse-grained surfaces (D_{50} between 38 to 204 mm). The formula takes the form:

$$q_b = 257\, A^{-3.41} Q^{(-2.45q^{*}+3.56)} \tag{3.15}$$

$$q^{*} = \left(\frac{\tau_{Q_2}-\tau_{D_{50s}}}{\tau_{Q_2}-\tau_{D_{50ss}}}\right)^{\frac{3}{2}} \tag{3.16}$$

where q_b is the unit bedload transport rate (kg/s/m), A is the drainage area (km^2), Q is the discharge (m^3/s), q* is a relative armoring term, τ_{Q_2} is the total average shear stress at the cross section for a 2-year return discharge (N/m^2), $\tau_{D_{50s}}$ is the critical shear stress required to mobilize the surface layer (N/m^2), and $\tau_{D_{50ss}}$ is the critical shear stress for the subsurface layer (N/m^2).

The Barry et al. general power formula (Barry) is essentially a rating curve where 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. In the exponent, the average cross sectional shear stress at bankfull is compared with the critical shear stress required to mobilize the surface and subsurface layers. Barry et al. [2004] used the 2-year discharge in lieu of the bankfull discharge identified in the field, although they state the discharge associated with bankfull indicators can also be used. The coefficient may be calibrated to fit measured bedload data. Their work included a recommendation that the Barry formula be tested against other sites with different geologies and climatic regimes.

3.3.5 Pagosa Good/Fair and Poor (Pagosa)

The Pagosa Good/Fair and Poor (Pagosa) method was developed by David Rosgen from the data of 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. The two power fit relationships are

$$G_* = -0.0113 + 1.0139 Q_*^{2.1929} \quad \text{[Good/Fair]} \qquad (3.17)$$

$$G_* = 0.07176 + 1.0217 Q_*^{2.3772} \quad \text{[Poor]} \qquad (3.18)$$

where G* is the dimensionless bedload transport term equal to the ratio of the given transport rate with the transport rate at bankfull and Q* is the dimensionless discharge term equal to the ratio of the given discharge with bankfull discharge [Rosgen et al., 2006].

The Good/Fair curve represented the streams (three) exhibiting good/fair stabilities while the Poor curve represented the streams (three) that exhibited significant degradation or aggradation. Only the Good/Fair curve is used in this analysis. Unlike the other formulae in this study, the Pagosa cannot be used in the absence of bedload data. The downside is that its use is predicated on the implementation of a sampling program to collect the necessary measurement(s) prior to its use, while other methods can be used without site specific data.

3.4 Study Sites & Methods

A subset of the bedload database described in Chapter 2 was used to compare the formulae. Data were selected based on the availability of the information necessary to solve the formulae. All bedload data used for comparison were collected with Helley-Smith pressure differential samplers. The features of this sampler including its limitations are described in detail by Emmett [1980] and also by Ryan and Porth [1999a; b]. As discussed in Appendix A, it has been reported that the Helley-Smith sampler tends to over predict sediment transport at low discharges and under predicts at high discharges [Bunte et al., 2010].

The sites included in this study are coarse bed channels with surface median diameters ranging from 10 to 146 mm. Surface grain size distributions were measured using standard pebble count methodology while subsurface grain size distributions were measured by collecting bulk core samples in the field and then analyzing the composition in the laboratory. Water surface slopes ranged from 0.001 to 0.055.

Nearly 2,600 distinct bedload measurements were included from 31 sites. The data represent various geologic compositions with drainage areas ranging from 3 to 16,000 square kilometers. Because few sites included measurements of the bottom channel width, the top width was used for channel width. Some sites, as indicated in Table 3.2, 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. Additional information regarding the sites and measurement techniques can be found in the references shown in Tables 3.2 and 3.3.

Many bedload transport formulae were developed with the following assumptions:

- Steady state for flow and sediment properties
- There is a unique relationship between bedload transport and corresponding flow and sediment properties
- Sediment is being transported at its maximum rate, thus achieving an equilibrium state [Gomez and Church, 1989b]

Table 3.2: Study sites and general information including data source

#	Data Set Name	State	Count	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*[2,3]
10	Fivemile Creek	OR	12	91	*Klamath Dataset*[4]
11	North Fork Sprague River	OR	11	91	
12	Paradise Creek	OR	11	65	
13	South Fork Sprague River	OR	11	161	
14	Sycan River above Marsh	OR	17	256	
15	Annie Creek	OR	20	73	
16	Cherry Creek	OR	22	41	
17	Spencer Creek	OR	22	93	
18	Big Wood River near Ketchum	ID	92	356	*Idaho Dataset*[5,6]
19	Little Slate Creek	ID	134	162	
20	Lolo Creek Data	ID	82	106	
21	Main Fork Red River	ID	174	129	
22	Middle Fork Salmon River	ID	28	2,693	
23	Rapid River	ID	166	280	
24	Salmon River Near Shoup	ID	40	16,151	
25	South Fork Red River	ID	170	99	
26	Thompson Creek	ID	84	56	
27	Trapper Creek	ID	156	21	
28	Fall Creek	CO	81	12	*Rosgen dataset*[7]
29	West Fork San Juan at Bridge	CO	63	131	
30	West Fork San Juan Lower	CO	49	221	
31	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.*

Table 3.3: Channel characteristics of study sites

#	Data Set Name	Average Water Surface Slope[1] *m/m*	Subsurface D_{50ss} *mm*	Surface D_{50s} *mm*	$Q_{1.5}$ *m^3/s*	Q_{bf} *m^3/s*
1	East St. Louis Creek	0.055[1]	13.1	51.0	0.86	-
2	Fool Creek	0.054[1]	14.1	38.0	0.30	-
3	St. Louis Creek Site 1	0.019[1]	16.5	129.0	4.41	-
4	St. Louis Creek Site 2	0.013[1]	14.1	76.0	4.75	-
5	St. Louis Creek Site 3	0.019[1]	16.4	82.0	4.59	-
6	St. Louis Creek Site 4	0.016[1]	12.5	91.0	3.61	-
7	St. Louis Creek Site 4A	0.020[1]	12.7	79.0	3.37	-
8	St. Louis Creek Site 5	0.050[1]	13.3	146.0	2.63	-
9	Little Granite Creek	0.020	18.0	89.0	5.95	6.48
10	Fivemile Creek	0.012	19.4	42.1	-	2.44
11	North Fork Sprague River	0.006	16.1	76.2	-	8.21
12	Paradise Creek	0.003	7.9	31.2	-	6.46
13	South Fork Sprague River	0.007	12.4	66.5	-	5.37
14	Sycan River above Marsh	0.001	5.9	11.2	-	8.92
15	Annie Creek	0.003	4.7	10.0	-	4.45
16	Cherry Creek	0.005	17.1	52.8	-	3.09
17	Spencer Creek	0.001	10.7	13.5	-	3.71
18	Big Wood River near Ketchum	0.009	25.0	119.0	21.86	-
19	Little Slate Creek	0.027	24.0	102.0	-	12.17
20	Lolo Creek Data	0.010	20.0	68.0	-	11.75
21	Main Fork Red River	0.006	18.0	57.0	-	9.34
22	Middle Fork Salmon River	0.004	36.0	146.0	213.76	-
23	Rapid River	0.011	16.0	75.0	-	17.72
24	Salmon River Near Shoup	0.002	28.0	96.3	325.60	-
25	South Fork Red River	0.015	25.0	95.0	-	7.25
26	Thompson Creek	0.015	43.0	62.0	-	2.48
27	Trapper Creek	0.041	17.0	75.0	-	2.56
28	Fall Creek	0.035	13.1	78.4	-	1.13
29	West Fork San Juan at Bridge	0.012	75.9	76.1	-	16.99
30	West Fork San Juan Lower	0.003	43.5	42.1	-	31.15
31	Wolf Creek at Bridge	0.016	42.8	48.9	-	7.93

1 *Values represent average local water surface slope for sampling cross section measured over a distance of 1 to 2 channel widths.*

However, in practice, these same formulae are being used constantly for situations where these assumptions do not apply because of the lack of any other practical or convenient options.

Selecting an appropriate formula for the given situation and hydraulic conditions is a necessary step. Calibration may not be enough to compensate for using the wrong equation for the stream in question because the slope of the predicted values may not match measured data.

Using the methods listed earlier, four formulae with one bedload measurement for calibration and two un-calibrated formulae were tested as shown in Table 3.4. Channel geometry and hydraulic measurements collected simultaneously with the bedload samples were used as input parameters for the various bedload formulae to predict bedload transport. The calibration point was used to match the predicted values to the measured values by adjusting the reference shear stress for the Parker and Wilcock formulae and the leading coefficient of the Barry et al. power relationship. The predicted rates were then compared with the actual measurements of transport rate. The Idaho data and one stream from the Rosgen dataset (West Fork San Juan at the Bridge) were used to derive relationships tested in this analysis; however, no formula was tested using data from which it was derived.

Table 3.4: Bedload transport formulae to be tested

Equation	Calibrated
MPM (2006)	No
Barry et al. (2004)	Yes
Pagosa	Yes
Wilcock 2001	Yes
Parker 1990 (Calibrated)	Yes
Parker 1990 (Uncalibrated)	No

The root means square error (RMSE) was used as a statistical comparison between predicted and measured values of bedload transport. The root mean square error can be taken as:

$$RMSE = \sqrt{\frac{\sum_{i=1}^{n}\left(x_{p,i}-x_{m,i}\right)^2}{n}} \tag{3.19}$$

where x_p is the predicted bedload transport, x_m is the measured bedload transport, and n is the number of samples. A similar comparison was used by others [Gomez and Church, 1989b].

Because the RMSE looks at the differences between predicted and measured values, errors calculated at higher discharges will be emphasized. In other words, relatively small percent differences between predicted and measured values for high discharge will produce much higher errors than the same relative difference for low discharge. 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 applied to the transformed values. The transformation and resulting RMSE equation is summarized in Equation 3.20, referred to as the root mean square error of the logarithmic values or RMSEL.

$$\text{RMSEL} = \sqrt{\frac{\sum_{i=1}^{n}\left(\log_{10} x_{p,i} - \log_{10} x_{m,i}\right)^2}{n}} \tag{3.20}$$

3.5 Results and Discussion

The RMSE and RMSEL values comparing predicted and measured bedload transport rates and the logarithms of the predicted and measured rates are reported in Tables 3.5 through 3.7. The tables are grouped by source and report errors for each stream individually. Overall errors for five scenarios are shown at the bottom of Tables 3.5 and 3.6. Table 3.7 shows the RMSEL summary divided by discharge classes relative to bankfull.

The four calibrated formulae produced lower errors than the two un-calibrated formulae. A direct comparison between the two Parker 1990 formulae shows that calibration significantly improved accuracy. However, calibration cannot be used as a substitute for selecting the appropriate equation for a given situation. This is obvious from the wide range of errors reported for calibrated formulae in the following tables.

Table 3.5: Root mean square errors (RMSE) reported for six prediction formulas and 31 streams

Data Set Name	Count	MPM	Barry	Pagosa	Wilcock	Parker Calib.	Parker Uncalib.
		RMSE	RMSE	RMSE	RMSE	RMSE	RMSE
East St. Louis Creek	109	80.8	0.011	0.011	0.789	0.315	0.955
Fool Creek	95	16.2	0.006	0.005	0.220	0.284	2.71
St. Louis Creek Site 1	98	4.97	0.070	0.063	3.04	1.01	6.33
St. Louis Creek Site 2	117	7.28	0.066	0.062	3.60	0.741	0.120
St. Louis Creek Site 3	107	2.37	0.067	0.069	2.37	0.622	5.56
St. Louis Creek Site 4	208	1.94	0.033	0.034	0.671	0.305	0.180
St. Louis Creek Site 4A	185	4.11	0.032	0.031	5.08	0.647	2.84
St. Louis Creek Site 5	93	52.3	0.021	0.021	0.576	32.3	1,110
Little Granite Creek	69	17.0	0.098	0.140	1.54	0.261	3.87
Fivemile Creek	12	10.6	0.014	0.012	0.016	0.017	0.017
North Fork Sprague River	11	0.020	N/A	0.009	0.017	0.020	0.355
Paradise Creek	11	0.023	N/A	0.011	0.015	0.021	0.198
South Fork Sprague River	11	0.015	0.115	0.004	24.3	3.60	1.93
Sycan River above Marsh	17	0.214	0.945	0.104	0.598	1.40	0.191
Annie Creek	20	0.738	0.257	0.295	99.5	5.08	6.70
Cherry Creek	22	0.007	N/A	0.006	0.020	0.435	0.551
Spencer Creek	22	0.002	N/A	0.002	0.002	0.026	0.011
Big Wood River near Ketchum	92	0.450	-	0.523	2.70	0.639	9,160
Little Slate Creek	134	141	-	0.038	8.80	0.996	2.52
Lolo Creek Data	82	35.1	-	0.017	2.16	0.450	0.049
Main Fork Red River	174	0.916	-	0.041	0.124	3.11	9.03
Middle Fork Salmon River	28	8.04	-	7.52	167	12.0	153
Rapid River	166	10.4	-	0.412	9.74	0.432	5.56
Salmon River Near Shoup	40	15.0	-	13.5	17.6	12.9	26.9
South Fork Red River	170	5.52	-	0.028	1.69	1.73	2.40
Thompson Creek	84	0.914	-	0.033	0.850	0.172	0.783
Trapper Creek	156	60.1	-	0.022	0.042	36.6	28.8
Fall Creek	81	5.42	0.013	0.013	1.10	0.277	1.99
West Fork San Juan at Bridge	63	26.0	0.236	-	36.7	3.54	10.7
West Fork San Juan Lower	49	0.134	N/A	0.095	0.999	0.050	3.32
Wolf Creek at Bridge	72	48.8	0.064	0.058	3.33	0.260	15.9
All Samples	2,598	42.2	-	-	20.8	11.1	1,740
Idaho Data Excluded	1,339	30.4	0.086	-	14.9	8.60	294
Rosgen Data Excluded	2,533	42.5	-	1.88	20.2	11.2	1,760
Idaho & Rosgen Data Excluded	1,409	29.2	0.065	0.064	12.3	8.35	286
Gravel Bed Streams	780	36.0	0.306	0.062	16.3	1.76	6.67

(-) Indicates dataset was used to derive the given formula; (N/A) The formula was unable to make a prediction.

Table 3.6: Root mean square error of the logarithms (RMSEL) for the base 10 logarithm of the predicted and measured values reported for six prediction formulas and 31 streams

Data Set Name	Count	MPM	Barry	Pagosa	Wilcock	Parker Calib.	Parker Uncalib.
		RMSE (log)	RMSE (log)	RMSE (log)	RMSE (log)	RMSE (log)	RMSE (log)
East St. Louis Creek	109	1.86	0.005	0.005	0.141	0.100	0.224
Fool Creek	95	1.12	0.002	0.002	0.067%	0.088	0.380
St. Louis Creek Site 1	98	0.382	0.026	0.023	0.263	0.225	0.755
St. Louis Creek Site 2	117	0.458	0.024	0.023	0.336	0.142	0.045
St. Louis Creek Site 3	107	0.268	0.023	0.024	0.209	0.126	0.555
St. Louis Creek Site 4	208	0.250	0.014	0.014	0.121	0.085	0.056
St. Louis Creek Site 4A	185	0.381	0.013	0.013	0.336	0.148	0.431
St. Louis Creek Site 5	93	1.390	0.009	0.009	0.084	0.514	2.36
Little Granite Creek	69	0.792	0.031	0.046	0.162	0.070	0.433
Fivemile Creek	12	1.06	0.006	0.005	0.007	0.007	0.007
North Fork Sprague River	11	0.008	N/A	0.004	0.007	0.008	0.115
Paradise Creek	11	0.001	N/A	0.005	0.006	0.009	0.074
South Fork Sprague River	11	0.007	0.043	0.002	0.644	0.356	1.93
Sycan River above Marsh	17	0.079	0.077	0.035	0.134	0.207	0.069
Annie Creek	20	0.195	0.056	0.066	1.23	0.407	0.487
Cherry Creek	22	0.003	N/A	0.003	0.008	0.104%	0.121
Spencer Creek	22	0.001	N/A	0.001	0.001	0.011	0.005
Big Wood River near Ketchum	92	0.117	-	0.114	0.217	0.099	3.36
Little Slate Creek	134	1.91	-	0.015	0.238	0.126	0.255
Lolo Creek Data	82	0.969	-	0.007	0.209	0.095	0.019
Main Fork Red River	174	0.120	-	0.016	0.039	0.127	0.212
Middle Fork Salmon River	28	0.731	-	0.550	0.662	0.355	1.29
Rapid River	166	0.510	-	0.073	0.185	0.075	0.417
Salmon River Near Shoup	40	0.923	-	0.520	0.604	0.646	0.720
South Fork Red River	170	0.336	-	0.011	0.113	0.120	0.138
Thompson Creek	84	0.157	-	0.013	0.142	0.055	0.163
Trapper Creek	156	1.33	-	0.009	0.015	0.219	0.207
Fall Creek	81	0.578	0.005	0.005	0.131	0.069	0.265
West Fork San Juan at Bridge	63	0.924	0.062	-	0.404	0.220	0.618
West Fork San Juan Lower	49	0.051	N/A	0.034	0.046	0.047	0.137
Wolf Creek at Bridge	72	1.53	0.025	0.022	0.239	0.065	0.716
All Samples	2,598	0.884	-	-	0.244	0.185	0.858
Idaho Data Excluded	1,339	0.894	0.026	-	0.279	0.193	0.747
Rosgen Data Excluded	2,533	0.883	-	0.093	0.239	0.184	0.863
Idaho & Rosgen Data Excluded	1,409	0.849	0.021	0.021	0.258	0.184	0.718
Gravel Bed Streams	780	0.988	0.035	0.019	0.246	0.123	0.306

(-) Indicates dataset was used to derive the given formula; (N/A) The formula was unable to make a prediction.

Table 3.7: Summary of root mean square error of the logarithms (RMSEL) segregated by percent of bankfull.

	MPM	Barry	Rosgen	Wilcock	Parker (C)	Parker (UC)
		RMSEL	RMSEL	RMSEL	RMSEL	RMSEL
				Less Than 50% Bankfull		
All Samples	0.684	-	-	0.079	0.166	0.756
Idaho Data Excluded	0.545	0.014	-	0.123	0.226	0.667
WF San Juan (Bridge) Data Excluded	0.692	-	0.007	0.081	0.168	0.766
Idaho & WF San Juan (Bridge) Data Excluded	1.097	0.023	0.012	0.128	0.267	1.217
Gravel Bed Streams	1.211	0.028	0.013	0.144	0.298	1.350
				Between 50% and 120% Bankfull		
All Samples	1.001			0.182	0.141	0.888
Idaho Data Excluded	0.950	0.022		0.201	0.138	0.723
WF San Juan (Bridge) Data Excluded	1.013		0.038	0.184	0.143	0.899
Idaho & WF San Juan (Bridge) Data Excluded	1.208	0.060	0.045	0.221	0.171	1.072
Gravel Bed Streams	1.817	0.099	0.068	0.331	0.257	1.609
				Greater than 120% Bankfull		
All Samples	1.113			0.666	0.370	1.129
Idaho Data Excluded	1.071	0.048		0.657	0.263	0.807
WF San Juan (Bridge) Data Excluded	1.120		0.292	0.670	0.373	1.136
Idaho & WF San Juan (Bridge) Data Excluded	1.453	0.472	0.378	0.870	0.485	1.475
Gravel Bed Streams	2.487	0.841	0.645	1.492	0.832	2.523

Errors in Table 3.7 increase with discharge. Errors for discharges less than 50 percent bankfull were less than for discharges between 50 and 120 percent bankfull. The errors between the first two categories (less than 50 percent and 50 – 120 percent) also tend to be smaller than the difference between the last two categories (50-120 percent and greater than 120 percent).

Gomez and Church [1989b] observed that if a formula matched the general trend of the data, prediction could be improved by shifting the formula up or down to match the data. The shifting of the formula mentioned in their analysis is essentially the calibration process used in this analysis. The biggest factor affecting the accuracy of the formulae was the slope of the predicted values versus discharge. The comparison data for all formulae were divided between three graphs for clarity. Figures 3.1, 3.3, and 3.3 show the predicted versus measured transport rate and include a 1:1 relationship line for comparison. If the predicted values perfectly matched the measured values, they would fall right on top of the 1:1 line. These figures also illustrate the difference in slopes between the different methods. The Barry and Pagosa formulae shown in Figures 3.1 and 3.2 approximate a 1 to 1 correlation between measured and predicted values. The Parker 1990 and Wilcock 2001 formulae in Figure 3.2 and Figure 3.3, however, exhibit a much steeper slope, under predicting low transport and over predicting high transport relative to the measured data. The MPM, shown in Figure 3.1, appears to predict a constant value over the range of predicted values.

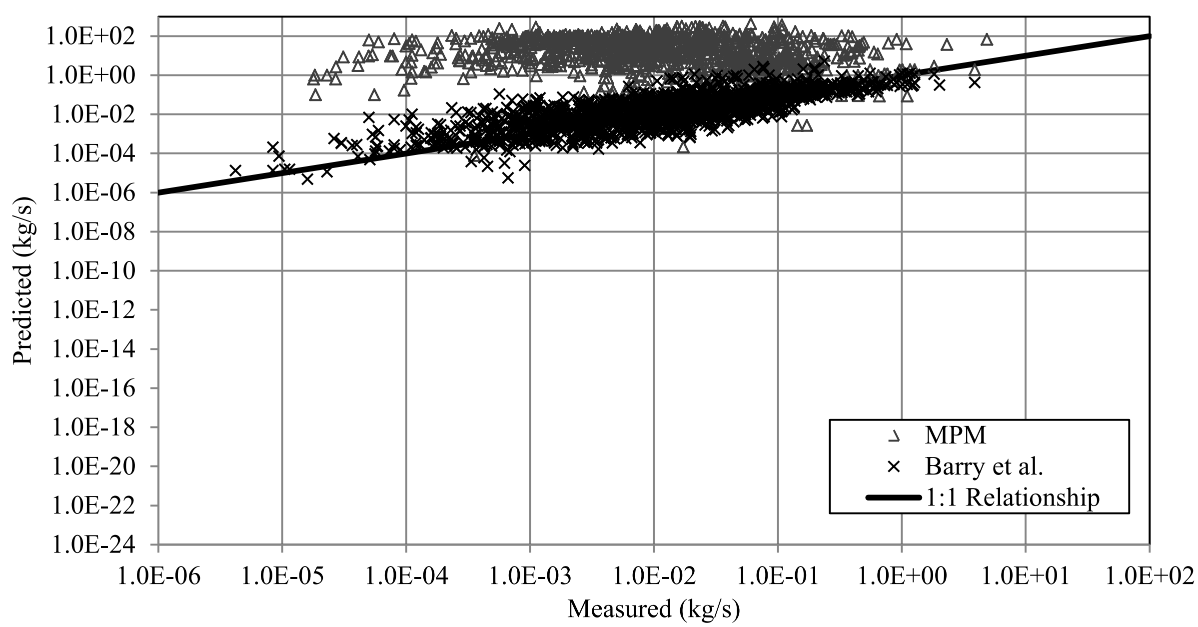

Figure 3.1: Predicted versus measured values of transport for the MPM and Barry formulae

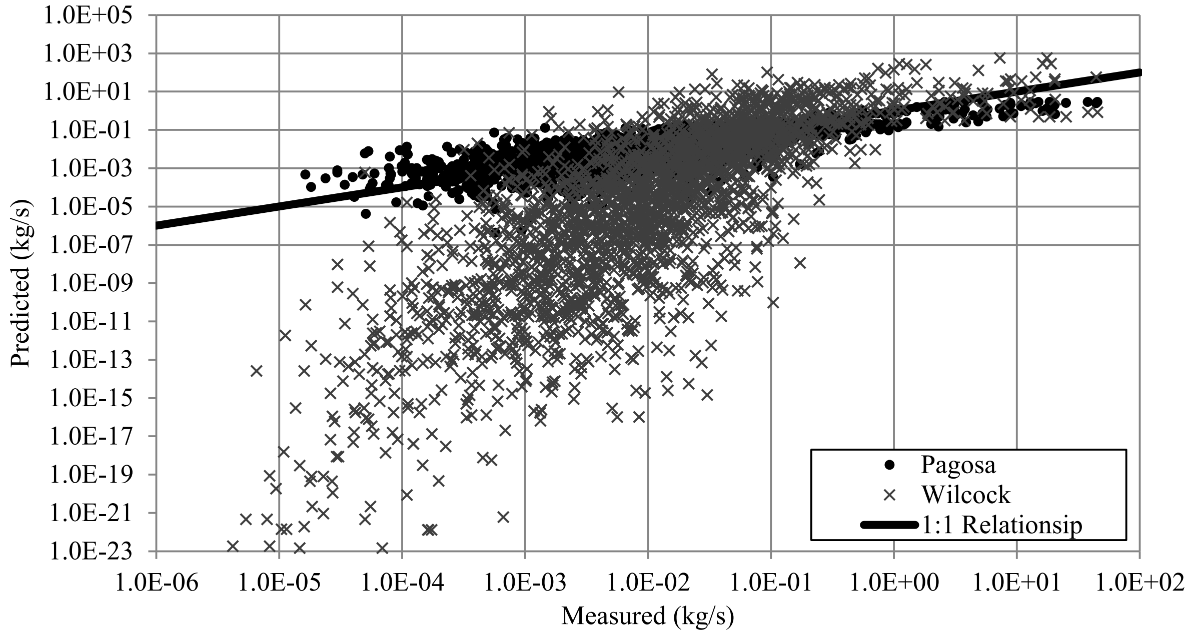

Figure 3.2: Predicted versus measured values of transport for the Pagosa and Wilcock 2001 formulae

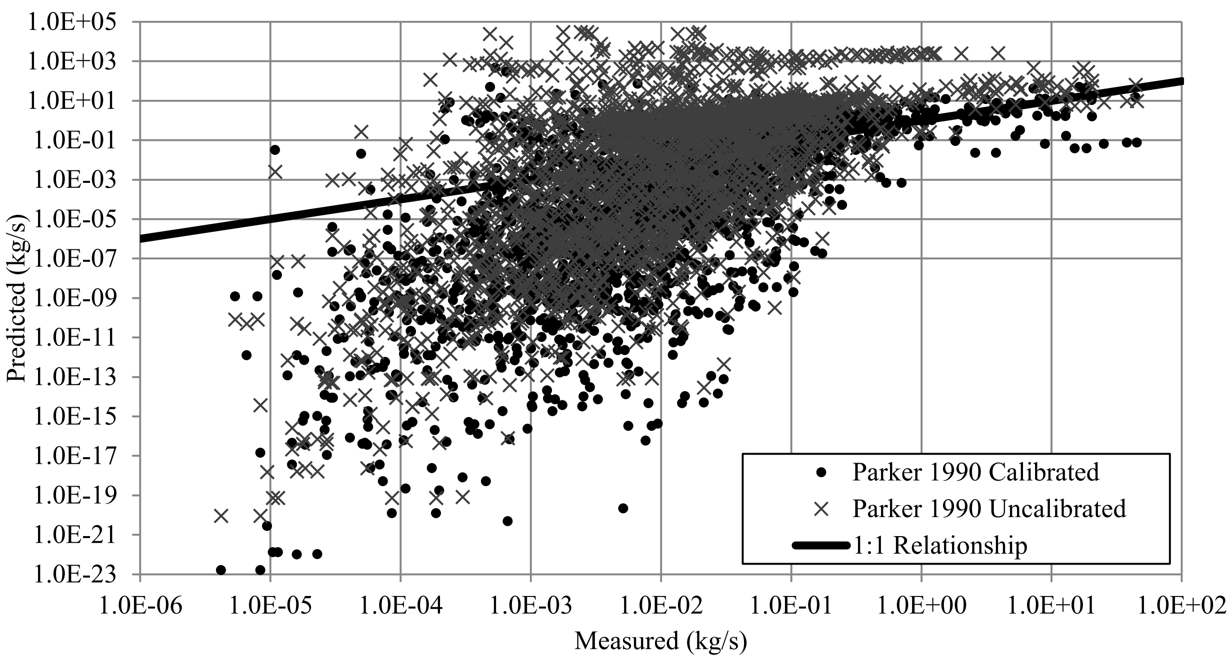

Figure 3.3: Predicted versus measured values of transport for the calibrated and un-calibrated Parker 1990 formulae

An evaluation of each formula's performance is included in the following subsections.

3.5.1 MPM

The MPM consistently came in last when computing accuracy with the RMSEL. In addition, the MPM provided excessive erroneous zero-transport predictions. In this analysis, more than 60 percent (~1,540 count) of the MPM predictions were zero-transport predictions. It has previously been reported that the MPM produced excessive zero-transport predictions due to its use of a transport threshold [Barry *et al.*, 2004; Gomez and Church, 1989b; Martin, 2003; McLean, 1980] and our findings support that assessment. The inaccuracy of the MPM reported in this analysis also support findings by previous studies [Almedeij and Diplas, 2003; Barry *et al.*, 2004; Gomez and Church, 1989b; Martin, 2003; McLean, 1980] but are not supported by studies that looked at streams with high sediment input [Bravo-Espinosa *et al.*, 2003; Reid *et al.*, 1996].

As an un-calibrated formula, the errors listed in the preceding tables emphasize the importance of calibration. The MPM competed with the un-calibrated Parker formula for the least accuracy.

3.5.2 Barry

Barry et al. [2004] reported that there were three streams in their study for which the exponent could not be calculated. For the same reason, this study could not use data from North Fork Sprague River, Paradise Creek, Cherry Creek, Spencer Creek, and West Fork San Juan Lower because the exponent was undefined. Some of the difficulties in calculating the exponent lie with the determining bankfull discharge. Significant controversy exists in whether the channel-forming discharge should be determined with bankfull indicators in the field, by selecting a discharge with a given return period, or by calculating the effective discharge [Doyle et al., 2007].

RMSE and RMSEL values reported are done so by excluding the four streams for which the exponent could not be calculated. For streams where an exponent was calculated, the formula performed well and second only to the Pagosa formula. The success of the Barry formula in predicting the measured sediment transport rates may possibly be due to its derivation from Helley-Smith sampler data. Other formulae (MPM, Wilcock, and Parker 1990) that were not as successful were derived from data collected by other means.

3.5.3 Pagosa

The Pagosa formula was most successful at predicting bedload transport with only the Barry formula being comparable. The Pagosa formula did not have shortcomings of excessive zero-transport prediction as for the MPM nor the undefined exponent condition of the Barry formula. The Pagosa formula was also the easiest method to apply. The success of the Pagosa formula relative to the other semi-empirical formulae creates a strong case for using an empirical bedload predictive formula.

The success of the Pagosa formula in predicting the measured sediment transport rates may possibly be due to its derivation from Helley-Smith sampler data. Other formulae (MPM, Wilcock, and Parker 1990) that were not as successful were derived from data collected by other means.

3.5.4 Wilcock

Of the calibrated formulae in this study, the Wilcock formula was least accurate. It still performed better than either un-calibrated formulae (MPM or Un-calibrated Parker 1990). Only for the RMSE with the Gravel Bed Streams scenario did an un-calibrated formula perform better than the Wilcock (Uncalibrated Parker 1990 – 6.67; Wilcock – 16.3).

Based on the findings of this work, it is recommended that the Wilcock 2001 formula be calibrated using net trap data and not Helley-Smith or other differential sampler data. Wilcock [2001] recommended using bedload samples collected from pit or net traps because those sampling methods are thought to be more accurate at low transport rate than pressure differential samplers. A related observation is that pressure differential (Helley-Smith) data tend to over predict low transport and under predict high transport relative to net trap data [Bunte et al., 2010; Pitlick et al., 2009]. This is attributed to the potential for pressure differential samplers to scoop or disturb the stream bed during sampling, thus artificially increasing the amount of bedload collected. The sampler opening of pressure differential samplers also tend to be smaller than that of net or pit traps, making it more difficult for larger sediment to be captured at high discharge.

Similar to the observations between the net trap and pressure differential data, the trend of the Wilcock 2001 formula (see Figure 3.2) significantly under predicted transport at low flows and then increased with discharge more rapidly than the measured data. Although it was calibrated to a measurement near bankfull, this discrepancy at low and high discharges resulted in significant errors. It is reasonable to conclude that the Wilcock 2001 formula would better fit net or pit trap data than the data used in this analysis.

3.5.5 Parker 1990

Limitations included in the original publication of this formula meant for its application only on medium to small streams with moderate slopes and minimal through-put sediment load, although no specific range was given. The method is based on the assumption of near equal mobility [Parker, 1990], which is often applicable to gravel-bed streams [Lisle, 1995]. By limiting the calibrated version of the Parker 1990 equation to the 14 streams that meet the preceding criteria, the RMSE significantly improves to a value of 1.76, but still does not improve its standing for relative accuracy among the six formulae. The results of this study stand in contrast to Reid et al. [1996] and Duan et al. [2006] where the Parker 1990 formula performed satisfactorily.

The use of a single calibration point significantly improved the prediction accuracy of the Parker 1990 formula. For the scenario that used all data, using a calibration point resulted in RMSEL values that were three to four times smaller than the un-calibrated formula and RMSE values that were orders of magnitude smaller.

As with the Wilcock 2001, the slope of the Parker 1990 formula also tended to under predict transport at low flows and over predict at high flows (see Figure 3.4 and 3.5). This too may be a symptom of the over-prediction of low-flow transport observed from other Helley-Smith data [Bunte et al., 2010]. Because this method was derived using Oak Creek data collected using a highly accurate and precise vortex sampler [Milhous, 1973], it is possible that this formula also would be better applied to net trap samples. The relative trends between bedload transport and discharge of the various formulae on two sample streams are shown in the following figures.

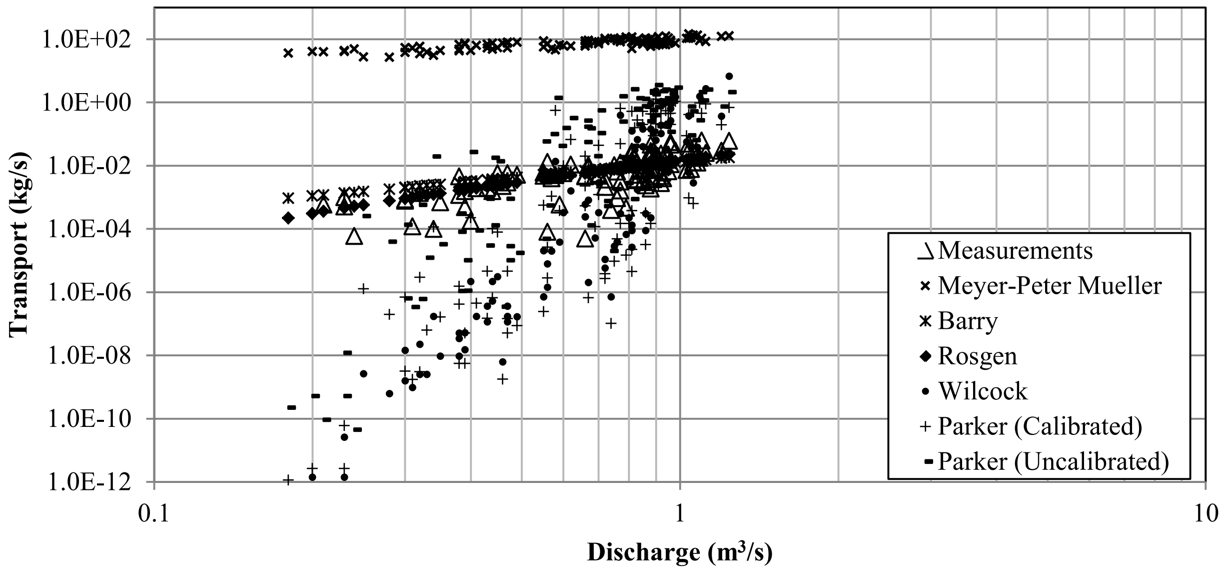

Figure 3.4: Comparison of formulae prediction on East St. Louis Creek

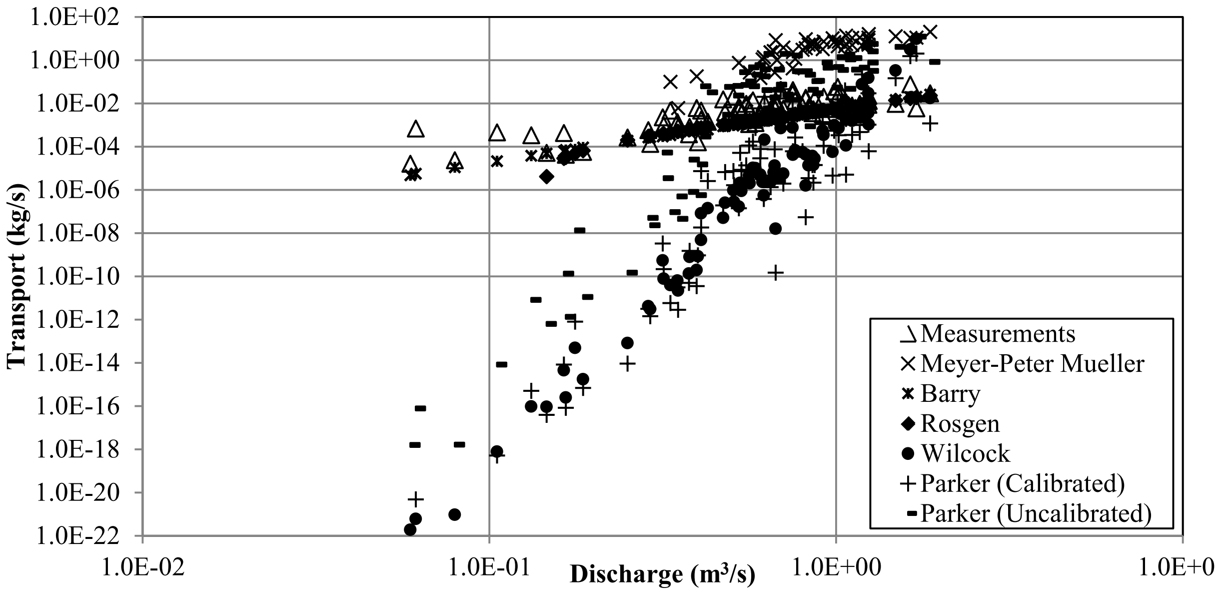

Figure 3.5: Comparison of formulae prediction on Fall Creek

3.6 Future Work

As more net trap data become available, a similar comparison of these formulae should be performed to determine the effect of sampling technique. The effect of using data collected in net traps, where the measured transport rate increases more rapidly with discharge than data collected with Helley-Smith samplers, needs to be examined. While the Helley-Smith data were better represented in this study by the Pagosa, Barry, and MPM formulae, it may be that the net trap data will be better represented by the Parker 1990 and Wilcock 2001 formulae. It may also be that using data from different sampling methods simply close the performance gap between the Pagosa and the Wilcock formulae without changing the overall result.

3.7 Conclusion and Summary

Comparisons of five bedload transport prediction formulae to 2,600 measurements from 31 different streams within the western United States were made and their relative accuracies were assessed using calculated RMSE and RMSEL values. The sites included in this study had water surface slopes reported between 0.001 and 0.055 and median diameters between 10 and 146 mm. Drainage areas varied between 3 and 16,000 km^2.

Of the five formulae compared, the Pagosa Good/Fair equation was the best predictor of bedload transport. Of the four semi-empirical formulae tested, the Barry formula provided the most accurate results. Only the Barry and Pagosa formulae were developed using measurements collected in a similar fashion to the data used in this study. This suggests that sampling techniques are important considerations for formula selection as it influences the ability of a bedload formula to predict transport rates.

Calibration of bedload transport formulae using a single measurement near bankfull improved predictive accuracy by several orders of magnitude. However, calibration alone was not enough to ensure accurate prediction; appropriate selection and use of a bedload transport formula was required to yield accurate predictions as shown by the range of prediction accuracies among the calibrated formulae in this study. Additionally, bedload sampling methodology influences the ability of bedload formulae to predict transport rates.

3.8 Acknowledgements

The author wish to acknowledge the advice and encouragement of John Buffington, Yantao Cui, Marwan Hassan, Gary Parker, Tim Randle, and Peter Wilcock. David Rosgen's willingness to provide data and answer questions was also greatly appreciated.

4 ARMOR LAYER AND EQUAL MOBILITY

4.1 Introduction

Originally proposed in 1982, the hypothesis of equal mobility states the grain size distribution of a given stream's subsurface layer will match the grain size distribution of the average annual gravel bedload yield [Parker and Klingeman, 1982; Parker and Toro-Escobar, 2002]. It encompasses hiding effects and the relative mobility of different size classes of the gravel bed material and assumes the channel is relatively stable.

The problem with evaluating the equal mobility hypothesis is that it can only be discounted or confirmed if bedload data exists for multiple years with discharges ranging from low to above bankfull. Therefore, equal mobility conditions cannot be determined without extensive bedload sampling and no at-a-glance parameters currently exist for determining the validity of the equal mobility hypothesis for a given site.

The equal mobility hypothesis is closely linked with the armor layer. An armor layer occurs when the surface layer is coarser than the underlying subsurface and it forms in response to sediment input [Dietrich et al., 1989; Parker and Klingeman, 1982]. It becomes a protective skin that puts the coarser, more stable grains of the surface in greater contact with flow than the finer, more mobile particles hidden within the voids [Parker and Klingeman, 1982]. By equalizing the transport of the different grain sizes, its composition adjusts to match sediment input over time.

The armor layer has been described as both a valve and a reservoir in the way it regulates and stores sediment [Milhous, 1973]. Input sediment from the upstream watershed is stored within the granular interstices of the armor layer and in-stream or sub-surface sediment is shielded from the flow by the coarser grains of the surface. Armor layers tend to prevent or diminish sediment transport at low flows, but their effectiveness wanes as discharge and shear stress increase. Even at relatively large discharges, however, it appears that the armor layer persists [Clayton and Pitlick, 2008; Wilcock and DeTemple, 2005].

Armoring is defined as and numerically determined by the ratio of the surface median diameter (D_{50s}) and the subsurface (D_{50ss}):

$$AR = \frac{D_{50_s}}{D_{50_{ss}}} \tag{4.1}$$

However, no method has been proposed to objectively determine the degree or intensity of armoring. In the literature, the armor layer is often described as being well, strong, slight, low, less, or poor [Barry et al., 2004; Bunte et al., 2010; Clayton and Pitlick, 2008; Lisle and Church, 2002; Pitlick et al., 2008a; b; S E Ryan and Emmett, 2002; S E Ryan et al., 2005]. None of these designations have any physical justification other than subjective or relative judgment.

The purpose of this work is to relate the armor layer to sediment input by comparing an equal mobility parameter with AR. It introduces a process that, by determining values of D_{50s} and D_{50ss}, will assess whether a stream is supply or transport limited. Finally, it proposes a metric for light armoring that can be utilized in all subsequent studies. The findings of this study will aid bedload prediction, comparing stream characteristics, and estimating sediment input for channel design and stream restoration.

4.2 Literature Review

Equal mobility has been an important factor in developing much of the current thought on bedload transport in gravel bed streams. In the literature, however, equal mobility is often erroneously applied to (1) instantaneous bedload measurements [Almedeij and Diplas, 2003; Bathurst, 2007; Church and Hassan, 2002; Ferguson et al., 1996; Habersack and Laronne, 2001; Powell et al., 2001] and (2) questions of incipient motion [Bettess and Frangipane, 2003; Rickenmann, 2001]. Differing from the equal mobility hypothesis, these cases are better termed flood-scale equal mobility which occurs when the grain size distribution of the bedload for a given discharge approximates that of the subsurface; this generally occurs for relatively high discharges. True equal mobility is a composite of sediment transport movement during high and low discharges over a larger temporal scale, typically one year [Parker and Toro-Escobar, 2002].

In contrast to equal mobility, selective transport often prevails in channels with coarse beds and steep slopes often occurring in the upstream portions of the watershed. Limited scour and upstream sediment input result in a supply limited condition where a coarser armor layer and also an average bedload gradation is less representative of the subsurface particle size distribution (PSD). Lateral and longitudinal sorting of fine sediment into well-defined patches that move downstream relatively quickly is a likely mechanism for selective transport. The selectivity can be caused by the surface layer being strongly bimodal or poorly sorted such that the stream does not adjust by the natural sorting and arrangement of particles on the surface [Lisle, 1995].

In the literature, selective transport is the antithesis of flood-scale equal mobility but not necessarily the equal mobility hypothesis. This is because selective transport can occur in situations where the equal mobility hypothesis does apply. Selective transport applies to situations where only fine particles move sporadically at relatively low flows and the larger fractions of the surface are mobilized at higher discharges [Lisle and Madej, 1992]. Selective transport occurs when the sediment supply to the channel is less than the channel's ability to transport [Dietrich et al., 1989], also referred to as a supply-limited condition.

To test the validity of the equal mobility hypothesis, Lisle [1995] selected 14 streams with extensive bedload measurements. For each stream he analyzed the annual average yield of the gravel portion of the bedload (D_{50b}) and compared that with the gravel portion of the subsurface (D_{50ss}) as a ratio of the median diameters of the two. The equal mobility ratio, EM, can be written

$$EM = \frac{D_{50_{ss}}}{D_{50_b}} \quad (4.2)$$

Lisle then truncated all grain sizes smaller than 1 mm and larger than 64 mm from the bedload and subsurface PSDs. Those streams within the equal mobility (EM) range of 0.9 to 1.3 were deemed to support the hypothesis of equal mobility while anything higher did not [Lisle, 1995]. Those sites that had EM ratios higher than 1.3 tended to be smaller streams in the upper portions of the watershed [Parker and Toro-Escobar, 2002]. The EM ratio also tended to decrease with drainage area, bankfull discharge, and dimensionless stream power [Lisle, 1995].

Previous flume studies have shown that the quantity of sediment supplied to a channel (supply limited conditions) affects the coarseness or degree of armoring of the surface layer, but these findings have primarily been observations of trends [Lisle and Church, 2002]. Other work has shown that the armor layer reduces transport rates by inhibiting the movement of the finer sub-surface material until a discharge threshold is reached after which the armor layer is disrupted enough for the finer subsurface to be entrained. By the same token, the degree of armoring influences the accuracy of predictive methods but is not considered in most formulae

[Bathurst, 2007]. Because of the difficulty in determining supply limited conditions [Bravo-Espinosa et al., 2003], a predictive link between armor layer and sediment input would be a significant development. Dietrich et al [1989] proposed a relative armor parameter, q*, to evaluate a river's sensitivity to sediment input change based on, among other things, the median diameters of the surface and sub-surface PSDs. This parameter, however, has the disadvantages that it (1) varies with flow, (2) masks the effect of the armor layer, and (3) makes comparison with other sites difficult. A simpler correlation would be to link the AR to sediment input.

4.3 Study Sites and Methods

For the analysis, 20 sites with more than 1,500 measurements were selected to compare the armor ratio (AR) to the EM ratio. The equal mobility test group included 10 of the 14 sites from Lisle [1995] and an additional 10 sites from Idaho [King et al., 2004], Oregon [Lucas, 2011], and Wyoming [S E Ryan and Emmett, 2002]. These sites were selected based on the availability of the AR, long term bedload sampling regime spanning a wide range of flow conditions, and PSDs for the surface layer and bedload. PSDs were all in the gravel and cobble range, drainage areas ranged from 1.5 km^2 to 28,000 km^2, and slopes ranged from 0.0007 to 0.026 m/m. Bedload data were collected primarily using Helley-Smith samplers, although bedload traps and pits were also used. Site characteristics are summarized in Table 4.1.

For the additional ten sites, this study estimated annual average gravel yields by truncating the bedload PSD to include only that portion coarser than 1 mm and finer than 64 mm. Anything finer than 1 mm was assumed to be, at least intermittently, traveling in suspension and anything larger than 32 mm was considered suspect due to selective rejection by the 76-mm opening of the Helley-Smith sampler. This procedure is consistent with the 14 Lisle datasets. The individual bedload samples were also weighted and averaged according to transport rate in a manner similar to Lisle [1995]. The gradation of the bedload PSD was compared to the subsurface PSD as an equal mobility ratio, defined as the D_{50} of the subsurface divided by the D_{50} of the bedload. The EM ratio was then compared to the AR.

Table 4.1: Characteristics of study sites

(1)	(2)	(3)	(4)	(5)	(6)	(7)	(8)	(8)
Site Name	**AR**	**EM**	**Source**	**D.A. (km^2)**	**Q_{bf} (m^3/s)**	**Slope**	**D50s (mm)**	**D50ss (mm)**
Redwood Creek 2	1.2	1.0	*[Lisle, 1995]*	520	370	0.026	22	18
Tom McDonald	1.3	1.3	*[Lisle, 1995]*	18	4	0.006	15	11
Goodwin Creek	1.4	1.0	*[Lisle, 1995]*	18	3	0.002	12	8
Turkey Brook	1.4	1.5	*[Lisle, 1995]*	7	13	0.009	22	16
Tanana River	1.5	1.2	*[Lisle, 1995]*	28000	1700	0.001	30	20
Redwood Creek 1	1.6	0.9	*[Lisle, 1995]*	600	430	0.014	15	9
Salmon River (near Obsidian)	2.4	2.72	*[King et al., 2004]*	243	13	0.007	64	26
North Caspar	2.4	2.4	*[Lisle, 1995]*	5	3	0.013	57	24
Boise River	2.6	8.5	*[King et al., 2004]*	2154	167	0.004	60	23
Sycan River above Marsh	2.7	1.5	*[Lucas, 2011]*	256	9	0.001	16	6
South Fork Sprague River	3.1	2.1	*[Lucas, 2011]*	161	5	0.007	39	13
Little Granite Creek	3.3	1.6	*[S E Ryan and Emmett, 2002]*	55	6	0.020	58	18
Jacoby Creek	3.4	1.8	*[Lisle, 1995]*	36	20	0.006	22	6
Bambi Creek	3.4	3.3	*[Lisle, 1995]*	2	2	0.008	50	15
South Fork Red River	3.8	3.7	*[King et al., 2004]*	99	7	0.015	95	25
Rapid River	4.7	1.6	*[King et al., 2004]*	280	18	0.011	75	16
East Fork River	5.0	3.1	*Lisle*	466	20	0.001	5	1
Lochsa River	5.1	5.3	*[King et al., 2004]*	3054	446	0.002	132	26
Salmon River blw Yankee Fork	5.5	2.8	*[King et al., 2004]*	2101	118	0.003	138	25
Big Wood River	6.2	5.4	*[King et al., 2004]*	356	22	0.009	155	25

Notes: (2) AR = armor ratio = D_{50s}/D_{50ss}; (3) EM = equal mobility parameter = D_{50ss}/D_{50b}; (5) D.A. = drainage area; (6) Q_{bf} = bankfull discharge.

4.4 Results

EM ratios in this study ranged between 0.9 and 8.5. The D_{50} of the average annual bedload PSD ranged between 1 and 18 mm. In contrast to the other 19 streams, the analysis of the Boise River data reported 57 percent of the average annual bedload PSD was finer than 2 mm, even after truncation. Because the D_{50} for Boise River was below the 2 mm truncation limit, it was labeled an outlier and excluded from the analysis.

Plotting the EM ratio versus the AR for all data in Figure 4.1, excluding the Boise River, shows a weak but observable upward trend as the streambed coarsens. Despite the scatter, equal mobility seems to hold for all values of AR up to about 1.7, slightly higher than Lisle's 1995 results.

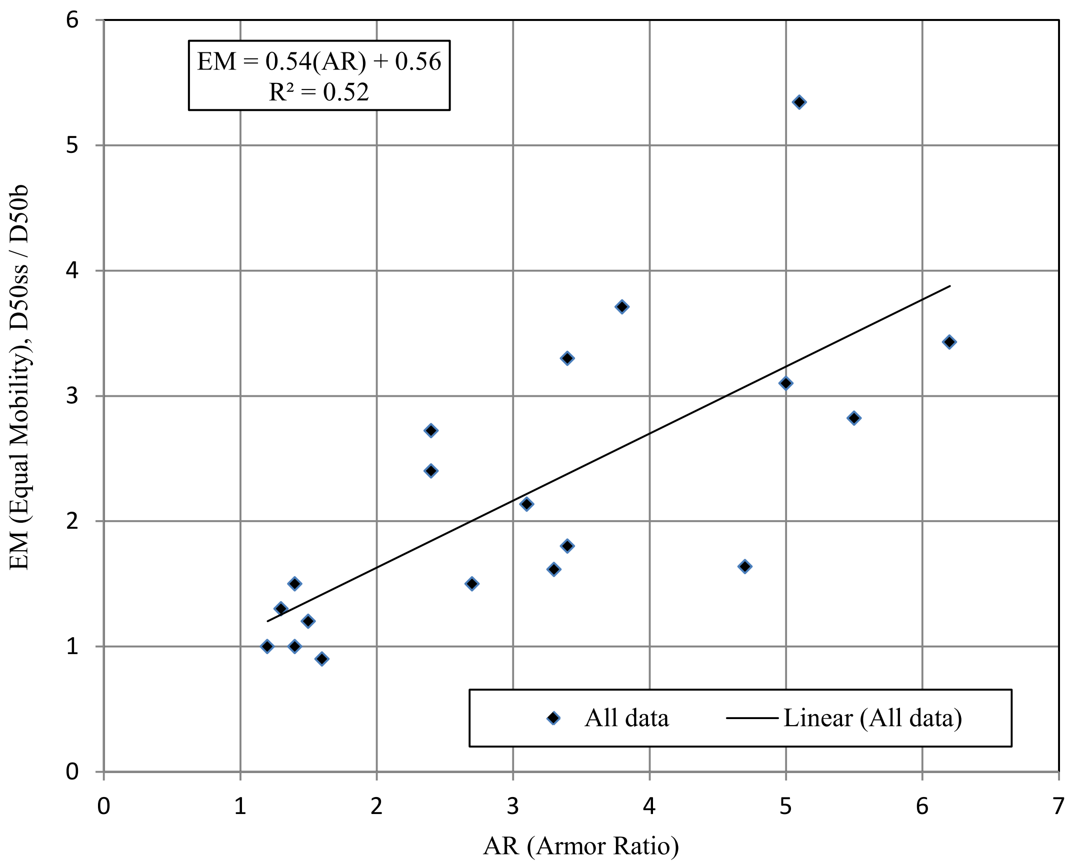

Figure 4.1: Equal mobility parameter versus the armor ratio

4.5 Discussion

Looking closer at the data in Figure 4.1, two families emerge as shown in Figure 4.2. The first family follows a close 1 to 1 relationship between equal mobility and armor ratio for all values of AR. The second family shows that EM is about one half AR. Linear best fit curves converge in the equal mobility range (equal mobility less than 1.7). This suggests that differences in stream response to sediment input follow two separate trends. The mean and standard deviations for the two families are summarized in Table 4.2.

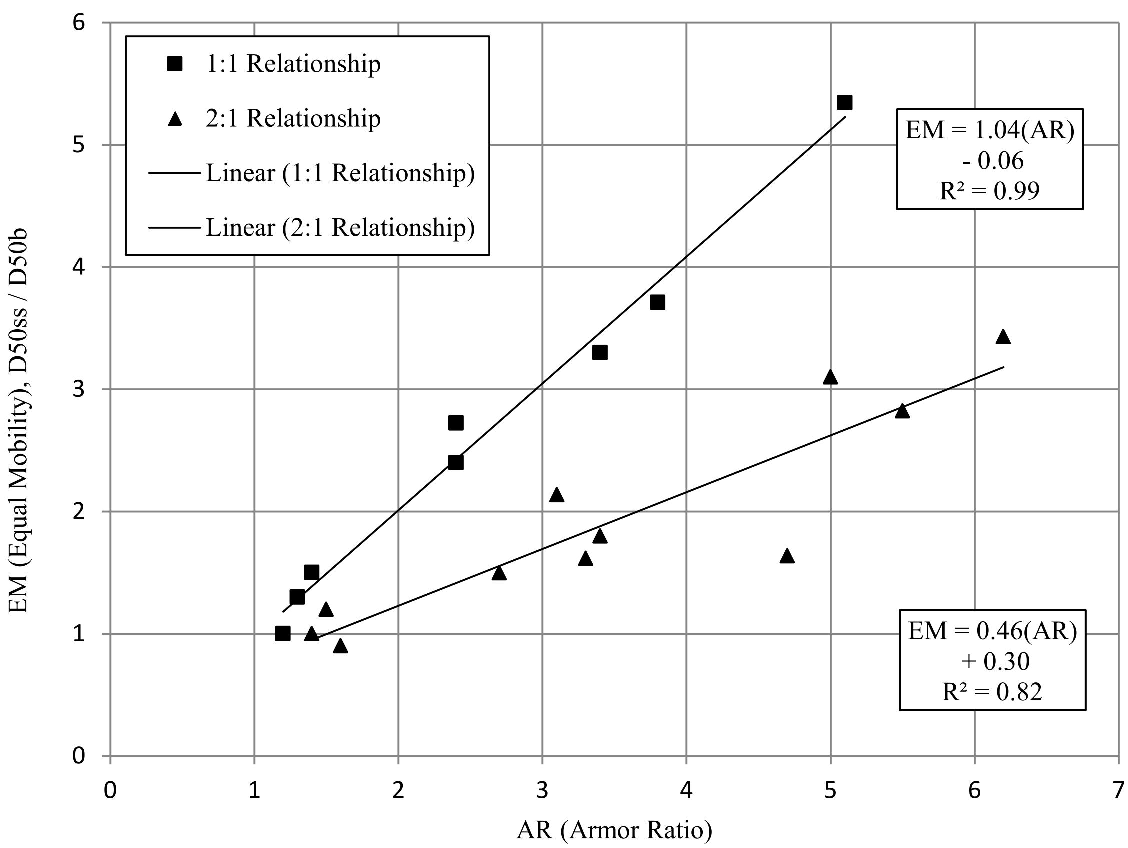

Figure 4.2: Equal mobility parameter versus armor ratio showing two families of data

As shown in Table 4.2, the family EM/AR equal to one corresponds to streams with coarser subsurface material and steeper slopes, both of which are characteristics of smaller, upland watersheds. These streams also tend to have greater discharge per unit of contributing drainage area.

Table 4.2: Summary of the general characteristics of two emergent families of data.

Family	(1) $D50_{ss}$ (mm)		(2) $D50_s$ (mm)		(3) Slope		(4) D.A. / Q_{bf} ($km^2/m^3/s$)	
	Mean	*Std. Dev.*	*Mean*	*Std. Dev.*	*Mean*	*Std. Dev.*	*Mean*	*Std. Dev.*
EM ~ AR	20	6	57	40	0.0107	0.0073	6.1	6.9
EM ~ 0.5AR	13	8	51	52	0.0068	0.0062	17.1	8.4

Notes: (1) Subsurface median diameter; (2) Surface median diameter; (3) Water surface slope; (4) Drainage area divided by bankfull discharge

As explained previously, this analysis takes equal mobility as streams where the EM ratio is 1.7 or less. For the family EM/AR of one, equal mobility would then apply to streams with an AR of 1.7 or less. For the family EM/AR of about one half, equal mobility would apply to streams with an AR of 3.0 or less. Streams within these limits would be considered lightly armored. Moderately and heavily armored streams would apply to AR values above these limits (For EM/AR = 1, AR = 1.7; For EM/AR = 0.5, AR = 3.0). Supply limited conditions would prevail for these moderately and heavily armored streams.

Lisle [1995] observed that equal mobility did not apply to smaller streams in the upper portions of the watershed. This analysis supports his findings and links equal mobility to specific AR values. Lisle also mentions that the EM ratio was linked to drainage area and bankfull discharge, which was also corroborated in the present study. By classifying the stream using the mean and standard deviations shown in Table 4.2, the application of equal mobility to a given stream can be determined directly from the AR.

If equal mobility does apply to the stream, then the subsurface PSD can be used to represent or predict annual patterns of bedload movement. This is an indication of what type of sediment input is being supplied upstream. If equal mobility does not apply to the stream, then it is supply limited and the PSD of the annual average bedload can be assumed to be finer than that of the subsurface PSD.

4.6 Summary

Common misconceptions found in the literature regarding equal mobility are identified. A stream's adherence to the equal mobility hypothesis can only be determined by considering a long-term sampling regimen. Many of the references to the equal mobility hypothesis found in the literature are actually referring to a flood-scale equal mobility. Selective transport, or a supply limited condition, occurs where the equal mobility hypothesis does not apply, but it is hard to distinguish supply limited from equal mobility conditions. The armor layer is used to differentiate between equal mobility and supply limited conditions.

An equal mobility (EM) ratio was calculated on 20 streams using the PSD of the annual average gravel bedload yield and the subsurface PSD. The EM ratio was compared with the armor ratio (AR) which revealed two families of data: EM/AR equal to one and EM/AR equal to one half. The family with EM/AR equal to one tends to include steeper streams, with coarser subsurface material, and more discharge per unit of drainage area.

A visual comparison of the two relationships provided two observations. First, slightly armored streams adhere to equal mobility and correspond to an upper AR value of 1.7 for EM/AR equal to one and an upper AR value of 3.0 for EM/AR values equal to one half. Second, streams with AR values greater than the limits mentioned can be referred to as moderately or heavily armored and are supply limited.

Additional work is needed to further refine the parameters for the two relationships (EM/AR = 1 and EM/AR = 0.5) found in this study. Data from this analysis would indicate that differences between the two would depend on drainage area, bankfull discharge, subsurface PSD, and water surface slope. Other potential influences that are harder to parameterize are sediment input and watershed landuse and soils.

5 THEORETICAL BASIS FOR ROSGEN'S PAGOSA GOOD/FAIR EQUATION

5.1 Introduction

The Pagosa Good/Fair formula is an empirical regression equation based on field measurements from three streams in southwestern Colorado [Rosgen et al., 2006]. Unlike other bedload predictive methods that adjust theoretical derivations to fit field or flume data [Hinton et al., 2012], the Pagosa Good/Fair formula (Pagosa) is fully empirical. The Pagosa formula has been criticized for its lack of theoretical underpinnings [Montgomery and MacDonald, 2002; Simon et al., 2007]. However, most, if not all, formulae are empirical at some level. Additionally, the physics of bedload transport are included in the data from which the Pagosa formula is derived, regardless of its format or how the data were non-dimensionalized.

The purpose of this work is to cast the Pagosa formula in a similar form to the Parker Surface-Based 1990 formula [Parker, 1990]. This exercise illustrates that empirical relationships capture the physics of bedload movement because of the field data from which the relationship was derived.

5.2 Literature Review

The controversy surrounding the Pagosa formula is due largely to its non-traditional format and unconventional methods. Instead of using a fluid mechanics approach by using a form of incipient motion as the reference condition, the Pagosa dimensionless parameter takes a geomorphic approach and uses bankfull as a reference. The selection of the bankfull discharge is also somewhat controversial in that it is hard to identify in the field and there are disagreements regarding the frequency of bankfull discharge [Doyle et al., 2007]. An additional concern voiced by critics is using a single exponent to represent all flow conditions.

The concerns regarding the Pagosa Curve exponent are partially mitigated by comparing it with other proposed rating curves. One such rating curve is a general power equation proposed by Barry et al. [2004]. The exponent of the equation is calculated using site specific parameters and varies from site to site. However, at any given site the exponent is the same for the full range of discharges. Exponents calculated for over 20 streams in Idaho ranged from 1.5 to 4. This range encompasses the value used in the Pagosa Curve.

Many of the other concerns voiced by critics of the Pagosa Curve are due to its non-traditional format as a dimensionless rating curve. This concern can be mitigated by casting the Pagosa Curve Formula in a format similar to other transport stage methods such as the Parker 1990 which can be written as:

$$Q_{b_i} = \frac{W_i^* F_i T u_*^3 \rho_s}{(s-1)g} \tag{5.1}$$

where Q_{b_i} is the bedload transport rate (kg/s) within a given sediment size class, W_i^* is the dimensionless bedload parameter for each size class of the surface layer gradation, F_i is the fraction of the surface gradation within a given size class, T is the channel top width (m), u^* is the shear velocity, ρ_s is the sediment density (kg/m3), s is the un-submerged specific gravity of the sediment, and g is the gravitational coefficient (m/s2).

The mathematical manipulation, derived by the author and others [Hinton et al., 2012], is shown in the following paragraphs.

5.3 Pagosa Formula Manipulation

Shear velocity and the Manning Equation can be written as

$$u_* = \sqrt{gR_hS} \tag{5.2}$$

$$Q = \frac{k}{n} A R_h^{\frac{2}{3}} \sqrt{S} \tag{5.3}$$

where Q is discharge [L^3/T], k is a coefficient equal to 1.0 for S.I. units (1.49 for English units), n is the roughness coefficient, A is the cross-sectional flow area [L^2], R_h is the hydraulic radius [L], and S is the slope [L/L]. Rearranging Equation 5.3 to solve for S and then substituting into Equation 5.2 gives Equation 5.4.

$$u_* = \frac{Qn\sqrt{g}}{kAR_h^{1/6}} \tag{5.4}$$

Replacing shear velocity in Equation 5.1 with Equation 5.4 and then simplifying results in Equation 5.5.

$$Q_b = \frac{W^* T n^3 \sqrt{g}}{R k^3 A^3 \sqrt{R_h}} Q^3 \tag{5.5}$$

This process can be repeated for any given flow. Performing this process for bankfull conditions provides an opportunity to develop a ratio of an arbitrary flow rate with that of bankfull, referred to as G^*. The ratio, G^*, can be simplified as

$$G^* = \frac{W^* T A_{bf}^3 \sqrt{R_{h_{bf}}}}{W_{bf}^* T_{bf} A^3 \sqrt{R_h}} Q_*^3 \tag{5.6}$$

where the subscripts bf refer to bankfull conditions and Q* refers to dimensionless discharge derived by the ratio of the given discharge (Q) with bankfull discharge (Q_{bf}). Assuming a rectangular channel, A^3 can be separated into $(TH)A^2$. Separating thus for A^3 and A_{bf}^3 produces Equation 5.7.

$$G^* = \frac{W^* T T_{bf} H_{bf} A_{bf}^2 \sqrt{R_{h_{bf}}}}{W_{bf}^* T_{bf} T H A^2 \sqrt{R_h}} Q_*^3 \quad (5.7)$$

Hydraulic relationships proposed by Parker [1979] for wide channels provide the next piece of the puzzle. Parker's relationship for slope is

$$S = \frac{0.0662 B_*^{0.819}}{\breve{Q}^{0.819}} \quad (5.8)$$

where

$$B_* = \frac{T}{D_{50}} \quad (5.9)$$

$$\breve{Q}_* = \frac{Q}{\sqrt{RgD_{50}}(D_{50})^2} \quad (5.10)$$

and D_{50} is the median grain size particle. Substituting Equations 5.9 and 5.10 into Equation 5.8 and rearranging results in Equation 5.11.

$$\left(\frac{T}{D_{50}}\right)^{0.819} = \frac{SQ^{0.819}}{0.0662\left[\sqrt{RgD_{50}} D_{50}{}^2\right]^{0.819}} \quad (5.11)$$

Multiplying both sides by $T^{0.181}(D_{50})^{0.819}$ and then simplifying gives Equation 5.12.

$$T = \frac{SQ^{0.819} T^{0.181}}{0.0662 D_{50}^{1.229}\left(\sqrt{Rg}\right)^{0.815}} \quad (5.12)$$

Repeating for bankfull top width (T_{bf}), substituting T and T_{bf} into Equation 5.7, and then simplifying gives Equation 5.13.

$$G^* = \frac{W^* T Q_{bf}^{0.819} T_{bf}^{0.181} H_{bf} A_{bf}^2 \sqrt{R_{h_{bf}}}}{W_{bf}^* T_{bf} Q^{0.819} T^{0.181} H A^2 \sqrt{R_h}} Q_*^3 \quad (5.13)$$

Assuming a wide channel such that R_h is roughly equivalent to the flow depth, Equation 5.14 is derived.

$$G^* = \frac{W^* T^{0.819} Q_{bf}^{0.819} H_{bf}^{3/2} A_{bf}^2}{W_{bf}^* T_{bf}^{0.819} Q^{0.819} H A^2} Q_*^3 \quad (5.14)$$

Recognizing that

$$\frac{Q_{bf}^{0.819}}{Q^{0.819}} = Q_*^{-0.819} \tag{5.15}$$

Equation 5.16 can thereby be developed.

$$G^* = \frac{W^* T^{0.819} H_{bf}^{3/2} A_{bf}^2}{W_{bf}^* T_{bf}^{0.819} H A^2} Q_*^{2.181} \tag{5.16}$$

For comparison, the good/fair version of the Pagosa regression equation is

$$G^* = -0.0113 + 1.0139 Q_*^{2.1929} \tag{5.17}$$

where G* and Q* were defined previously [Rosgen et al., 2006]. Neglecting the intercept (which likely relates to incipient motion), the primary focus is the coefficient and exponent. The exponent derived here of 2.181 is similar to the value of 2.19 used in Equation 5.17.

The coefficient of Equation 5.17 is independent of channel geometry and flow conditions unlike Equation 5.16. In order for Equations 5.16 and 5.17 to be compatible, the average coefficient of any given stream over a range of discharges must approximate unity.

5.4 Coefficient Comparison

To test how closely the coefficient of Equation 5.17 matches Equation 5.16, five gravel-bed streams were selected to determine an average coefficient. Selection criteria for the five sites included availability of the necessary data and a stream width to depth ratio at bankfull greater than ten so that the wide channel assumption could prevail. Some of the necessary data include channel geometry, bankfull discharge, bankfull channel geometry, and measurements of discharge and bedload transport rate over a range of flow conditions. Basic information for the five sites is included in Table 5.1.

The study sites used in this analysis have been described by others. East Fork River, WY was sampled using a belt sampler as described by Leopold and Emmett [1976]. Sagehen Creek

[Andrews, 1994], Big Wood River [King et al., 2004], Cache Creek [S E Ryan et al., 2005], and St. Louis Creek [S E Ryan et al., 2002] were sampled using pressure differential samplers such as the Helley-Smith sampler.

Table 5.1: Basic channel information for five sites selected to test the derived coefficient.

River Name	Basin Area km^2	Water Surface Slope (m/m)	$^{*}D_{50}$ mm	Q_{bf} m^3/s	$^{**}W/D$
East Fork River, WY	466	0.0007	5	20.0	15.0
Sagehen Creek, CA	27	0.0102	58	2.0	11.8
Big Wood River, ID	356	0.0091	150	21.9***	14.4
Cache Creek, WY	28	0.0210	46	2.1	13.0
St. Louis Creek #3	54	0.0190	82	4.6***	25.8

* Median diameter of the channel bed surface
** Width to depth ratio
*** Return period of 1.5 years

The coefficient for Equation 5.16 was calculated for more than 300 individual measurements from the five sites listed in Table 5.1. The mean coefficient for each individual site was derived, followed by the overall mean coefficient for all 300 measurements. The average coefficient for each site is listed in Table 5.2.

Table 5.2: Average coefficients calculated for selected streams.

River Name	Average Coefficient	Standard Deviation
East Fork, WY	1.924	2.5559
Sagehen Creek, CA	0.9844	0.7791
Big Wood River, ID	1.1569	1.8459
Cache Creek, WY	1.0572	0.9075
St. Louis Creek #3, WY	0.4307	1.1961

The overall average coefficient for all measurements derived from Equation 5.16 was 1.0128 compared to the value of 1.0139 of Equation 5.17. The difference between the derived value and the original coefficient (Equation 5.17) is 0.11 percent.

5.5 Conclusion

This manipulation of the Pagosa formula illustrates its similarity to more well-established formulae and suggests that criticism regarding the Pagosa formula's apparent lack of a physics-based underpinning may be unfounded.

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APPENDIX A BEDLOAD SAMPLING DURING 10- TO 15-YEAR RETURN-PERIOD EVENTS – SUCCESS AND FAILURE

A.1 Introduction

While we all want to portray ourselves well in front of our peers, doing so can sometimes have its drawbacks. The image we often inadvertently create is that we psychically see the end from the beginning, anticipate potential complications long before they are discovered, use infallible research methods, and exude scientific knowledge from our fingertips. Although portraying this image is natural, by hiding our flaws and challenges from the scrutinizing eyes of others we lose a valuable chance to teach others the lessons we learn from our failures.

Our bedload sampling team's experience sampling bedload on a small creek in central Utah demonstrates how easily the best laid plans can be foiled. Complications and setbacks related to flood flows threatened to shut down the project from the beginning of the sampling effort and throughout the season. The obstacles were introduced so consistently and continuously that it was almost humorous. Through sheer persistence, we circumvented each hurdle and achieved a successful completion to the project, despite flows that were four times above bankfull and a channel that effectively had no floodplain. However, it is our failures and not our successes that provided the greatest knowledge and progress. I intend to share some of the lessons we learned while navigating the river of hard knocks including a narrative of our setbacks, a critique of the three sampling methods we used, and some suggestions to others who may be collecting bedload samples.

A.2 Site Description

The left and right forks of Hobble Creek converge at the base of Powerhouse Mountain and then run generally westward from the mountains, through Springville, Utah, and on to Utah Lake (Figure A.1). It is a fourth-order stream with a significant armor layer and is characterized by a snowmelt-dominated hydrograph. Urbanization within the incorporated areas of Springville has highly altered the creek from its natural condition. Significant portions have been straightened and bank heights have been increased by the construction of earthen berms. Stream reaches have concrete- and gabion-lined banks through residential and commercial areas.

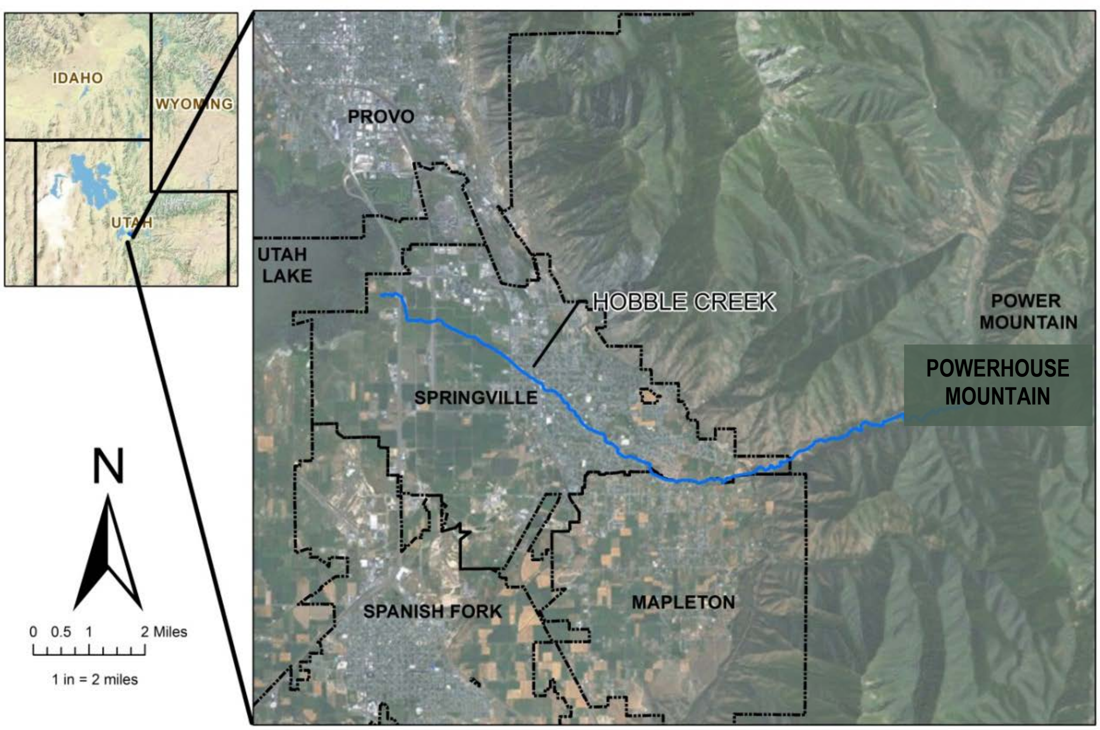

Figure A.1: Location of Hobble Creek, Utah

Hobble Creek has been identified as a key spawning ground for the endangered June Sucker which is endemic to Utah Lake [Belk, 1998; Billman, 2008]. As part of the June Sucker

Recovery Implementation Program, a bedload transport study was commissioned to evaluate patterns affecting the spawning substrate for the fish. Researchers from Brigham Young University have been part of this ongoing study on Hobble Creek since 2006.

During six years of study, only one year yielded any significant bedload movement with flows exceeding bankfull – a term that is applied loosely to this highly altered stream. In the absence of well-defined bankfull flow indicators, I defined bankfull discharge for Hobble Creek as the flood event associated with a 1.5-year return period. This discharge was determined using a Log Pearson III analysis of existing stream gauge data that began in the early 1900s.

A.3 Methods

Our initial sampling scheme included two wadeable methods: net trap and pressure-differential samplers. The net trap sampler, following the procedures outlined by Bunte et al [2007], consists of a series of traps that rest upon rectangular sampling plates that are staked to the stream bed with the opening of the nets facing normal to the flow. The pressure-differential (Helley-Smith) sampler has a square opening in front with a fine mesh bag behind and is lowered to the channel bottom via an attached pole held by someone wading in the stream. A good critique of differential samplers and its sampling techniques can be found in Ryan [1998]. A picture of both samplers is shown in Figure A.2.

Figure A.2: Net trap sampler (left) and Helley-Smith sampler (right)

Six net trap sampling plates and associated stakes were installed at three cross sections along Hobble Creek following the procedure outlined by Bunte et al [2007]. A portable bridge at each site enabled our team to deploy the net traps during high flow from above the sampling plates. Even with bridge access, we needed one person to wade just behind the plates and guide the net traps down over the stakes. The net traps are 12 inches wide, 8 inches tall, and are intended to have a sampling duration of 45 to 60 minutes, but sampling times can be reduced for high transport rates [Bunte et al., 2007].

Once the net traps were installed and functioning, another team member used the second method, the Helley-Smith sampler, to collect a separate set of bedload data. Although the Helley-Smith Sampler is considered a wadeable method, our original thought was to collect the bedload samples from the portable bridges already in place concluding it would be safer than actually wading the stream. Each cross section was divided into 20 equally spaced segments, avoiding the portions of the cross section where the net traps were already installed, and 60-second samples were collected consecutively at each of these segments across the channel. Care was taken to prevent sediment scooping on the streambed and perching the sampler on boulders.

A.4 Obstacles

Although we followed best practice procedures with both methods, we encountered four obstacles as discharge increased.

A.4.1 Obstacle #1 – Debris and Covered Plates

Despite our initial confidence in the sampling program, the honeymoon period faded quickly as debris clogged our net openings even though discharge was only 60 percent of bankfull. Because previous years had seen much lower flows than normal, woody debris and timber that had been stored on the banks during previous years began to move downstream and became ensnared in our stakes. In order to keep the stakes and plates from being ripped out by the floating debris, at least every other day a team had to clean off the stakes whether sampling was to occur or not. Even after the water level surpassed the top of the stakes, large limbs and other objects occasionally impacted the stakes, often knocking them loose. This process culminated in a wading excursion into Hobble Creek to free a bloated cow carcass that was caught in our stakes.

Even with continual maintenance, we were continually frustrated by lost stakes and plates caused by impacts from debris. And even when we were miraculously able to recover some of the plates, re-installing them was much more difficult than the original installation due to the rising river stage. With the increased stage and velocity of the creek, it was rather tricky to brace our bodies against the rapid current while extending two arms far enough into the stream to position the plate correctly without experiencing that exceptionally chilling sensation that follows submerging the top of our waders which, unfortunately, happened more than once. The frigid temperature of snowmelt runoff meant that it was also important to be very efficient (and lucky) with handling the plates under water. Hands and fingers ceased working after five to ten minutes in the water.

Another aspect of this obstacle that was both exciting and exasperating was that we could definitely tell that bedload was moving but we were often unable to measure it. The movement of bedload was most apparent when we tried to locate the plates when deploying the net traps. In direct contrast to previous years' experiences, bedload was moving rapidly downstream in large enough quantities to bury the plates. As long as the stakes were still in place we were able to locate the plates, but it still necessitated re-setting the plates flush with the stream bed. Between having debris knocking out stakes and losing the plates under layers of moving sediment, our sampling teams seemed to spend more time re-installing the equipment than actually collecting bedload samples. Often, sampling excursions had to be cancelled or postponed due to equipment losses. At one point we lost nearly a week of sampling because all of the spare plates had been lost and more had to be machined in the lab.

A.4.2 Obstacle #2 – Bridge over Troubled Waters

Eventually the river stage became high enough that debris-induced havoc diminished. Our next challenge centered on the technicalities of sampling from a portable bridge. On one sampling foray, two team members, John and Dan, were sampling from the bridge while two others assisted from the banks. Suddenly and without warning, the bridge buckled mid-span which happened to be right under John. He was instantly waist deep in water, although he was so focused on sampling it took him a few moments to realize what happened.

Dan was using the Helley-Smith sampler at the time and did not fall quite as gracefully as John. Feeling the bridge give way and not wanting the sampler to be damaged, he attempted to hold firmly to the end of the Helley-Smith sampler pole until it catapulted him into the air where he sailed downstream into the fast moving current. Luckily he was able to eventually move himself to the banks, with no help from the two team members on the bank who were incapacitated with laughter upon witnessing Dan's not-so-graceful pirouette in the air.

Not everyone found the experience comical. While we waited to have the broken bridge repaired, we contacted Risk Management on campus and requested advisement on how to increase the safety for those sampling. The recommendations we received from the responding safety officer, in addition to those already being practiced, included:

- Tethering and harnessing all personnel on the bridge to a steel cable running across the channel. The steel cable was already in place and used to help place the bridge over the stream according to the method proposed by Bunte et al [2007].
- Tying a rope to each person sampling on the bridge and extending the ropes to a team member on the bank who could then pull them out of the channel if they were to fall in.
- Replacing the waders with wet suits because of drowning potential.

After fixing the bridge and implementing the new safety procedures, we assumed things could only get better. However, the safety procedures introduced new difficulties. For one, the tethers became tripping hazards on the portable bridges and hampered mobility. Secondly, the wet suits were not as effective as the waders at keeping those who were in the water warm. Drowning potential was replaced by a concern for hypothermia.

To prevent hypothermia or prolonged exposure to the frigid snowmelt runoff, we began limiting the amount of time we were in the water to deploy the net traps over the stakes. Deploying the net traps as the stage of Hobble Creek continued to rise became increasingly difficult and nigh impossible without someone in the water. And, even more important, someone had to reach down into the water almost three feet to ensure that the net trap was resting squarely on the plate and flush with the channel bed.

The Helley-Smith samplers also proved problematic. Because we were attempting for safety reasons to remain on the bridge while we sampled, it was much more difficult to ensure that the sampler was not perched on a boulder or scooping sediment from the channel bottom. We also struggled to keep the sampler stationary on the channel bed against the flow. Eventually we chose to use the Helley-Smith while wading in the frigid water, but now with wet suits instead of the dry waders. However, our consternation was soon to get even worse.

A.4.3 Obstacle #3 – Exceeding Bankfull

As weather continued to warm, the stage of Hobble Creek rose past what would be bankfull if the Creek was not constrained by levees. After attempting to place the bridge across the stream and having another team member fall into the water, it was apparent that the 30-foot bridges were no longer of adequate length to span the Creek. Not to be deterred we tried each of the other sites to no avail. In addition, it was no longer remotely possible to even locate the stakes or plates and we had no confidence that they were even there. The good news was that we no longer had to wade into the stream – it was much too dangerous anyway. The bad news was that we had to abandon our three sites and come up with some way to collect the bedload we knew was moving down the channel.

Our solution was obvious the next day when the flow in the stream had again swelled overnight but this time to a discharge four times that of normal bankfull. We opted to sample from a large box culvert located just upstream from our middle site (see Figure A.3). We tethered the handle of the Helley-Smith sampler with ropes extending to both banks just upstream from the culvert and lowered the sampler into the flow. Almost immediately after submerging the top of the sampler, the mesh bag was torn off the back.

Figure A.3: Sampling from a culvert upstream of middle site

Not to be deterred, we drew upon prior experimentation. A few years previously students had mounted a net trap sampler to the edge of a long steel pole (Figure A.4) to collect bedload samples in locations where we could not install the plates and stakes. Named the Stanley Sampler after the innovator, its use was sporadic at best because it had never been calibrated. With historic discharge and sediment transport right in front of us, we opted to use this un-calibrated method primarily because we could see no other option. Tethering the pole-mounted net trap sampler with ropes secured to team members on both banks upstream, we lowered the sampler at six equally-spaced intervals across the culvert. Because the net trap has larger mesh openings, the drag on this sampler was significantly less than the Helley-Smith. Due to the volume of bedload moving into the nets, we sampled only 60 seconds at each location. Once completing one pass at the six intervals, we repeated the sampling a second time to average out temporal fluctuations.

Figure A.4: Pole-mounted Net Trap Sampler, or Stanley Sampler: in the lab (bottom right), in the field (top right), and suspended above Hobble Creek (left).

A.4.4 Obstacle #4 – Broken Pole-Mounted Net Trap Samplers

We continued sampling using the Stanley Sampler for several weeks with much success. In fact, most of us assumed that our challenges were over. Once again, we were wrong. There were two peaks in the snow-melt runoff hydrograph, each between a 10- and a 15-year event.

Using the Stanley Sampler was new for most on the sampling team. And, with the scramble to find some type of method that would capture bedload samples, little thought had been given to training those using the new method. The pole of the Stanley Sampler consisted of three lengths of galvanized round steel tubing that were connected with threaded couplings. Within one week, the joint between the lowest and next poles sheared off three separate times and required repair, costing us valuable sampling time. After investigating the cause, we found that those holding the tethers on both sides of the stream were not restraining the sampler well enough against the flow. The slack was taken up by the person holding the sampler on the top of the culvert who pulled gallantly on the top of the sampler (Figure A.5) but only succeeded in increasing the bending moment on the pipe until failure. Additional training helped ease the stress on the joint and on the operator holding the sampler over the culvert.

Figure A.5: Inappropriate sampling caused excessive strain on Stanley Sampler.

Sampling continued nearly without incident while the discharge gradually decreased. As the flow decreased, we were able to increase the sampling duration.

A.5 Sampling Method Insights

The methods originally incorporated in our sampling scheme are well known as wadeable methods [Emmett, 1980; S Ryan and Porth, 1999b]. It is also well known that bedload sampling is potentially dangerous and should be done with care [King *et al.*, 2004; McLean, 1980]. However, here are some additional insights into each of the three methods we used during our 2011 sampling season.

A.5.1 Pressure-Differential Sampler (Helley-Smith)

Most bedload data available publicly were collected with the Helley-Smith sampler. Due to its common use and its relatively easy deployment, it must always be considered when evaluating sampling options, especially when sand is considered a significant portion of the bedload. It is often used as a wadeable option where scooping and perching can be prevented or eliminated by direct observation [Bunte *et al.*, 2010; S Ryan and Porth, 1999b]. When wading is required, our experience shows that risks to the operator can include hypothermia and the danger of being struck by floating debris.

When wading is not an option, tethering the sampler to the banks for narrow channels or using a cable-mounted sampler are possible. For high discharge rates and especially in altered channels like Hobble Creek, the drag on the sampler was a significant challenge due to the small mesh opening (3.5 mm) in the collection bag. We found that the larger mesh openings of the net traps produced less drag in the high shear stress flows we experienced but with the loss of smaller sediment fractions.

Another aspect to consider when using a pressure-differential sampler is the composition of the bed material and bedload. Even when the operator could verify that the sampler was not perched on a boulder, the coarse nature of the bed surface caused concern that sediment was passing under the trap and evading capture. Although some reports have observed good performance in the 0.50 mm to 16 mm range [Emmett, 1980; 1984], the Helley-Smith Sampler specifically was designed to capture particles in the 2 – 10 mm range [Holmes Jr, 2010; Sterling and Church, 2002]. In addition, Sterling and Church recommend that the Helley-Smith Sampler not be used with coarse-bed rivers [2002] although an exact size limit was not provided. Since their study site had a D50 that ranged between 45 mm and 75 mm, it would be safe to assume that 45 mm would represent an upper limit for recommended use.

A.5.2 Net Trap

Bunte et al [2007] provide an accurate and in-depth description of bedload net trap procedures, uses, and limitations. The traps were designed to mitigate many of the concerns with the use of the pressure-differential sampler. Because sediment transport is notoriously unsteady [Bunte et al., 2007; Wilcock et al., 2009], the recommended 60 minutes for sampling with the net trap improves average bedload transport rate calculations. It also captures a larger proportion of transported material than its pressure-differential counterpart because multiple traps are deployed simultaneously. Using a 20-foot wide stream as an example and ignoring the time component, a typical deployment of six net traps should collect approximately 30 percent of the moving bedload. For comparison, a pressure-differential sampler on the same stream with an opening width of six inches would only collect three percent of the bedload at a time.

We experienced three disadvantages of using net sampler. First, net sampling is more complicated and subject to failure than the pressure-differential sampler. For example, for coarse bed streams, embedding a stake 12 to 18 inches into the streambed can be difficult and, once installed, the sampling crew is invested in that particular site. Losing plates and stakes at high flows due to debris in the channel can threaten the entire sampling program because of the difficulty in reinstalling the equipment correctly at high flows. Second, even when active sampling is not taking place, the installed stakes and plates collect debris that can produce local scour and alter the streambed before the next sampling effort. Third, net samplers are difficult to access and maintain for high flows. Unfortunately, these higher flows represent valuable data and end up being sampled using alternative, less accepted methods.

Much of the concern with the net traps, then, center around the definition of the term “wadeable.” This term suggests that safety, or the ability to remain standing, is the primary metric to determine whether it is appropriate to use the net traps in a given flow.

We recommend that the term “wadeable” be defined with respect to natural streams as a water depth less than 18 inches for net trap sampling. Once the water depth exceeded the height of the stakes (typically between 12 and 18 inches), the degree of difficulty in using the traps began to rise exponentially. Capping its use for flows in depths less than 18 inches would satisfy the safety question and also address being able to visually locate the stakes and traps in muddy water typical of flood flows; operate the traps appropriately; and replace damaged or lost equipment. For deeper flows, alternative methods should be considered.

In addition to wading safety, our experience on Hobble Creek suggests that other factors such as water turbidity, temperature, and amount of debris are other significant factors that need to be considered. High discharge tends to entrain sediment making it difficult to see whether the sampler is perched or scooping sediment. In watersheds that are snowmelt-runoff dominated, higher discharges tend to be related to lower water temperatures with increased hypothermia risks and more harm-inflicting debris.

Despite the limitations to the net traps, they perform remarkably well for the conditions for which they were designed (see [Bunte et al., 2007]). Bedload net traps provide high quality, time-average data when used according to their well-defined sampling procedure. In summary, we highly recommend the continued use of the net traps in coarse-bed streams under the following situations:

- Natural channel bed
- Where there is an absence of woody debris
- When the flow depth is less than 18 inches
- In conjunction with a back-up sampling method for flows that are not wadeable

A.5.3 Pole-Mounted Net Trap Sampler (Stanley Sampler)

The Stanley Sampler is a modified net trap in that the trap is attached to a long steel pole. Two threaded elbows fit over the left and right corners of the net trap with 8-inch long poles extending to the bottom of the net trap on either side (See Figure A.4). The two elbows are connected above the net trap by two six-inch poles threaded into an upward tee where the handle is attached. The handle can includes threaded ends that can be lengthened and shortened as needed to reach the stream bed while sampling. Unlike the net trap, sampling plates and stakes are not used.

The sampler excels in situations similar to Hobble Creek: severely altered channel, high debris potential, and flows in excess of bankfull. It does not produce the amount of drag experienced by the Helley-Smith Sampler because of the larger mesh openings and is more mobile and flexible than the traditional net trap sampler. Still, as a modified version of the net trap, this method is intended as a last line of defense and not as a replacement for the other two methods in most situations.

A.6 Results

Bedload sampling on Hobble Creek resulted in 41 bedload measurements at discharges exceeding bankfull discharge. The measurements of bedload transport, discharge, and channel width are included in Tables A.1 and A.2.

Table A.1: Hobble Creek data for 950 West Culvert site

Site	Date	Discharge (m3/s)	Transport (kg/s)	Channel Width (m)	D50 (mm) Subsurface	D50 (mm) Surface
950 W. Culvert	4/19/2011	15.22	0.7783	5.4	23.7	82.60
950 W. Culvert	4/20/2011	10.19	0.0406	5.4	23.7	82.60
950 W. Culvert	4/20/2011	9.68	0.0418	5.4	23.7	82.60
950 W. Culvert	4/21/2011	10.02	0.0164	5.4	23.7	82.60
950 W. Culvert	4/21/2011	10.11	0.0049	5.4	23.7	82.60
950 W. Culvert	4/22/2011	9.37	0.0076	5.4	23.7	82.60
950 W. Culvert	4/23/2011	8.96	0.0823	5.4	23.7	82.60
950 W. Culvert	4/23/2011	8.34	0.0001	5.4	23.7	82.60
950 W. Culvert	4/25/2011	6.99	0.0022	5.4	23.7	82.60
950 W. Culvert	4/25/2011	7.09	0.0011	5.4	23.7	82.60
950 W. Culvert	5/7/2011	12.40	1.0169	5.4	23.7	82.60
950 W. Culvert	5/10/2011	14.47	0.3713	5.4	23.7	82.60
950 W. Culvert	5/11/2011	12.26	0.0028	5.4	23.7	82.60
950 W. Culvert	5/11/2011	12.09	0.0276	5.4	23.7	82.60
950 W. Culvert	5/12/2011	11.36	0.0059	5.4	23.7	82.60
950 W. Culvert	5/14/2011	14.57	0.0572	5.4	23.7	82.60
950 W. Culvert	5/17/2011	14.51	0.0630	5.4	23.7	82.60
950 W. Culvert	5/24/2011	11.72	0.1016	5.4	23.7	82.60
950 W. Culvert	5/25/2011	11.87	0.0165	5.4	23.7	82.60
950 W. Culvert	5/26/2011	12.25	0.0029	5.4	23.7	82.60
950 W. Culvert	5/27/2011	11.19	0.0110	5.4	23.7	82.60
950 W. Culvert	5/27/2011	11.04	0.0146	5.4	23.7	82.60
950 W. Culvert	5/28/2011	10.79	2.1827	5.4	23.7	82.60
950 W. Culvert	5/29/2011	10.45	0.0041	5.4	23.7	82.60
950 W. Culvert	5/30/2011	9.97	0.0079	5.4	23.7	82.60
950 W. Culvert	6/1/2011	7.95	0.0008	5.4	23.7	82.60
950 W. Culvert	6/2/2011	8.10	0.0063	5.4	23.7	82.60

Table A.2: Hobble Creek data for 200 West Culvert site

Site	Date	Discharge (m3/s)	Transport (kg/s)	Channel Width (m)	D50 (mm) Subsurface	D50 (mm) Surface
200 W. Culvert	5/7/2011	14.09	0.3448	5.9	24.4	71.29
200 W. Culvert	5/12/2011	11.84	0.0053	5.9	24.4	71.29
200 W. Culvert	5/13/2011	11.91	0.3309	5.9	24.4	71.29
200 W. Culvert	5/14/2011	14.84	0.2424	5.9	24.4	71.29
200 W. Culvert	5/17/2011	14.20	0.0545	5.9	24.4	71.29
200 W. Culvert	5/19/2011	10.93	0.0399	5.9	24.4	71.29
200 W. Culvert	5/20/2011	10.62	0.1032	5.9	24.4	71.29
200 W. Culvert	5/21/2011	10.42	0.0237	5.9	24.4	71.29
200 W. Culvert	5/24/2011	11.88	0.0162	5.9	24.4	71.29
200 W. Culvert	5/25/2011	11.62	0.0031	5.9	24.4	71.29
200 W. Culvert	5/26/2011	12.05	0.0076	5.9	24.4	71.29
200 W. Culvert	5/27/2011	11.11	0.0239	5.9	24.4	71.29
200 W. Culvert	6/1/2011	8.21	0.0013	5.9	24.4	71.29
200 W. Culvert	6/2/2011	7.82	0.0003	5.9	24.4	71.29

Hobble Creek bedload measurements are plotted versus discharge with more than 750 bedload measurements from other coarse bed streams (median grain size in the gravel range or higher) in Figure A.6. All of the comparison data were collected using a 3-inch Helley-Smith Sampler. The streams have drainage areas between 205 km^2 to 356 km^2, compared to 260 km^2 for Hobble Creek. The Idaho data were described by King et al [2004] and the Sycan River data were collected by the U.S. Forest Service as part of the Klamath River Adjudication in 1996 [Lucas, 2011].

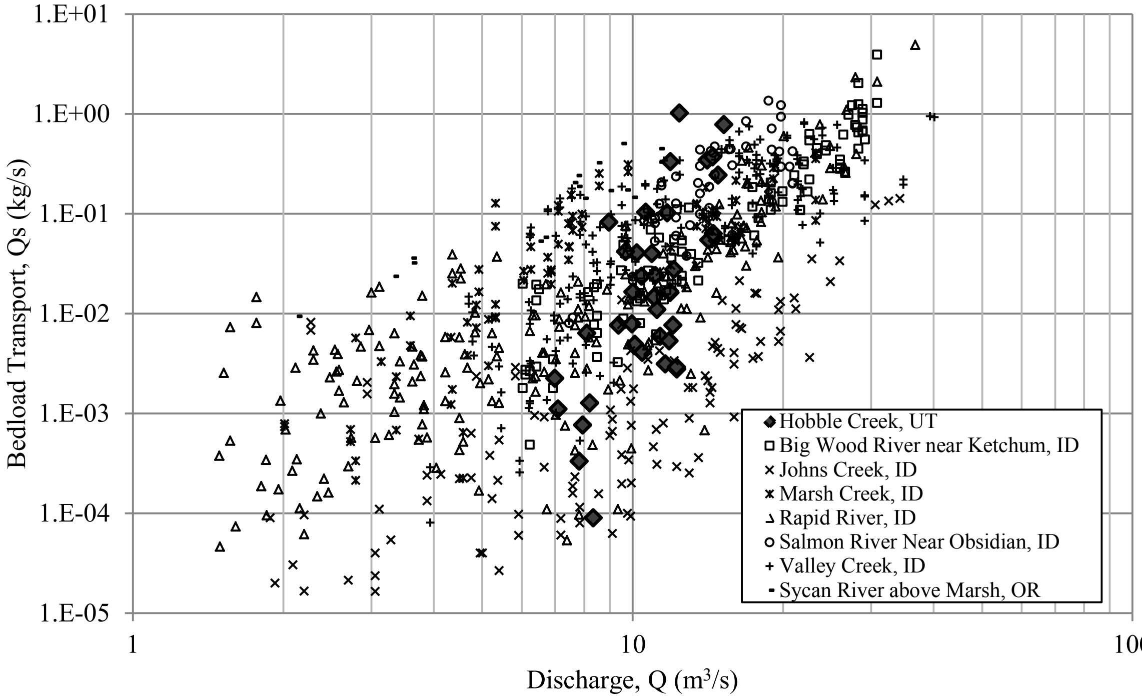

Figure A.6: Bedload measurements on Hobble Creek compared with Helley-Smith data from seven other streams.

Of particular interest is how the 2011 Hobble Creek data compare with the other data despite the difference in samplers. Bunte et al. [2010] report that, despite a difference in mesh opening, the Helley-Smith and net trap samplers report similar values at high flows. They also observed that sediment transport collected using the net trap sampler increased with discharge at a rate greater than Helley-Smith samples. This observation holds true for the data in Figure A.6. The Hobble Creek data collected using the modified net trap sampler (Stanley Sampler) exhibits a much steeper slope than the Helley-Smith data collected in Idaho and Oregon, but at high flows the data tend to converge, although allowances are needed for site variations.

Recent tests by Bunte et al [2010] have shown that in mountain streams the Helley-Smith over-predicts low flow bedload transport and under-predicts high flow transport and they ascribe it to scooping bed material with the underside of the sampler. The Stanley Sampler, unlike the net trap, will also have direct contact with the channel bed and so has the potential of scooping bed material; thus it is not recommended for low flows. However, at high flows such as was experienced on Hobble Creek during the 2011 spring runoff, the bedload rating curve of the Stanley Samplers should approximate that of the net trap.

To test how closely the Stanley Sampler compares to the net trap, data from Little Granite Creek [Bunte and Abt, 2005] collected using net traps are compared with the Hobble Creek measurements in Figure A.7. The measurements are plotted versus discharge and are fitted with a power relationship. The exponent of the Little Granite Creek data is 8.06 which is similar to Hobble Creek's exponent of 7.08. Helley-Smith data tend to have exponents on the order of two to four while net trap data tend to have exponents between seven and sixteen [Bunte et al., 2010]. The Stanley Sampler data on Hobble Creek fits into this range.

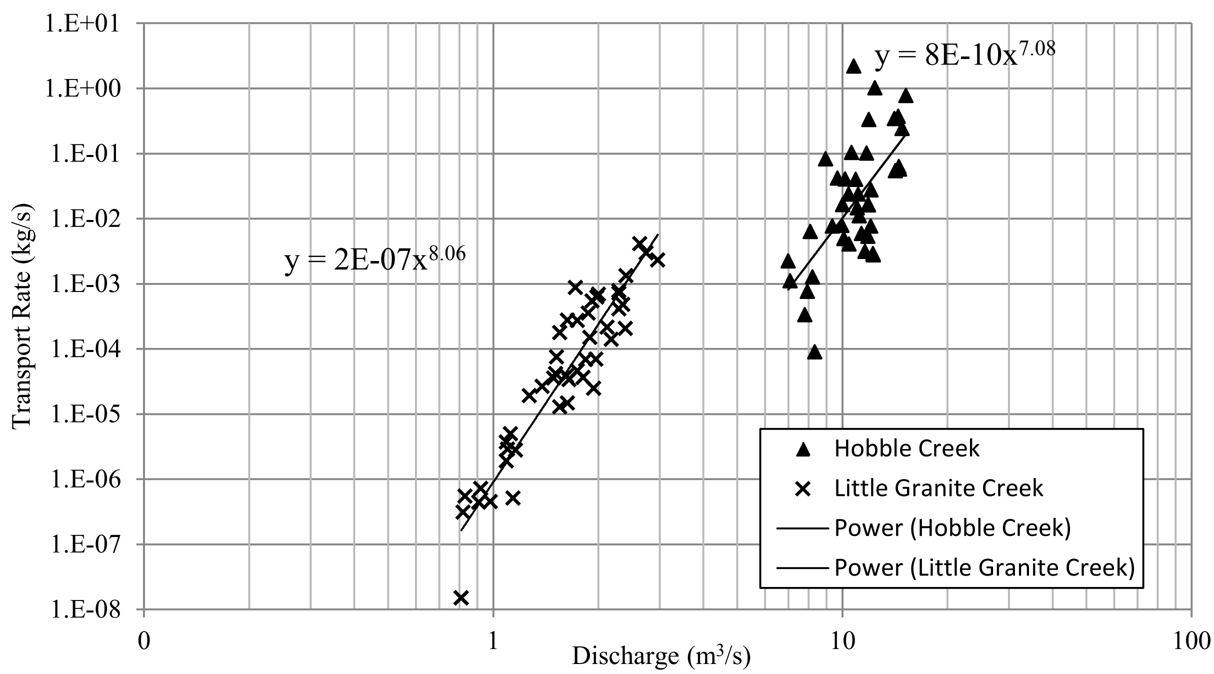

Figure A.7: Hobble Creek measurements compared with net trap measurements on Little Granite Creek.

The Hobble Creek and Little Granite Creek data are shown in Figure A.8 and are used to evaluate the performance of the most accurate predictive method from Chapter 3, the Pagosa Good/Fair Formula. The data in Chapter 3 were all collected using Helley-Smith samplers. As shown in Figure A.8, the Pagosa formula does not match the measurements very well. The Pagosa formula predicts the transport rate increasing slower relative to discharge than the measured data.

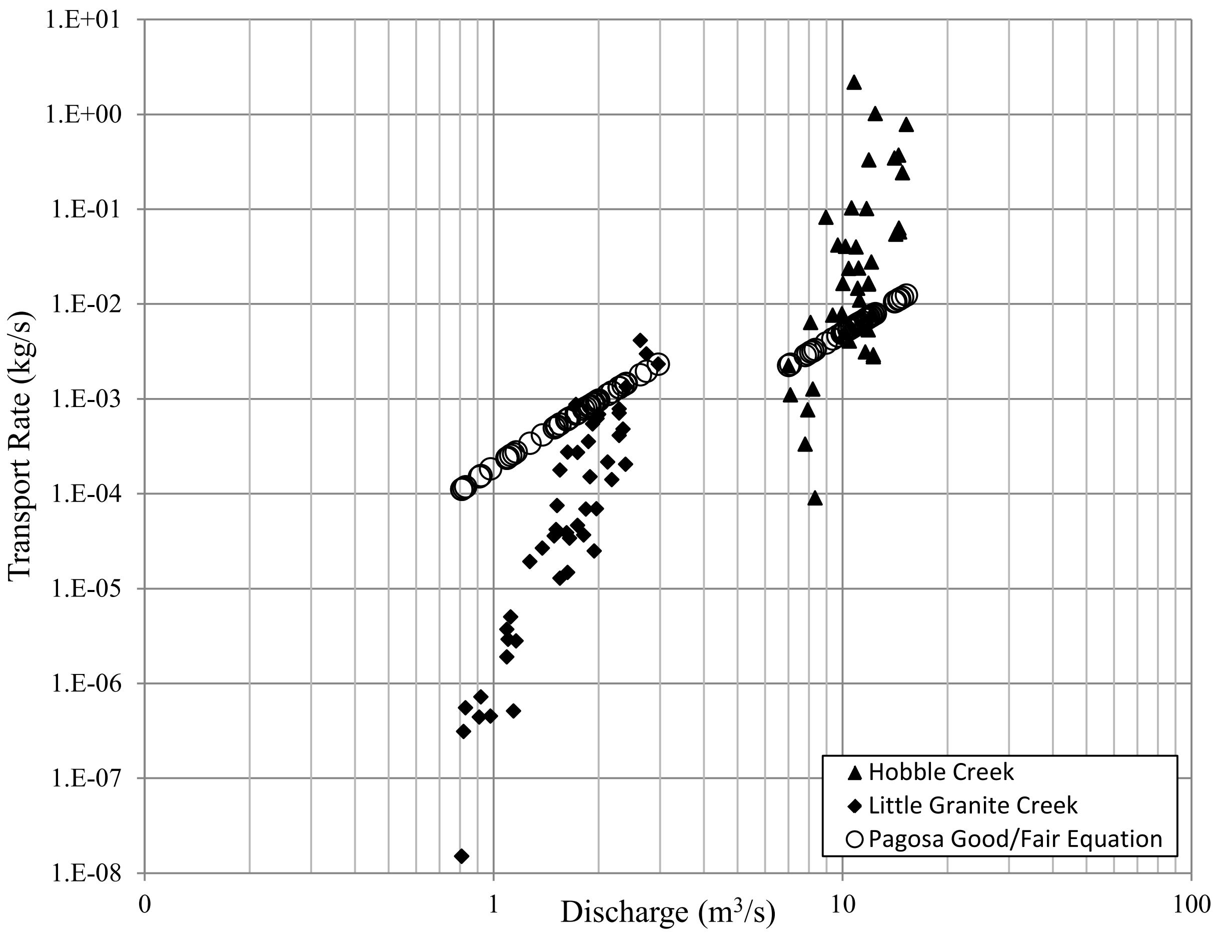

Figure A.8: Hobble Creek and Little Granite Creek data compared with predicted values from the Pagosa formula.

A.7 Conclusions and Summary

A series of four obstacles during the 2011 snowmelt runoff season resulted in the use of the Stanley Sampler, a modified net trap sampler. Data collected using this sampler are included and compared with data collected using the Helley-Smith and net trap samplers. The comparison illustrates the similarity between the Stanley and net trap samplers and show that predictive methods developed from Helley-Smith data (e.g. Pagosa Good/Fair Equation) may not perform well for net trap data. The Stanley Sampler shows promise as a low cost alternative to sampling bedload in altered, urbanized streams during large discharges. It is not recommended for measuring low flow transport. Additional flume and field work is needed to calibrate the sampler relative to the net trap sampler.