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To the Graduate Council:

I am submitting herewith a dissertation written by Patrick Lasater McMahon entitled "Bedload Transport Sampling, Characterization and Modeling on a Southern Appalachian Ridge and Valley Stream." I have examined the final electronic copy of this dissertation for form and content and recommend that it be accepted in partial fulfillment of the requirements for the degree of Doctor of Philosophy, with a major in Civil Engineering.

John S. Schwartz, Major Professor

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Glenn A. Tootle, Daniel C. Yoder, Devon M. Burr

Accepted for the Council:

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Vice Provost and Dean of the Graduate School

(Original signatures are on file with official student records.)

**Bedload Transport Sampling, Characterization and Modeling on a
Southern Appalachian Ridge and Valley Stream**

A Dissertation Presented for the

Doctor of Philosophy

Degree

The University of Tennessee, Knoxville

Patrick Lasater McMahon

December 2013

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ABSTRACT

Estimates of bedload transport rates developed from existing transport models are notoriously inaccurate. The gravel bed models addressed in this study include the Meyer-Peter and Muller; Parker, Klingeman, and McLean; and Wilcock two-fraction models. The question of whether or not these models predict bedload transport rates in a Southern Appalachian Ridge and Valley stream is complicated by the fact that these models have only been previously assessed in terms of their agreement with bedload transport rates measured in the Western regions of the U.S. Further, due to the strongly non-linear form of bedload transport models discrete errors and cumulative uncertainty in input parameters can result in excessive error and uncertainty in results.

The research presented in this dissertation approaches these issues through introduction of a new bedload transport data set collected on Little Turkey Creek in Farragut, Tennessee using a continuously monitoring bedload collection station with estimated collection efficiencies of nearly 100%. Use of 20-liter pail pit samplers is addressed for estimating bedload particle size distributions and transport model calibration. Finally, the issue of error and uncertainty in model input parameters is addressed through evaluation of the results of discrete error and cumulative uncertainty within the region of observed variation in bedload transport observations.

The results of this research suggest similarity between bedload transport characteristics in Southern Appalachian Ridge and Valley streams and those of streams in the Western region of the U.S. It was found that 20-liter pail pit traps are suitable for collection of bedload transport particle size distribution data and only marginally well suited for model calibration. It was illustrated that selected bedload transport models are most sensitive to errors in estimates of Manning's n and slope. Further, it was found that uniform uncertainty of more than 20% in model input parameters produces results that are at the outer edge of the observed variation in bedload transport rates. The body of work presented in this dissertation is intended to provide stream restoration design professionals with additional background to inform bedload transport estimates on streams in the Southern Appalachian Ridge and Valley Region.

TABLE OF CONTENTS

INTRODUCTION	1
CHAPTER I Performance Assessment for a Continuously Recording Bedload Pit Trap.....	6
Chapter I Abstract	7
1. Introduction	8
2. Methods	9
2.1. Study Design.....	9
2.2. Study Location and Pit Trap Construction.....	10
2.3. CFD Modeling Analysis	12
2.4. Saltation Step Length Estimation.....	15
3. Results	17
3.1. Vertical Velocity Vector Distributions	17
3.2. Saltation Travel Length.....	21
3.3. Performance Assessment	21
4. Summary	24
5. Notations	25
6. References	26
CHAPTER II Characterizing Bedload Transport in a Southern Appalachian Ridge and Valley Stream	28
Chapter II Abstract.....	29
1. Introduction	30
2. Methods	30
2.1. Study Area	30

2.2.	Bedload Monitoring Station Design	33
3.	Trapping Efficiency.....	34
3.1.	Reach Hydraulics	35
3.2.	Material and Data Collection	36
3.3.	Sediment Particle Size Characterization	36
3.4.	Compilation of Bedload Transport Data.....	36
4.	Results	39
4.1.	Particle Size Distributions of Bed and Bedload Materials.....	39
4.2.	Bedload Transport Rates	40
4.3.	Qualitative Comparison with Other Datasets	41
5.	Discussion	43
6.	Notations	45
7.	References	46
CHAPTER III Use of 20-liter Pail Pit Traps for Bedload Characterization and Model Calibration		48
Chapter III Abstract		49
1.	Introduction	50
2.	Methods	52
2.1.	Study Design.....	52
2.2.	20-liter Pail Pit Trap Installation and Use	53
2.3.	Bedload Size Characterization and Statistical Comparison.....	54
2.4.	Maximum Grain Shear Estimation	55
2.5.	Bedload Transport Model Calibration	56
3.	Results and Discussion.....	57

3.1.	Comparative Analysis of Captured Bedload Size Distributions.....	57
3.2.	Calibration of the Wilcock (1998) Two-fraction Model.....	62
4.	Summary	64
5.	Notations	64
6.	References	66
CHAPTER IV Uncertainty in Selected Bedload Transport Models: Support for Stream Restoration Design in the Southern Appalachian Ridge and Valley Region.....		69
Chapter IV Abstract		70
1.	Introduction	71
2.	Study Design and Methods.....	72
2.1.	Models Tested.....	73
2.2.	Model Input Parameters	78
2.3.	Error and Uncertainty in Input Parameters	80
3.	Results and Discussion.....	81
3.1.	Calibrated Model Results.....	81
3.2.	Effect of Errors and Uncertainty.....	82
4.	Summary	88
5.	References	90
SUMMARY OF CHAPTERS I-IV		92
APPENDIX.....		95
VITA.....		96

LIST OF TABLES

Table I:1 –	Maximum Vertical Velocity Vector Magnitudes (mm/s) for the flow Domain 0.0 to 0.1 Below the Trap rim at Various Confidence Limits.....	18
Table I:2 –	Maximum Vertical Velocity Vector Magnitudes (mm/s) for the flow Domain 0.0 to 0.1 Above the Trap rim at Various Confidence Limits.....	18
Table I:3 –	Particle Step Length Estimates for Gravels Saltation during Bank Full Flows on Little Turkey Creek based on Nino and Garcia (1994)	21
Table I:4 –	Critical Vertical Velocity Component Vector Values for Gravel Particles Using a CD of 1.5.....	23
Table II:1 –	Little Turkey Creek Research Reach Properties	33
Table II:2 –	Average Particle Size Distribution Size Class Summary, Based on Data in Figure II:6	40
Table III:1 –	Attributes of Various Bedload Samplers, (Modified from Bunte et al. (2004)).....	51
Table III:2 –	Summary of Bedload Transport Characteristics per Collection Event for LCM Bedload	59
Table IV:1 –	Individual Parameter Error Ranges from the Known Value Evaluated for each Model	73
Table IV:2 –	Input Parameters for the Selected Bedload Transport Models.....	79
Table IV:3 –	Ranges of Uniform Uncertainty Applied to Each Model	80

LIST OF FIGURES

Figure I:1 –	Flow Domain Illustration.....	9
Figure I:2 –	Farragut, Tennessee location map.....	10
Figure I:3 –	Research station location and contributing watershed boundary of Little Turkey Creek, Farragut, Tennessee	11
Figure I:4 –	View of continuously recording bedload pit traps: (Left) concrete vaults being installed in stream subgrade where traps were designated by letters A through D progressing from river left to right; and (Right) finished construction of pit traps.....	12
Figure I:5 –	Study reach topography as modeled in FLOW3D®.....	13
Figure I:6 –	Normal three mixture model fit to the distribution of vertical velocity components within the domain below the trap rim for Trap A at the 0%, 50%, 60%, 70%, and 80% full condition (m/s)	15
Figure I:7 –	Dimensionless saltation lengths (λ_s) vs. Dimensionless Shear Stress (τ_*):	16
Figure I:8 –	Cumulative frequency distribution of vertical velocity vectors at the trap rim for various depths of fill for pit traps A, B, C, and D, domain above trap rim (dashed), domain below trap rim (solid).....	19
Figure II:1 –	Farragut, Tennessee location map.....	31
Figure II:2 –	Research station location and contributing watershed boundary	32
Figure II:3 –	Photo of bedload monitoring station pit trap at base flow, downstream flow from left to right.	34
Figure II:4 –	Stage–discharge relationship developed for Little Turkey Creek, Farragut, Tennessee at the bedload sampling station.	35
Figure II:5 –	Particle size distribution of bedload material using 1:10 sub-sampling (dashed) and full-volume sampling (solid)	38

Figure II:6 – Particle size distribution for Little Turkey Creek bedload, bed, and bar samples	39
Figure II:7 – Bedload transport data for Little Turkey Creek.....	41
Figure II:8 – Bedload transport Data at Little Turkey Creek with respect to bedload transport data sets for the East Fork River and the Snake River.	42
Figure II:9 – Bedload transport data at Little Turkey Creek with respect to bedload transport data sets for Oak Creek and the Snake River.....	43
Figure III:1 – Farragut, Tennessee location map.....	52
Figure III:2 – Conceptual representation of an installed 20-liter (5-gal) pail sampler recessed in the streambed.	53
Figure III:3 – Mass captured by the 20-liter samplers vs. root mean squared deviation	58
Figure III:4 – Mass captured by the 20-liter samplers vs. maximum event grain shear	60
Figure III:5 – Mass captured by the 20-liter samplers vs. sand fraction error	61
Figure III:6 – Peak grain shear vs. sand fraction from 20-liter samplers	61
Figure III:7 – Results of the Wilcock (1998) two-fraction model calibrated using 20-liter sampler data presented with measured bedload transport rates for Little Turkey Creek	63
Figure IV:1 Comparison of stock bedload transport models to Little Turkey Creek bedload data	74
Figure IV:2 Conceptual illustration of the Monte Carlo simulation process used	81
Figure IV:3 – Modified bedload transport model predictions compared to field data collected from Little Turkey Creek, Tennessee (2010-2011).....	82

Figure IV:4 – Effect of discrete errors in Manning’s n (n), slope, (S), particle diameter (D_{90b}) and reference shear (τ_r) for the modified MPM model and comparison to Little Turkey Creek bedload data.....	84
Figure IV:5 – Effect of discrete errors in Manning’s n (n), slope, (S), particle diameter (D_{50s}) and reference shear (τ_r) for the modified PKM model and comparison to Little Turkey Creek bedload data.....	85
Figure IV:6 – Effect of discrete errors in Manning’s n (n), slope, (S), particle diameter (D_{65b}) and reference shear for sand (τ_{rs}), reference shear for gravel (τ_{rg}), and gravel fraction (f_s) for the W98 model and comparison to Little Turkey Creek bedload data	86
Figure IV:7 – 95% Confidence intervals for 10% and 20% uniform uncertainty in input parameters for the modified MPM and PKM models and 10% and 15% for the W98 model.....	88

INTRODUCTION

Successful design and construction of dynamically stable alluvial stream restoration projects is largely dependent on the design of reach-scale hydraulic geometry that provides a long-term balance between bed-material sediment supply and transport capacity. The prediction of bedload movement in alluvial systems has been studied for decades due to its importance in understanding fluvial hydraulics, river engineering, river morphology, dam and reservoir designs, irrigation projects, and other related subjects (Khorram and Ergil, 2010). Since the first “modern” bedload transport equation presented by Paul Francois du Boys in 1879, there have been upwards of 40 numerical models developed to describe the rate of bedload transport in alluvial systems (Gomez and Church, 1989; Khorram and Mustafa, 2010; Hager 2005). The bulk of these models deal with sand-bed streams, while comparatively less work has been done in gravel dominated systems (Thomas and Chang 2007). The majority of gravel bed models that have been developed were derived on a comparatively restricted database and their utility has been established on the basis of relatively few field data (Gomez and Church, 1989). As such, the accuracy of these predictive models has often been called into question and in many practical situations prediction errors of these models are observed to be unacceptably high (ASCE Task Committee on Preparation of Sediment Manual 1971; Bhattacharya and Solomatine 2006; Gomez and Church 1989; Van Rijn 1993; Wilcock 1987; Yalin 1972).

The gravel bed models addressed specifically in this study include the Meyer-Peter, Muller (1948); Parker, Klingeman, and McLean (1982); and Wilcock (1998) models. The question of whether or not these models predict bedload transport rates in a Southern Appalachian Ridge and Valley stream is further complicated by the following:

- The field datasets that these models have been partially derived from and frequently compared to are by in large those collected in perennial snow melt dominated rivers in Western regions of the United States (Khorram and Ergil 2010; Williams and Rosgen 1989). While the physics of particle motion within any part of the world are conceptually the same, there can be wide variation between the bedload transport characteristics of systems in different regions due to the combined effects of differences in soil cohesion, vegetation, and the relative fraction of sand and gravel.
- There is a lack of published bedload transport observations in the Eastern regions of the United States with which to compare these models. This may be due in part to the fact that streams located in the Southern Appalachian Ridge and Valley region of the United States are dominated by storm flow as opposed to perennial snowmelt, making bedload transport rate sampling a difficult proposition (Gracie and Thomas June 2004; Pizzuto 2013; Reed 1999).
- Application of these models at any given site requires some form of estimate for the reference (near critical) shear stress, the particle gradation of bed-material in motion, the particle gradation of the bed, the channel roughness, and the slope of the energy grade line. The sampling necessary to collect even a modest number of bedload transport rates in storm dominated systems can be difficult and there is a lack of consensus on the techniques suitable to the task.

With regard to these issues, the research presented in this study attempts to address the evaluation of error and uncertainty in the selected models applied to a Southern Appalachian Ridge and Valley stream through completion of the objectives described in the following sections.

1. Estimate the Collection Efficiency of Bedload Pit Traps at the Selected Research Reach

A computational fluid dynamic model of the pit trap bedload samplers at the research reach (Little Turkey Creek in Farragut, Tennessee) was developed and applied to evaluate local flow velocity vectors in and around the pit traps for a variety of stage and depth of fill conditions. For each test condition, statistical distributions to resultant velocity vectors within the pit traps and within the mobile bedload layer above the traps were fitted. These distributions were used to estimate the 80, 90, and 95% confidence interval for the resultant average vertical velocity magnitude within the pit traps. These confidence intervals were used to estimate the resulting range of lift and drag forces on sand and gravel particles in temporary suspension within the pit traps and immediately above them. These forces were compared to the combined forces of gravity and buoyancy to establish the probability of deposition of bedload material within the traps for each test condition and the particle size distribution of mobile material. The potential impact of saltation on the collection efficiency of the pit traps was also addressed through estimation of probable saltation step lengths and heights of individual grains.

2. Collect and Characterize Bedload Transport for a Southern Appalachian Ridge and Valley Stream

A real-time bedload transport data collection station using large-scale pit traps was designed and installed on Little Turkey Creek in Farragut, Tennessee. The station was used to collect bedload transport data for near bank full flow events including real-time bedload transport rates, flow rates, particle size distributions and energy slopes over a period of two years in an effort to characterize bedload transport in a Southern Appalachian ridge and valley stream. The resulting data were qualitatively compared to well-known Western perennial snow melt stream bedload transport of Milhous (1973); Emmett (1976); and Leopold and Emmett (1976) with regard to the relation between bedload transport rate and shear stress.

3. Evaluate the use of 20-liter Pail Pit Traps for Bedload Characterization and Model Calibration

Twenty-two paired bedload data sets were collected using two 20-liter pail pit traps and the continuously monitoring bedload transport station, which used the large-scale pit traps. Data collected include stage, slope, and particle size distribution of material captured by each device. The data were compared to evaluate the ability of the 20-liter pail pit samplers to collect a representative sample of the bedload particle size distribution. Further, the data collected using

the 20-liter pail pit samplers were evaluated for use in estimating the reference shear values for sand and gravel at the research site. These data were used to calibrate the Wilcock model and the resulting calibrated model is qualitatively compared to the full bedload transport data set collected at Little Turkey Creek.

4. Evaluate the Effect of Errors and Uncertainty in Selected Bedload Transport Models for a Southern Appalachian Ridge and Valley Stream

This portion of the study addresses the result of error and uncertainty in input parameters for three different bedload models: 1) a modified form of the Meyer-Peter Muller model, 2) a modified form of the Parker, Klingeman, and Mclean model, and 3) the Wilcock (1998) model. The independent input parameters selected for testing were reach slope, channel Manning's n , reference shear stress, and particle size distribution data specific to each model. The effect of errors and uncertainty in these parameters was evaluated with regard to their input into both the bedload transport relations themselves and the hydraulic resistance relations the models rely on. Results based on discrete differences in individual parameters are presented for each model in the context of the observed variation in bedload transport measurements collected at Little Turkey Creek. The effect of uniform uncertainty of up to 20% was evaluated through application of Monte Carlo simulations and results are presented with regard to a 95% confidence interval for model results and again the observed variation in bedload transport measurements collected at Little Turkey Creek.

The remainder of this study is presented in a series of four independent chapters developed for publication in the Journal of Hydraulic Engineering (Chapter 1), the Journal of Water Resources Research (Chapter 2), the Journal of Hydraulic Engineering (Chapter 3) and the International Journal of Sediment Research (Chapter 4). These chapters are followed by a brief summary and an appendix of referenced material and related records, photos, and project documentation.

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CHAPTER I PERFORMANCE ASSESSMENT FOR A CONTINUOUSLY RECORDING BEDLOAD PIT TRAP

CHAPTER I ABSTRACT

Bedload transport samplers that are installed within the bed of a stream and collect bedload material primarily through gravitational deposition are referred to as pit traps. Pit trap bedload samplers have been used previously by researchers studying bedload transport in gravel bedded rivers. Data collection activities and subsequent analyses for pit traps assume that the collection efficiency for these devices is at or acceptably near 100% for material in the mobile gravel size range. However, this assumption has not been assessed by coupling field measurements with computational fluid dynamics modeling and analysis. Subject to pit trap design, collection efficiency may be impacted by internal recirculation velocities, causing preferential deposition of coarser gravel particles and/or saltation of particles over the trap openings. The collection efficiency of bedload pit traps on Little Turkey Creek in Farragut Tennessee were evaluated in this study in support of data collection efforts at that site to characterize bedload transport on a Southern Appalachian Ridge and Valley stream.

A three dimensional computational fluid dynamics model was developed for the study reach and bedload pit traps. This model was applied to evaluate local flow velocity vectors in and above the pit traps for a range of fill depths of deposited material within the traps during near bank full flow. For each test condition, a statistical distribution was fit to the vertical velocity vectors within the flow domain immediately above the pit traps to a depth of the approximate thickness of the mobile bed layer and the flow domain immediately below the lip of the pit traps to the same thickness. The fitted distributions were used to determine the upper 80, 90, 97.5, and 99.9% confidence limit for the maximum vertical velocity vector within the flow domains of interest. The maximum vertical velocity vectors at each confidence limit were then used to estimate the resulting forces acting on gravel particles within the flow domains of interest with respect to the combined forces of gravity, buoyancy, and friction to establish the probability of deposition of bedload material within the traps. In addition, the potential for sediment particles to overpass the bedload traps through saltation was addressed through application of the plotted relations developed by Nino and Garcia (1994).

Statistical analysis of the modeled velocity vectors within the flow domains of interest suggest that the individual traps are unaffected by vertical velocities at an upper confidence limit of 97.5%. Further, collection efficiency does not appear to be impacted by the depth of deposited material in the traps. This may be plausible to a limit at which the top of the collected material within the traps is at an elevation relative to the trap rim for the deposited material to be remobilized by near bed shear. It is conceivable that this would occur when the deposited material is at an elevation below the trap rim by a distance equal to the thickness of the mobile bedload layer. In the case of the pit traps at Little Turkey Creek, this suggests trap efficiency is at or near 100% until the traps become approximately 75% full.

1. INTRODUCTION

Bedload transport samplers that are installed within the bed of a stream and collect bedload material primarily through gravitational deposition are referred to as pit traps. Pit trap bedload samplers have been used previously by researchers studying bedload transport in gravel bedded rivers (Batalla et al. 2010; Sear et al. 2000; Sterling and Church 2002). Leopold and Emmett (1976) used a pit trap system with variable slot openings on the East Fork River in Wyoming; weighing variable slot pit traps have been used in gravel-bedded rivers including Turkey Brook in Chase, England (Reid et al. 1980), Goodwin Creek near Batesville Mississippi USA (Kuhnle et al. 1988), the Nahal Yatir near Beer Sheva, Israel (Laronne et al. 1992), and the Rio La Tordera in Barcelona, Spain (Garcia et al. 2000). The purpose of a pit style bedload sampler is to intercept all material that would otherwise be in intermittent contact with the bed at the location of the pit during a mobile bed event; such material might be rolling, sliding or saltating downstream (Sterling and Church 2002). Pit traps have an advantage over bedload sampling methods such as the Helley-Smith sampler and other devices that are deployed at the bed surface, because the pits themselves do not extend into the velocity profile above the bed where would influence the local velocity profile.. Data collection activities and subsequent analyses for pit traps assume that the collection efficiency for these devices is at or acceptably near 100% for material in the mobile gravel size range (Hubbell 1987; Sterling and Church 2002; Wilcock 2001), but this assumption has not been assessed by coupling field measurements with computational fluid dynamics modeling and analysis.

Subject to pit trap design, collection efficiency may be impacted by internal recirculation velocities causing preferential deposition of coarser gravel particles and/or saltation of particles over the trap openings. Habersack et al. (2001) attempted to assess the lumped impact of these factors on the trapping efficiency of pit samplers using a Helley-Smith sampler as a basis for comparison to pit traps, but conclude that additional laboratory investigations were necessary to develop meaningful results. Bergman (2007) applied the hydraulic observations of Habersack (2001) for flow velocities within a pit trap relative to those immediately above the pits and asserts that trap efficiency is acceptably close to 100% for trap fill depths up to 80% of the pit capacity. The theoretical efficiency of pit traps with regard to the impact of recirculation velocities was explored by Sterling and Church (2002) using measured horizontal fluid velocities within pit traps and extrapolation to circulation velocities within the trap to estimate collection efficiencies that range from 100% for all particles in the gravel size class to 100% for all particles larger than 16 mm; depending on the local hydraulic conditions at the location of the trap. The work presented in this study approaches the issue by using a combination of field calibrated computational fluid dynamic modeling and statistical analysis to assign confidence intervals for the performance of the traps at Little Turkey Creek. .

The objective of this study was to analytically evaluate the collection efficiency of continuously monitoring weighing pit style bedload samplers constructed on Little Turkey Creek in Farragut, Tennessee with an emphasis on recirculation velocities and particle saltation step length. It is hypothesized that the collection efficiency of the individual pit traps at bank full conditions is predictable as a function of the depth of collected material within the traps and particle size according to computational fluid dynamics modeling and analysis of velocity vectors within and near the trap.

2. METHODS

2.1. STUDY DESIGN

To test the hypothesis that bedload collection efficiency is predictable, a three dimensional (3D) computational fluid dynamics (CFD) model was developed for the study reach and installed bedload pit traps. This model was applied to evaluate local flow velocity vectors in and above the pit traps for a range of fill depths of deposited material within the traps during bank full flow. For each test condition, a statistical distribution was fit to the vertical velocity vectors within the flow domain immediately above the pit traps to a depth of the approximate thickness of the mobile bed layer (0.1 m) and the flow domain immediately below the lip of the pit traps to the same thickness, 1:1. The vector data were collected when flow was at steady state and represent a snapshot in time. The assumption was made that once the particle moves below this flow domain it will settle to the surface of the trapped material within the pit. The fitted distributions were used to determine the upper 80, 90, 97.5, and 99.9% confidence limit for the maximum vertical velocity vector within the flow domains of interest. The maximum vertical velocity vectors at each confidence limit were then used to estimate the resulting forces acting on gravel particles within the flow domains of interest with respect to the combined forces of gravity and buoyancy to establish the probability of deposition of bedload material within the traps. In addition, the potential for sediment particles to overpass the bedload traps through saltation was addressed through application of the plotted relations developed by Nino and Garcia (1994)..

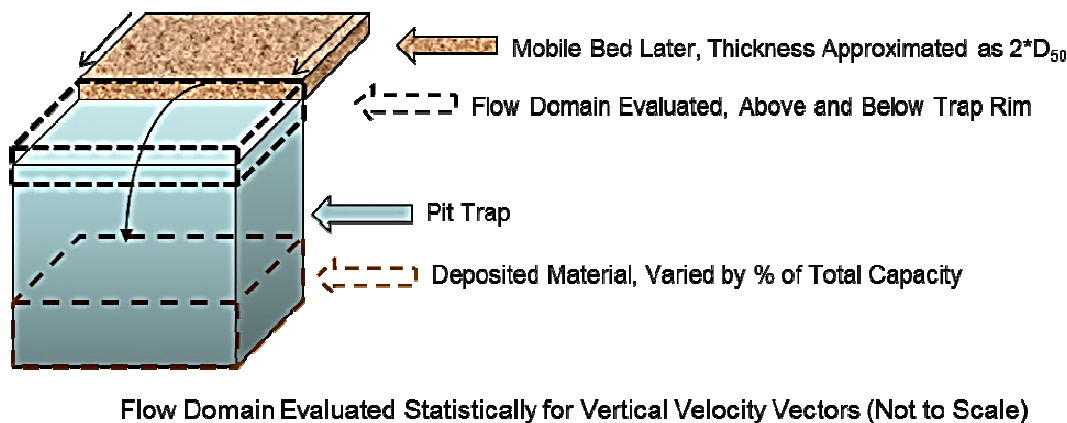


Figure I:1 – Flow Domain Illustration

2.2. STUDY LOCATION AND PIT TRAP CONSTRUCTION

The continuously weighing pit style bedload samplers analysed in this study were constructed in August 2010 on Little Turkey Creek in Farragut Tennessee (Figure I:1 and I:4). These traps were established to characterize bedload transport for streams in the Southern Appalachian, Ridge and Valley Province. At the location of the bedload traps, Little Turkey Creek drains an area of approximately 11.6 square kilometers and 21.1 kilometers of Stream. The watershed slope is approximately 2.8%. The basin is partially urbanized and has seen a steady progression from forest land, to agricultural development, to suburban development over the past 100 years. Each of these elements is still present in the watershed to varying degrees.

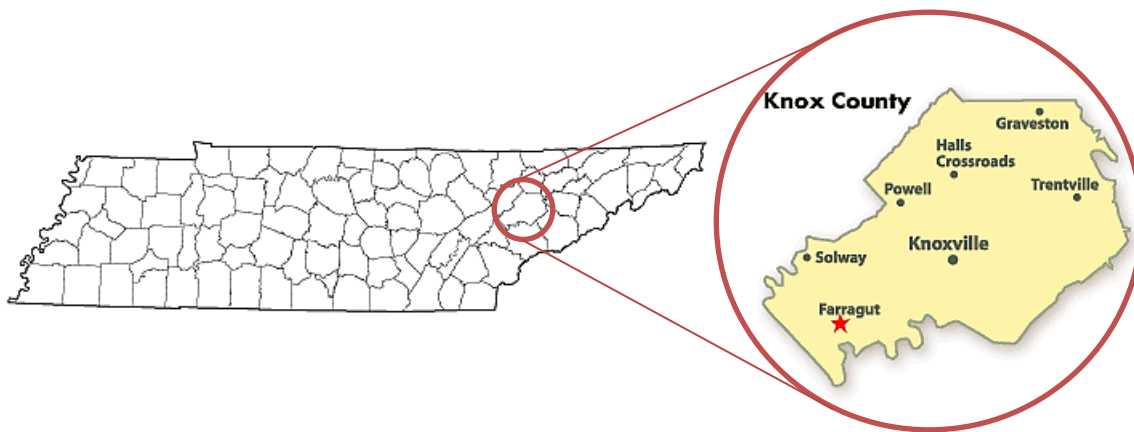


Figure I:2 – Farragut, Tennessee location map

The traps on the site consist of four Birkbeck-type pit traps (Reid et al. 1980), extending perpendicular to flow across the channel bottom in series (Figure I:4). The bedload traps were reinforced concrete vaults with stainless steel loading box inserts resting on four submersible load cells (Omni Instruments, model DDEN-5KN-C25). The concrete vaults were standard inlet boxes purchased from Sherman Dixie Precast, a local manufacturer. The outside dimensions were approximately 71 cm by 71 cm by 91 cm (WxLxD). The wall thickness was approximately 15 cm. The loading box inserts fit within the vaults and were flush with the top of the concrete. The loading boxes have a 1 cm or less horizontal clearance from the concrete vault on each side wall. This gap was partially sealed at the bed elevation with a thin soft foam insert. The total collection volume of each trap was 1.6 m³. The four load cells per loading box were individually connected to a Campbell data logger (Model #CR1000), reading weights on a 15-second interval and recording a time averaged weight every 5 minutes. Water level loggers were located 11 m upstream and 27 m downstream from the traps.

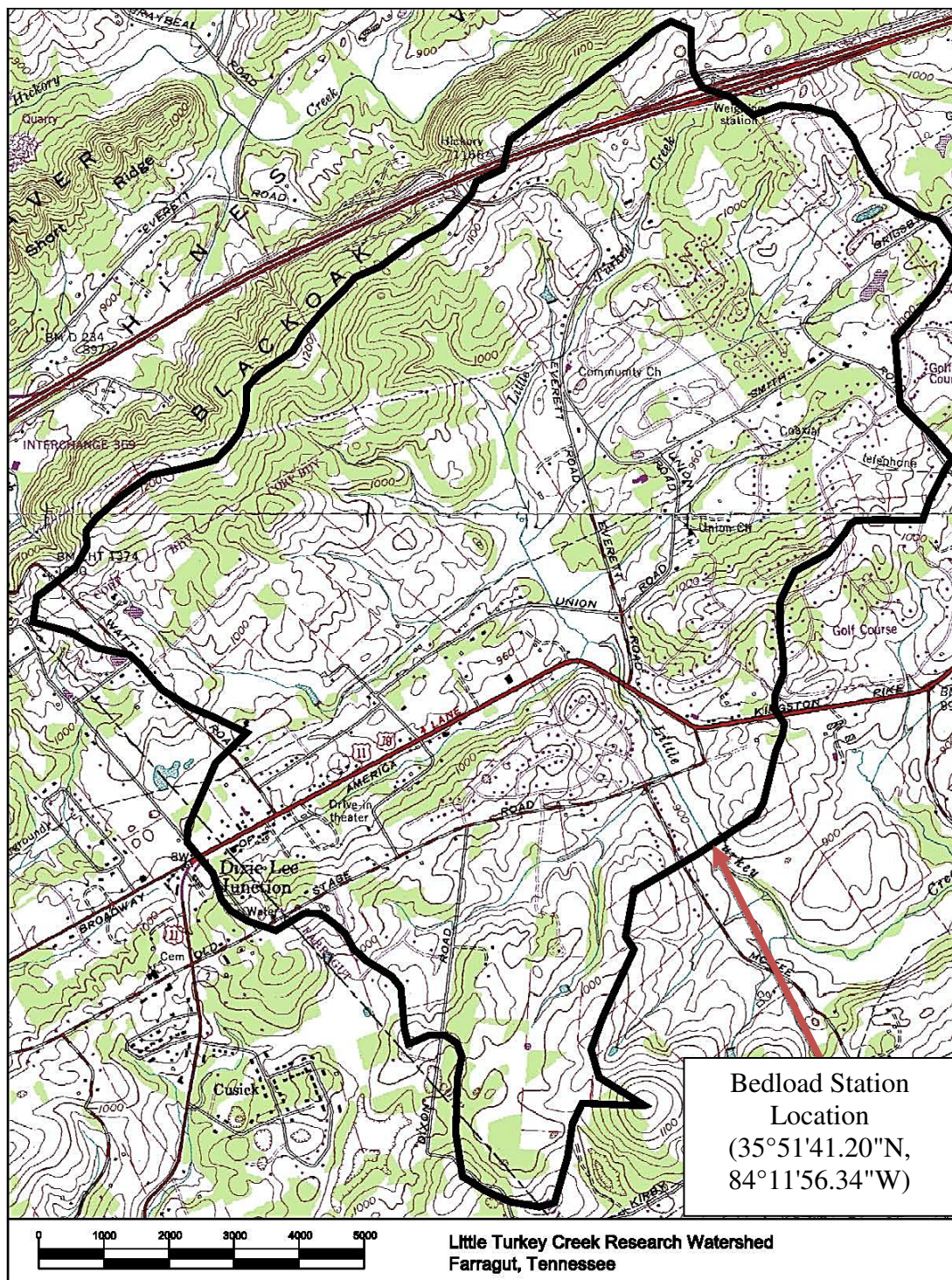


Figure I:3 – Research station location and contributing watershed boundary of Little Turkey Creek, Farragut, Tennessee

They were time synchronized with the data logger at the bedload station and were tied to an established datum on the greenway adjacent to the site. The water level loggers consist of vented pressure transducers (Global Water, Model WL16) installed within 3-inch polyvinylchloride tubes that were perforated below the water surface. The water level sensors were programed to record pressures every 15 minutes and were used to estimate the energy grade line slope and stage during bedload events. A stage discharge relationship was developed at the site using the standard USGS velocity-area methods and a Marsh-McBirney FloMate2000™ when the stream could be safely waded; a YSI/SonTek RiverSurveyor™ was used during near bank full flow conditions.



Figure I:4 – View of continuously recording bedload pit traps: (Left) concrete vaults being installed in stream subgrade where traps were designated by letters A through D progressing from river left to right; and (Right) finished construction of pit traps.

2.3. CFD MODELING ANALYSIS

In order to develop estimates for the drag forces on bedload particles in the vicinity of the pit traps a CFD (FLOW3D®) model was used to simulate the velocity vectors for bank full flow and a range of depth of fill conditions within the pit traps as defined in the Study Design section. FLOW3D® uses the Reynolds averaged Navier-Stokes (RANS) equations for fluid motion simulation estimates. Skin friction was estimated using Nikuradse's equivalent sand grain k_s . The standard wall function for turbulent flow was used (Prandtl 1931) and the turbulent closure model used was the Renormalized Group (RNG) model which is a variation of the k - ϵ model (Yakhot et al. 1992).

2.3.1. Study Site CFD Model Development and Pre-Processing

Development of the CFD model for the study site required the input of topographic details upstream and downstream of the pit traps, defining the boundary conditions necessary to simulate bank full flows. The reach topography and pit trap dimensions were extracted from a detailed topographic survey of the channel and banks in the immediate vicinity of the bedload traps. The survey was conducted in October of 2012 using a Nikon DTM-322 series, 3-second total station and a Tripod Data Systems Recon 400X data logger. The surveyed area extends approximately 3 m downstream and 17 m upstream of the pit samplers and from the lowest bed elevation to approximately 0.2 m above bank full. The survey data were exported into CAD software and a triangulated irregular network (TIN) surface was developed. This surface was then sampled on a regular grid of 0.15 m to develop an ASCII input file that can be read by FLOW3D® as a topographic surface. Figure I:5 shows the resulting surface as displayed in FLOW3D®.

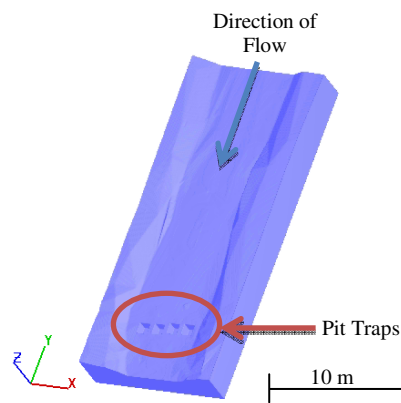


Figure I:5 – Study reach topography as modeled in FLOW3D®

The extents of the topographic data shown in Figure I:5 are $x = 0.0$ to 9.5 m, $y = 0.0$ to 22.3 m, and $z = -1.5$ to 1.5 m. The study reach topography data was amended in FLOW3D® to include an additional 40 m upstream of the surveyed channel shown in Figure I:5. This extension allowed for sufficient flow path length to fully develop the turbulent boundary layer upstream of the pit trap area.

Next, the 3D finite element mesh (FEM) was generated using tools in FLOW3D®. The FEM was constructed to encapsulate the flow domain with an initial grid spacing of 0.15 m. The upstream boundary was defined as a known volumetric inflow rate with a fixed water surface elevation at bank full; approximately 0.9 m. The downstream boundary was set to a static

pressure boundary with a fixed water surface elevation at bank full. The bankfull condition was chosen for analysis because it is thought to be the condition under which the greatest amount of bedload is mobilized.

The model was then run until a steady-state solution was reached. Steady-state conditions were then used as the next starting point in a series of successive iterations where the grid spacing was reduced to a size such that further reductions did not affect estimated velocity parameters near the pit traps. For each subsequent simulation, the initial conditions were discretized into the new and finer grid spacing by FLOW3D® based on the steady state of the previous run. A grid independent solution was achieved with a uniform mesh sizing of approximately 5 cm. Further discretization of the grid spacing to a value of 3 cm was carried out to more closely resolve the geometry of the pit traps at the interface with the bed; simplifying post processing efforts.

Model parameters for surface roughness along the channel bed and banks were then adjusted to calibrate the CFD model to approximate field conditions; a gravel bed and a thickly vegetated bank. The roughness of the gravel bed was determined using the Manning-Strickler relation and a back calculated value for the Manning's n based on field measurements at base flow conditions. This effort resulted in an estimated roughness height (k_s) of 9.8 cm. This value is approximately equal to twice the D_{50} particle size for the bed surface and is similar to the roughness height that would be estimated using relations by Wilcock (2003) or Parker (1990). A similar effort was made to determine the appropriate roughness height for the bank material using a partition between the bed and bank roughness and Manning's n back calculated for measured bank full flow conditions. However, this exercise produces a k_s value that is many orders of magnitude higher than that of the bed and well beyond a reasonable value for the bank, suggesting an upper limit to the usefulness of the Manning-Strickler relation in this application.

The bank roughness value was then estimated through iterative trials, comparing the simulated bank full cross channel velocity profile near the bedload traps with the velocity profile measured at bank full flow using a YSI/ Sontek River Surveyor velocity profiler. This approach resulted in an estimated 1.5 m roughness height for the banks. Using the Manning-Strickler relation, this is equivalent to a Manning's n of 0.043, which falls within accepted values for vegetated banks. Once the converged and calibrated model was developed for the empty trap conditions, the model was rerun for trap conditions with 50, 60, 70, 80, 90, and 100% of the trap filled with solids.

2.3.2. CDF Model Post Processing

Simulated flow velocities were evaluated for each of the four pit traps separately. For each combination of pit trap, flow domain (0 to 0.1 m above and below the trap rim), and depth of fill percentage, steady state instantaneous 3-D velocity vector components were exported from FLOW3D® into text files for analysis. The vertical velocity vector data were input into the statistical analysis software JMP. A cursory review of histograms of the data sets revealed that they were frequently bi or tri modal in their distribution and would be poorly described using strictly parametric techniques. JMP was used to fit and evaluate a range of nonparametric and parametric mixture models to the resulting vertical velocity vector distribution output for each scenario. Non-parametric models evaluated in JMP included the Johnson SI, Johnson SU, and

Generalized Log models (Johnson 1949). Normal mixture models included the two and three mixture models (Lindsay 1995). In all cases, the Normal three mixture models were identified as the best fit to the data. Additional information on the statistical distribution fit to the data can be found in the appendix of this dissertation. An illustration of the bi and tri modal nature of the data sets is provided in Figure I:6 below which shows a normal three mixture model fit to the distribution of vertical velocity vectors within the domain 0.0 to 0.1 m below the trap rim for Trap A at the 0%, 50%, 60%, 70%, and 80% full condition. Model fits to each data set are provided in the Appendix.

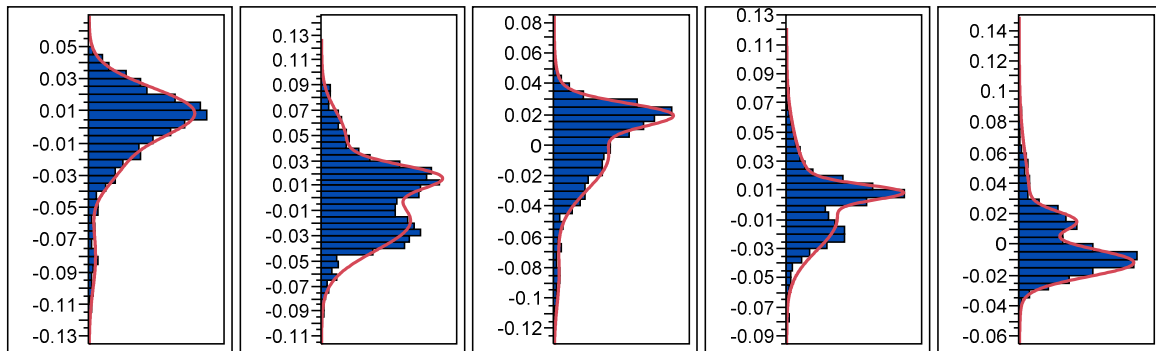


Figure I:6 – Normal three mixture model fit to the distribution of vertical velocity components within the domain below the trap rim for Trap A at the 0%, 50%, 60%, 70%, and 80% full condition (m/s)

2.4. SALTATION STEP LENGTH ESTIMATION

The potential for particles to saltate over pit traps occurs when the length of an individual saltation event for a given particle is longer than the dimension of the pit trap opening normal with the saltation direction. Saltation is thought to be the dominant mode of bedload transport, with rolling and sliding occurring to a lesser extent, mainly near the threshold of entrainment and between individual saltation events (Bridge and Dominic 1984). The particle mechanics of saltation in turbulent flowing water has been described by various researchers including Einstein (1950), Bagnold (1973), Bridge and Dominic (1984), and Nino and Garcia (1994).

Through experimentation and observation, Einstein (1950), working primarily with fine gravels and sands, suggests the approximation that the distance between consecutive points of deposition of a saltating particle is independent of the flow condition, the rate of transport, and the bed composition and can be assumed to be 100 nominal grain-diameters in length. Bagnold (1973) did not explicitly address step length in his work on saltation, but did suggest the importance of upward particle momentum imparted by successive contacts with the bed. Both studies rule out the effect of turbulence as an important mechanism that sustains saltation in an effort to

distinguish the saltation process from that of transport in suspension. Nino and Garcia (1994) present and test a model for particle saltation of gravel materials that includes the effects of rebound, turbulence, and the Magnus force caused by the rotation of a saltating particle.

Nino and Garcia (1994) used experimental results from high speed video recordings of gravel saltation in a laboratory flume to test their Lagrangian equation for particle motion that is averaged over flow turbulence and specialized to the case of coarse sediment particles saltating in water using a stochastic model for particle collision with the bed. A comparison between experimental results and the resulting relation for saltation length is provided in Figure I:7 below.

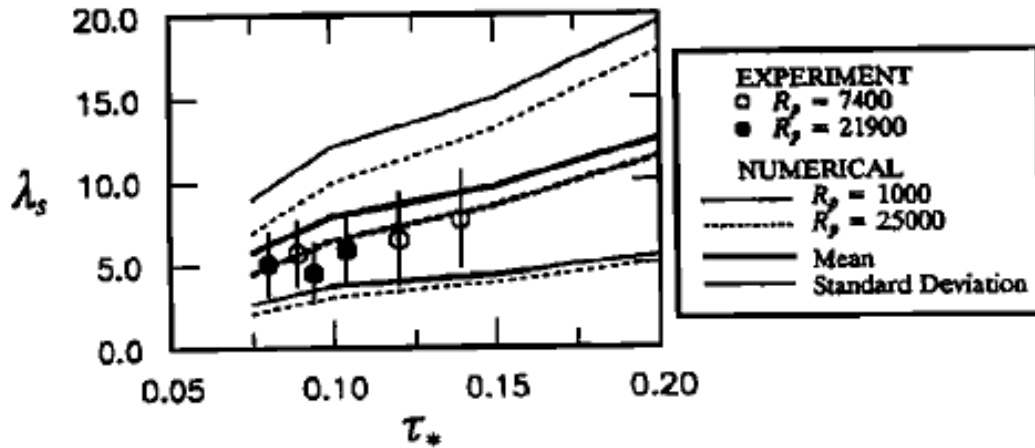


Figure I:7 – Dimensionless saltation lengths (λ_s) vs. Dimensionless Shear Stress (τ_*):
Thicker lines represent mean values and thinner lines represent mean values plus and minus one standard deviation. Symbols correspond to experimental mean value and vertical lines represent a total length of two standard deviations (Niño and García 1994).

In Figure I:7, the dimensionless saltation length is defined as the ratio of dimensioned saltation length, λ_s , to the nominal particle diameter and the dimensionless particle diameter, R_p , is calculated as per Equation I:1:

$$R_p = \frac{[(R - 1)gD_n^3]^{0.5}}{v_k} \quad \text{I:1}$$

Where,

R = specific weight of the particle

g = gravitational acceleration

D_n = nominal particle diameter

ν_k = kinematic viscosity

Applying standard values for parameter constants, it can be seen that the range of R_p values of 1,000 to 25,000 shown in Figure I:7 corresponds to a range of particle sizes of approximately 4 mm to 34 mm. The trends in Figure I:7 indicate a weak relationship between the dimensionless particle diameter, R_p , and dimensionless step length, λ_s , and a comparatively strong relationship between dimensionless step length and dimensionless shear stress, τ^* , as a surrogate for the combined influences of the effects of rebound, turbulence, and the Magnus force. The dimensionless shear stress, τ^* , in Figure I:7 is calculated using equations I:2 and I:3.

$$\tau^* = \frac{\tau}{(s - 1)\rho g D} \quad \text{I:2}$$

Where,

τ = reach average shear

s = specific gravity of the particle of interest

ρ = density of water

g = gravitational constant

D = nominal diameter of the particle of interest

$$\tau = RS\gamma \quad \text{I:3}$$

Where,

R =hydraulic radius

S =energy gradient

γ =unit weight of water

As a complement to the analysis of recirculation velocities, the relations presented in Figure I:7 were used to estimate the step length of gravel particles in Little Turkey Creek during bank full flows. Using the mean and standard deviation data provided in Figure I:7, a normal distribution was assumed for step length variations and maximum step lengths were estimated for the 80, 90, 97.5, and 99.9% confidence limit.

3. RESULTS

3.1. VERTICAL VELOCITY VECTOR DISTRIBUTIONS

The distributions of the vertical component of velocity vectors for the domains 0.0 to 0.1 m above and below the pit trap are summarized in Figure I:8. Dashed lines in Figure I:8 represent data in the domain 0.0 to 0.1 m above the trap rim. Solid lines represent data in the domain 0.0

to 0.1 m below the trap rim. Different colors represent various depth-of-fill conditions expressed as a percentage of the total trap capacity. Maximum vertical velocity vector components for each pit trap for the confidence intervals calculated using the fitted normal three mixture distributions at each trap are summarized in Table I:1 and Table I:2. The implication of these values is discussed in the following section.

Table I:1 – Maximum Vertical Velocity Vector Magnitudes (mm/s) for the flow Domain 0.0 to 0.1 Below the Trap rim at Various Confidence Limits

Pit Trap	Upper Confidence Limits (CL)			
	80% CL	90% CL	97.5% CL	99.9% CL
A	24.6 (60%)	40.1 (60%)	67.5 (60%)	105.9 (80%)
B	19.9 (60%)	34.8 (60%)	79.6 (80%)	141.7 (80%)
C	26.5 (60%)	43.7 (60%)	86.7 (80%)	170.0 (80%)
D	59.6 (60%)	101.9 (60%)	158.9 (80%)	242.6 (60%)

Note: Values in parentheses reflect the volume of trap capacity met for which the velocity value was recorded

Table I:2 – Maximum Vertical Velocity Vector Magnitudes (mm/s) for the flow Domain 0.0 to 0.1 Above the Trap rim at Various Confidence Limits

Pit Trap	Upper Confidence Limits (CL)			
	80% CL	90% CL	97.5% CL	99.9% CL
A	5.3 (60%)	13.1 (60%)	42.0 (80%)	81.7 (80%)
B	9.9 (60%)	19.8 (80%)	46.8 (60%)	112.9 (80%)
C	11.3 (60%)	22.4 (60%)	58.1 (70%)	123.0 (80%)
D	13.3 (60%)	48.7 (60%)	125.7 (60%)	185.5 (60%)

Note: Values in parentheses reflect the volume of trap capacity met for which the velocity value was recorded

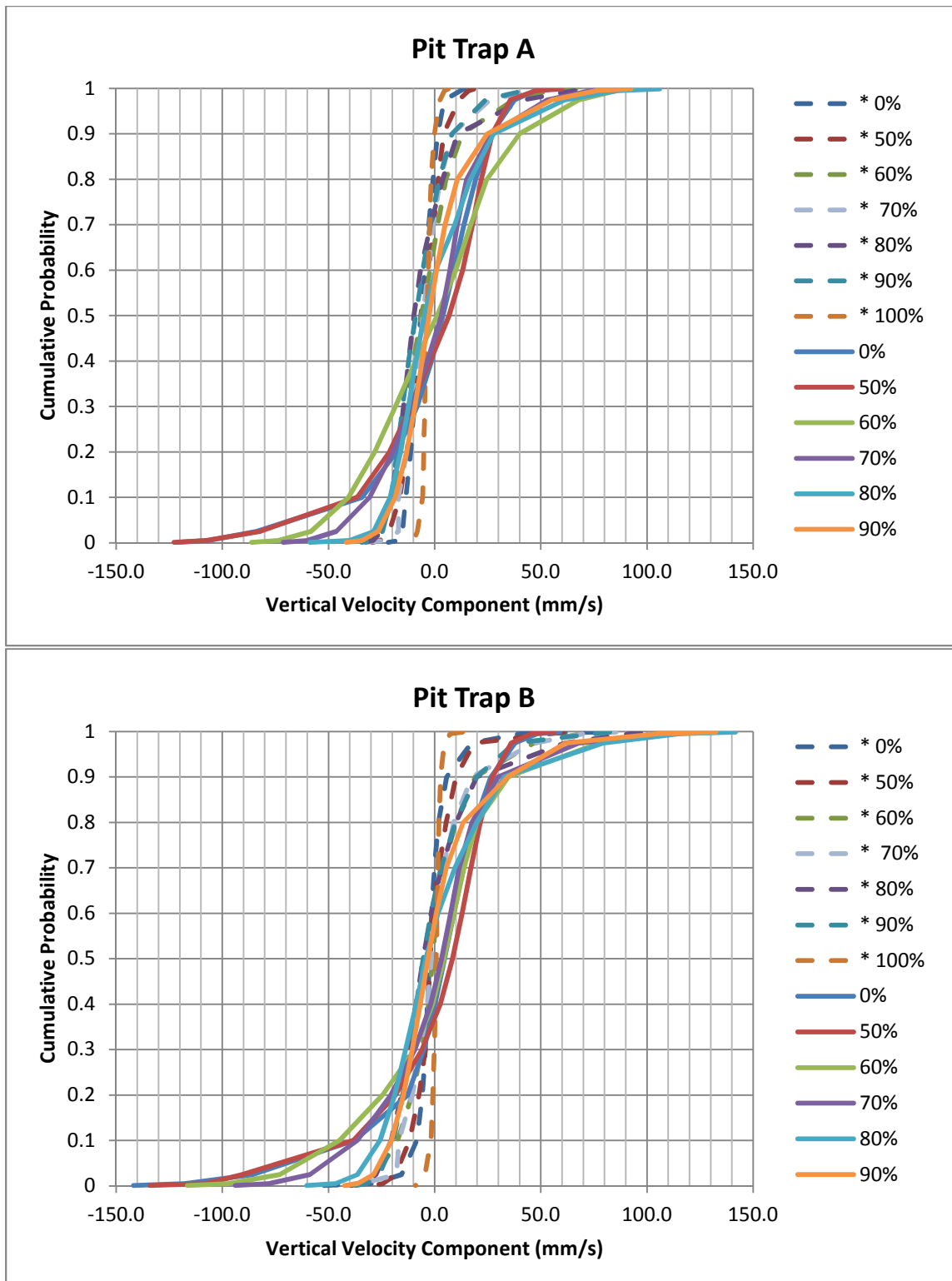


Figure I:8 – Cumulative frequency distribution of vertical velocity vectors at the trap rim for various depths of fill for pit traps A, B, C, and D, domain above trap rim (dashed), domain below trap rim (solid)

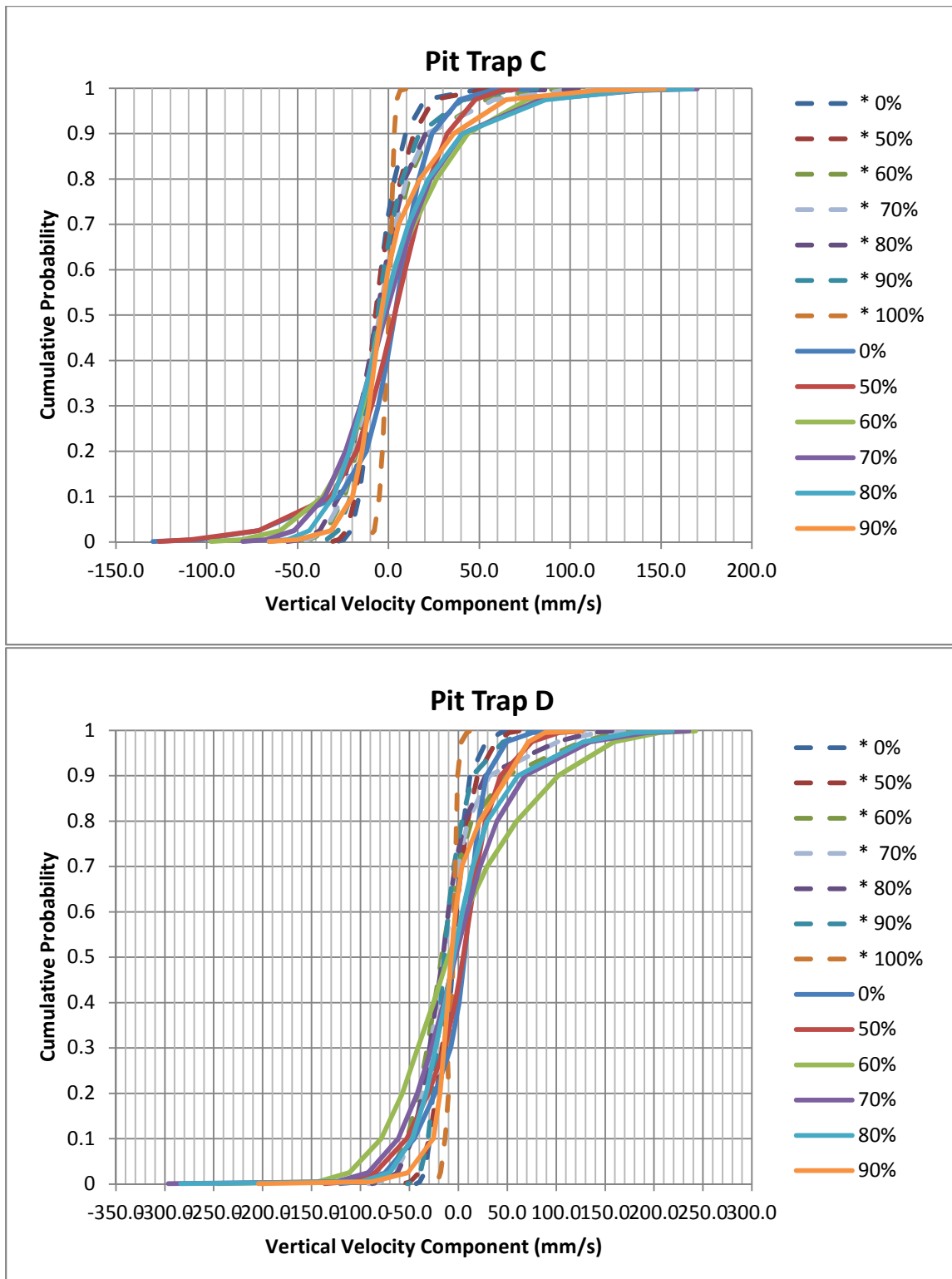


Figure I:8 (continued) – Cumulative frequency distribution of vertical velocity vectors at the trap rim for various depths of fill for pit traps A, B, C, and D domain above trap rim (dashed), domain below trap rim (solid)

3.2. SALTATION TRAVEL LENGTH

Using the relationships presented by Nino and Garcia (1994) in Figure I:7, particle step lengths and step heights for gravel particles during bank full flows are summarized in Table I:3 in terms of average step length and the 80, 90, 97.5, and 99.9% confidence limits estimated using the assumption of normality. At the 99.9% confidence limit, the longest step length, 320 mm, is for a 64 mm particle.

Table I:3 –Particle Step Length Estimates for Gravels Saltation during Bank Full Flows on Little Turkey Creek based on Nino and Garcia (1994)

Particle Size (mm)	Dimensionless Shear Stress, τ_*	Confidence Limit				
		50%	80%	90%	97.5%	99.9%
		Particle Step Length, mm				
2	0.83	146	170	208	270	146
4	0.41	146	171	208	270	146
8	0.21	146	171	208	271	146
16	0.10	170	197	239	310	170
32	0.05	170	197	239	310	170
64	0.03	174	201	243	313	174

3.3. PERFORMANCE ASSESSMENT

The potential for the vertical velocity vectors to influence particle collection exists when the magnitude of the submerged weight of a given particle is less than the drag force caused by the upward component of velocity associated with flow recirculation at entrance of the pit trap. The submerged particle weight, F_g , is calculated as follows, Equation I:4.

$$F_s = g(\rho_s - \rho)V \quad \text{I:4}$$

Where,

g = gravitational acceleration

ρ = density of water

ρ_s = density of the particle

V = particle volume

The drag force, F_d , on the particle is calculated as follows; Equation I:5.

$$F_d = \frac{C_D \rho v^2 A}{2} \quad \text{I:5}$$

Where,

C_D = Drag coefficient

v = vertical component of relative velocity

A = projected area of the particle

Combining Equation I:4 and Equation I:5, and assuming that each grain can be idealized as a sphere of equivalent volume and nominal diameter D_n and density $\rho_s = 2,650 \text{ kg/m}^3$, an approximation is made for a critical vertical velocity component for which a particle of a given grain diameter and roughness coefficient will be launched using Equation I:6.

$$\left(\frac{21.6 D_n}{C_D} \right)^{0.5} = v_c \quad \text{I:6}$$

Where,

D_n = Nominal diameter of the particle size of interest

v_c = Critical vertical velocity component

Sterling and Church (2002) found through experimentation that C_D can be approximated as 1 for particles in the gravel range. The experimental work of Engelund and Hansen (1967) suggest a C_D value of approximately 1.5 for particles in the gravel range and larger (for Particle Reynolds Number >300). Using the larger of the two values Table I:4 summarizes the relationship between particle size and the calculated critical vertical velocity component vector. The vertical velocity component vector distributions summarized in Figure I:8 indicate the absence of values greater than the smallest critical value summarized in Table I:4 at a confidence limit of 97.5%. At a confidence limit of 99.9%, only results for Pit Trap D suggest possible relaunching or collection bias for particles in the 2 to 4 mm range.

Results presented in Table I:3 suggest that at a 99.9% confidence limit the longest step length that should be anticipated for gravels when Little Turkey Creek is at bank full flow is 0.32 m ($\lambda_s = 5$ for a 64 mm particle and a CL of 99.9%). This length is approximately 75% of the

downstream dimension of the pit trap openings at the bed surface, suggesting that saltation over the pit traps is unlikely to occur, even at bank full flows. It is noted here that the dimensionless shear stress (τ^*) range for the plotted relations of Nino and Garcia (1994) is 0.075 to 0.200 and the range of values at Little Turkey Creek are 0.30 to 0.83. Therefore the plotted relations of Nino and Garcia (1994) were extrapolated for values outside of the range of 0.075 to 0.200. Extrapolation did not exceed an order of magnitude.

Table I:4 – Critical Vertical Velocity Component Vector Values for Gravel Particles Using a C_D of 1.5

Nominal Particle Diameter (mm)	Critical Vertical Velocity (mm/s)
2	170
4	240
8	339
16	480
32	679
64	960

The largest calculated dimensionless shear stress on Little Turkey Creek was 0.83, corresponding to bed shear normalized to a 2 mm particle using Equation I:2. For this shear stress value, the extrapolated results from the plotted relations of Nino and Garcia (1994) are a step length of approximately 50 times the nominal particle diameter. This value is close to that suggested by Poreh et al (1970), who assert that a pit trap with a downstream dimension approximately 40 times the nominal diameter of the smallest particle of interest will be 100% efficient (Sterling and Church 2002).

Under the assumption that the collection efficiency of a pit trap (as a whole with regard to recirculation velocities) is primarily dependent on the vertical component of the recirculation velocities within the flow domain of plus or minus one mobile bed layer thickness from the rim,

these results show that recirculation velocities have no impact on the collection efficiency of the pit traps at Little Turkey Creek during bank full flow conditions, with a confidence limit of 97.5%. Assuming that particle saltation occurs consistently parallel to the square pit trap opening in the downstream direction and that the plotted relations of Nino and Garcia (1994) can be extrapolated to the conditions on Little Turkey Creek, these results demonstrate that saltation length has no impact on trap efficiency during bank full flow at a confidence limit of 99.9%.

In the practical use of the pit traps under study, the findings and assumptions with regard to relauching of particles by recirculation velocities within the traps are deemed plausible and agree well with the assumptions and findings of researchers with similar pit trap installations (Batalla et al. 2010; Garcia et al. 2000; Kuhnle et al. 1988; Laronne et al. 1992; Leopold and Emmett 1976; Reid et al. 1980; Sear et al. 2000; Sterling and Church 2002). The reliability of these results would be in question, however, for any event in which irregular deposition of partially submerged large woody material or other debris is sufficient to significantly disturb the flow hydraulics within the pit traps and or above the rim of the pit traps through partial extension into the velocity profile or otherwise. The findings and assumptions with regard to particle overpassing through saltation are, however, less plausible for such a high confidence limit. With regard to step length, estimates in the literature vary widely, but seem to maintain the Einstein (1950) value of 100 times the nominal particle diameter to be a conservatively large value for gravel streams, so the step length values estimated using the plotted relations of Nino and Garcia (1994) appear reasonable. The assumption, however, that particle steps occur consistently parallel to the downstream dimension of the square pit trap opening is weak.

4. SUMMARY

The collection efficiency of four Birkbeck style (Reid et al. 1980) pit trap bedload samplers on Little Turkey Creek in Farragut, Tennessee has been analytically evaluated with regard to impact of recirculation velocities and saltation step length on particle collection. A CFD model of the pit traps and the research reach was used to simulate velocity vectors within the reach and the pit traps for a range of trap fill conditions including 0, 50, 60, 70, 80, 90, and 100% full. The model was tested for grid dependency based on changes on modeled velocity values near the pit traps and was calibrated according to field measurements of the 2D velocity profile at a cross section immediately downstream of the pit traps using a velocity profiler. Statistical analysis of the modeled cumulative distributions of simulated vertical velocity vectors within the flow domain from 0.0 to 0.1 m above and below the pit trap rims was used to fit normal-three-mixture models to each distribution. The fitted distributions were used to estimate the maximum vertical velocity vectors within the flow domain for the 80, 90, 97.5, and 99.9% upper confidence limit.

These values were compared to a calculated range of values for vertical velocities capable of relauching material from the pit traps prior to deposition with the trap. The results suggest that the individual traps are unaffected by vertical velocities at an upper confidence limit of 97.5%. At an upper confidence limit of 99.9%, the collection efficiency of pit trap D is impacted for particles in the 2-4 mm range.

Extrapolation of the plotted relations of Nino and Garcia (1994) was used to estimate particle step lengths for bedload gravels mobile on Little Turkey Creek at bank full flow. The

assumption of normality was used to estimate step lengths for the upper 80, 90, 97.5, and 99.9% confidence limit. The results indicate that at the 99.9% confidence limit, maximum step lengths for all particles in the gravel range are between 27 and 32 cm. Based on the assumption that particle step trajectories are parallel to the pit trap openings, the pit trap openings of 41 cm is adequate to collect 100% of all saltating gravel particles.

Results of this analysis suggest individual trap efficiencies are nearly 100%. In practical terms, this research is evidence that the pit traps at Little Turkey Creek and similar systems have a high collection efficiency. A significant finding is that collection efficiency does not appear to be impacted by the depth of deposited material in the traps. This is plausible to a limit at which the top of the collected material within the traps is at an elevation relative to the trap rim for the deposited material to be remobilized by near bed shear. It is conceivable that this would occur when the deposited material is at elevation below the trap rim by a distance equal to the thickness of the mobile bedload layer. In the case of the pit traps at Little Turkey Creek, this corresponds to a depth of fill of approximately 75%.

5. NOTATIONS

A	projected particle area
C_D	drag coefficient
D_n	Nominal diameter of the particle size of interest
F_d	drag force
F_g	submerged particle weight
g	gravitational acceleration
k_s	Roughness Height
n	Manning's roughness coefficient
R	specific weight of the particle
R_p	dimensionless particle diameter
V	particle volume
v_c	critical vertical velocity component vector
λ_s	dimensionless saltation length
ρ	density of water
ρ_s	density of the particle
ν_k	kinematic viscosity
τ^*	dimensionless shear stress

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**CHAPTER II CHARACTERIZING BEDLOAD TRANSPORT IN A
SOUTHERN APPALACHIAN RIDGE AND VALLEY
STREAM**

CHAPTER II ABSTRACT

Published bedload transport data sets for gravel bed rivers in North America have been developed primarily in the mountainous Western regions of the continent. These data sets have been used by researchers to develop and/or test a number of commonly used bedload transport models. By comparison, published bedload transport data sets for streams in the Eastern regions of the continent are few in number and brief in content.

The objective of this study was to characterize the bedload transport flux rates in a Southern Appalachian Ridge and Valley stream and the particle size distribution of the bedload material relative to that of the bed surface and bar samples. To meet this objective a continuously monitoring bedload transport station was installed in August of 2010 on Little Turkey Creek in Farragut, Tennessee. The bedload monitoring station includes four Birkbeck-type pit traps, extending perpendicular to flow across the channel bottom in series. The bedload traps each consist of a reinforced concrete vault and a stainless steel loading box insert resting on four submersible load cells rated for 5 kN each. The four load cells in each vault were individually connected to a data logger adjacent to the channel. The data logger reads weights on a 15-second interval and records a time averaged weight every 5 minutes. The system was powered by a 12-volt marine battery and a 40-watt solar panel. Water level loggers were located 11 m and 27 m upstream and downstream respectively and were time synchronized to the data logger. This station was used to collect bedload transport rate observations from August 2010 to May of 2012. The resulting data set includes observations for 11 independent bedload events with real time recording of bedload transport rate, stage, water surface slope, and bulk particle size distributions for each event. Particle size distribution data were also recorded for the bed surface material and bulk bar samples on the research reach.

Observed trends in bedload transport rates relative to grain shear are consistent with the observations of Milhous (1973) on Oak Creek, Emmett (1976) on the East Fork River, and Leopold and Emmett (1976) on the Snake and Clear Fork Rivers. Observations at Little Turkey Creek are also consistent with the theoretical behavior predicted by Bagnold (1960, 1973). Data for a small number of events demonstrate a clockwise hysteresis over the course of the bedload event; transport rates on the rising limb of the hydrograph are significantly higher than the transport rates at the same discharge on the falling limb of the hydrograph. This observation is consistent with relatively recent observations of Gaeuman (2010) on the Trinity River in California. Finally, data collected at Little Turkey Creek are observed to have similar trends and thresholds for motion as the East Fork River and the Clear Fork River data sets when a shear partition is considered for Little Turkey Creek. The Little Turkey Creek bedload data were observed to have similar trends and thresholds for motion as the data sets from Oak Creek and the Snake River without consideration of a shear partition.

1. INTRODUCTION

Published bedload transport datasets for gravel bed rivers in North America have been developed primarily in the mountainous Western regions of the continent (Emmett 1976; Hollingshead 1968; Leopold and Emmett 1976; Milhous 1973; Williams and Rosgen 1989). These data sets have been used by researchers to develop and / or test a number of general bedload transport models (Bakke et al. 1999; Parker 1990; Parker and Klingeman 1982; Parker et al. 1982; Wilcock 1998; Wilcock and Crowe 2003). By comparison, published bedload transport data sets for streams in the Eastern regions of the continent are few in number and brief in content (Gracie and Thomas June 2004). This may be due in part to the fact that streams in the Eastern United States are dominated by storm flow rather than snowmelt, and that runoff events that move bedload are usually of short duration and have even shorter periods of steady state flow.

The objective of this study was to characterize the bedload transport flux rates in a Southern Appalachian Ridge and Valley stream and the particle size distribution of the bedload material relative to that of the bed surface and bar samples. It is hypothesized that the relation between bedload transport rate and shear will be comparable to that characteristic of existing Western datasets. However, it is not known if the combined effects of differences in geology, climate, and vegetation will manifest in observable distinction between data for the mountainous Western regions and for the Southern Appalachian Ridge and Valley Province. Bedload transport measurements presented in this study were collected on Little Turkey Creek in Farragut Tennessee. The following sections provide a discussion of the methods applied in this study, a summary of collected data, a qualitative visual comparison to the transport rate data sets of Milhous (1976), Emmett (1976), and Leopold and Emmett, and a discussion of the data.

2. METHODS

2.1. STUDY AREA

A continuously monitored bedload transport station was installed in August of 2010 on Little Turkey Creek in Farragut, Tennessee (Figure II:1 and Figure II:2). The site selection criteria were established based on those set forth in Wilcock et al. (2008) as well as the specific project goals. Selection criteria are listed below in order of assigned importance.

- The reach should have an alluvial gravel bed, and not be bedrock dominated.
- The reach should lack large roughness elements (boulders, debris jams, etc.) and be relatively straight.
- Total boundary shear stress should be relatively uniform for the reach.
- Bank full width should be between 3 to 8 meters.
- The watershed should have a mix of land cover types with some human land use activities.
- The reach should be on public land to allow for long-term access, should accommodate vehicle access, and should be within a reasonable travel distance from the University of Tennessee, Knoxville campus.

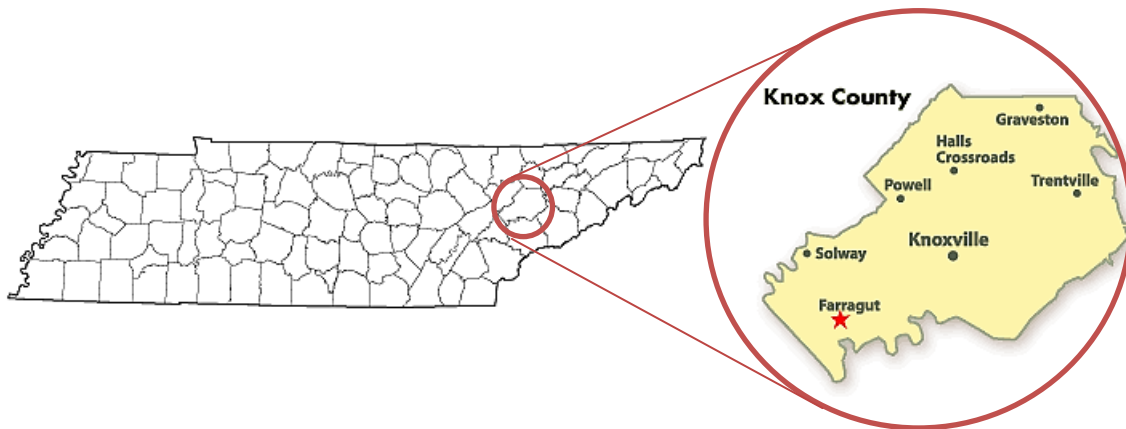


Figure II:1 – Farragut, Tennessee location map

At the location of the research site, the Little Turkey Creek watershed includes an area of approximately 11.6 km², with about 21.1 km of stream channel. The average watershed slope is approximately 2.8%. Over the past 100 years land use in the watershed has seen a steady progression from forest land, to agricultural development, to suburban development. At the time of this study, each of these land uses was still present in the watershed to varying degrees.

The research reach includes approximately 315 m of stream that borders an existing municipal greenway. Little Turkey Creek was straightened along this reach in the early 1900s to accommodate adjacent agricultural practices. The reach is a threshold channel with bedrock controlling in the vertical dimension and thick riparian vegetation controlling in the lateral dimension. Table II:2 provides a summary of some basic geomorphic metrics for the research reach. Within the study reach, a stable riffle was identified for installation of the bedload monitoring station.

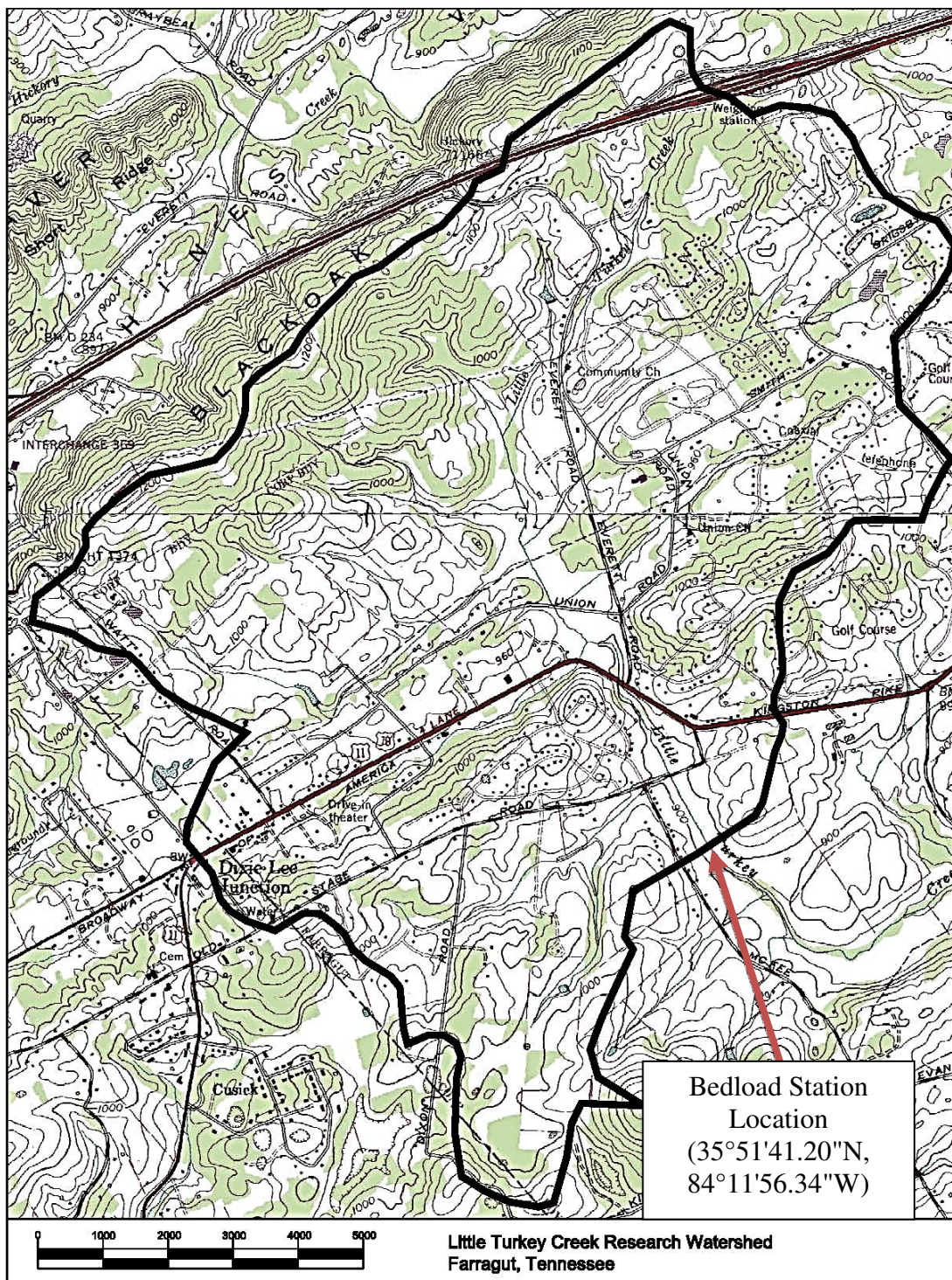


Figure II:2 – Research station location and contributing watershed boundary

Table II:1 – Little Turkey Creek Research Reach Properties

Parameter	Value	Units
Bank full Width	7.3	m
Bank full Depth	0.9	m
Slope	0.0074	m/m
Bed D ₅₀	28.3	mm
Bed D ₆₅	39.3	mm
Bed D ₈₄	58.5	mm
Bar D ₅₀	5.6	mm
Bar D ₆₅	8.5	mm
Bar D ₈₄	12.4	mm
Summer Baseflow	0.06	cms
Bank full Flow	3.1	cms

2.2. BEDLOAD MONITORING STATION DESIGN

The bedload monitoring station includes four Birkbeck-type pit traps (Reid et al. 1980), extending perpendicular to flow across the channel bottom in series (Figure II:3). The bedload traps each consist of a reinforced concrete vault and a stainless steel loading box insert resting on four submersible load cells (Omni Instruments, model DDEN-5KN-C25). The concrete vaults were standard inlet boxes purchased from Sherman Dixie Precast, a local manufacturer. The outside dimensions were approximately 71 cm by 71 cm by 91 cm (WxLxD). The wall thickness was approximately 15 cm. The loading box inserts sit on top of the load cells within the vaults and were flush with the top of the concrete. The loading boxes have a 1 cm or less horizontal clearance from the concrete vault on each side wall, and this gap was partially sealed at the bed elevation with a thin soft foam insert. The total collection volume of each trap was 1.6 m³.

The submersible load cells placed in each box were approximately 6.5 cm tall and were rated for 5 kN each. These load cells were threaded on each side along the loading axis, allowing the researchers to use threaded plates to vary the vertical dimension of the load cells in order to compensate for irregularities in the surfaces of the concrete vaults. The four load cells in each vault were individually connected to a Campbell data logger (Model #CR1000) mounted on an instrument panel adjacent to the channel. The data logger reads weights on a 15-second interval and records a time averaged weight every 5 minutes. The system was powered by a 12-volt marine battery and a 40-watt solar panel.

Water level loggers were located 11 m and 27 m upstream and downstream respectively. They were time synchronized with the data logger at the bedload station and were tied to an established datum on the greenway adjacent to the site. The water level loggers consist of vented pressure transducers (Global Water, Model WL16) installed within 3-inch polyvinylchloride tubes that were perforated below the water surface. The water level sensors were programmed to

record pressures every 15 minutes and were used to estimate the energy grade line slope and stage during bedload events.



Figure II:3 – Photo of bedload monitoring station pit trap at base flow, downstream flow from left to right.

3. TRAPPING EFFICIENCY

Data collection activities and subsequent analyses for pit trap installations generally assume that the collection efficiency of pit traps is at or acceptably near 100% for material in the mobile gravel size range (Hubbell 1987; Sterling and Church 2002; Wilcock 2001). However, in some instances it may be possible for the trapping efficiency of pit traps to be impacted by systematic short comings such as internal recirculation velocities causing preferential collection of coarser gravel particles and the saltation of particles over the pit trap openings.

Habersack et al. (2001) attempted to assess the lumped impact of these factors on the trapping efficiency of pit samplers using a Helley-Smith sampler as a basis for comparison to pit traps but concluded that additional laboratory investigations were necessary to develop meaningful results. Bergman (2007) applied the hydraulic observations of Habersack (2001) for flow velocities within a pit trap relative to those immediately above the pits and asserts trap efficiency is acceptably close to 100% for trap fill depths up to 80% of the pit capacity. The theoretical efficiency of pit traps with regard to the impact of recirculation velocities was explored by Sterling and Church (2002) using measured horizontal fluid velocities above pit traps and extrapolation to circulation velocities within the traps concluding that trap efficiencies were upwards of 90% for particles in the gravel range.

The trap efficiencies for the pits at Little Turkey Creek were estimated based on computational fluid dynamics modeling of vertical velocity vectors and particle step heights and lengths calculated using the published figures of Nino and Garcia (1994). Details of this analysis are discussed in Chapter I of this dissertation. According to this research, the pit traps at Little Turkey Creek are expected to operate at 100% collection efficiency for all particles equal to or larger than a nominal diameter of 2 mm until the traps are filled to 75% capacity. At 75% capacity, selective particle collection may occur as individual particles move into and out of the trap.

3.1. REACH HYDRAULICS

The Manning's roughness value of the research reach was estimated to be 0.10 at bank full flow. This estimate was based on flow data obtained using a YSI/ Sontek River Surveyor® velocity profiler, slope data from water level loggers installed upstream and downstream of the bedload station, and cross sectional data surveyed using a Nikon DTM-322 series, 3-second total station and a Tripod Data Systems Recon 400X data logger. This value is consistent with reported values for floodways with heavy timber along the banks (Chow 1959). Additional flow measurements made with the velocity profiler and with a Marsh-McBirney FloMate2000™ point velocity meter were used to calibrate the stage versus channel discharge curve presented in Figure II:4 (flows beyond the banks are not represented in this curve).

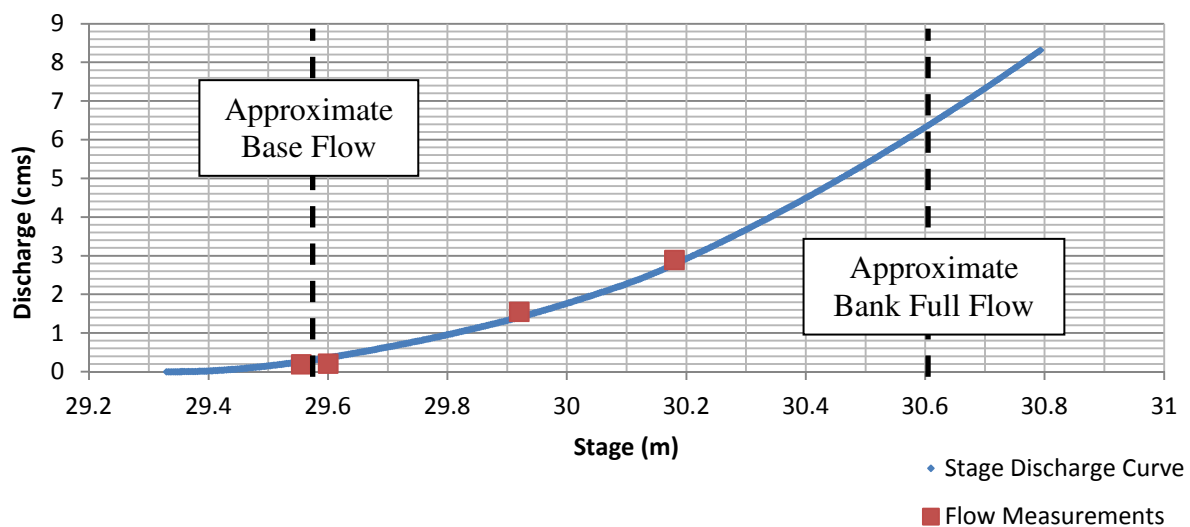


Figure II:4 – Stage–discharge relationship developed for Little Turkey Creek, Farragut, Tennessee at the bedload sampling station.

3.2. MATERIAL AND DATA COLLECTION

Following each bankfull event the data from the stage recorders and load cells were downloaded from the Campbell data logger and the content of the pit traps was collected. Data points were reviewed for quality and consistency for each event. The content of the pit traps was subsampled on site at a volumetric ratio of 1:10 for dry sieve analysis in the lab. Sub sampling was adopted over full volume sampling early in the project to address logistical issues related to the transport, storage and processing of full volume samples of the bedload material. The volumetric subsampling was carried out using a round point 6.4 x 30.5 cm blade shovel. Full shovel loads were excavated from the center of the trap, depositing the first of every ten shovel loads into a 70 x 102 cm woven polypropylene sack and discarding the remaining nine shovel loads downstream. This technique was checked for potential bias in four independent trials. A Pearson χ^2 test on the paired 1:10 sub sample and the full volume sample particle size distributions from the four trials suggests that the particle size distributions are identical at an alpha level of <0.01. Particle distributions for the four 1:10 sub sample and the full volume samples are presented in Figure II:5.

Datasets were eliminated if there was supporting evidence for equipment performance issues. . Poor equipment performance was most often linked to low or excessive voltage caused by a charge controller that began to malfunction in early 2011. The charge controller was replaced in early March of 2011.

3.3. SEDIMENT PARTICLE SIZE CHARACTERIZATION

Bedload material collected in the bedload traps was dried and mechanically sieved according to ASTM C136 – 06 06 using standard 51 mm 25 mm 13 mm, 6 mm, No. 18, No. 35, No. 60, and No. 200 sieve trays. Bar samples were wet sieved in the field according to field methods specified in Rosgen (1996) and using standard 25 mm, 13 mm, No. 4, and No. 10 sieve trays. Pebble counts for characterizing the bed surface were completed according to field methods specified in Wolman (1955). Bar samples and pebble counts were collected on a limited number of site visits.

3.4. COMPILATION OF BEDLOAD TRANSPORT DATA

The bedload flux rate was calculated per unit width of stream according to load values collected by the data logger. The shear was calculated as grain shear to distinguish it from average reach-scale bed shear according to the calculated bank full Manning's n value and the water surface slope estimated from the stage recorders. The grain shear was calculated using the following relationships:

$$\tau' = \tau_0 \left(\frac{n_p}{n} \right)^{3/2} \quad \text{II:1}$$

Where,

τ' = grain shear

τ_0 = average reach average
 n_D = Manning-Strickler roughness coefficient
 n = bank full Manning's roughness coefficient

$$n_D = 0.040k^{1/6} \quad \text{II:2}$$

Where,
 k = roughness height

The Manning-Strickler roughness coefficient was calculated using a roughness height of twice the nominal diameter of the D_{65} particle on the bed surface (Wilcock and Crowe 2003). The reach shear was calculated using the following relationship.

$$\tau_0 = RS\gamma \quad \text{II:3}$$

Where,
 R = hydraulic radius
 S = energy gradient
 γ = unit weight of water

The hydraulic radius was estimated according to the average stage for each 5-minute data collection period and a stage versus hydraulic radius relationship that was developed based on surveyed cross section data at the bedload station. The energy gradient was estimated as the average water surface slope during the 5-minute data collection period for each point. Submerged load readings were adjusted to account for material buoyancy assuming an average specific gravity of 2.64 for the bedload material.

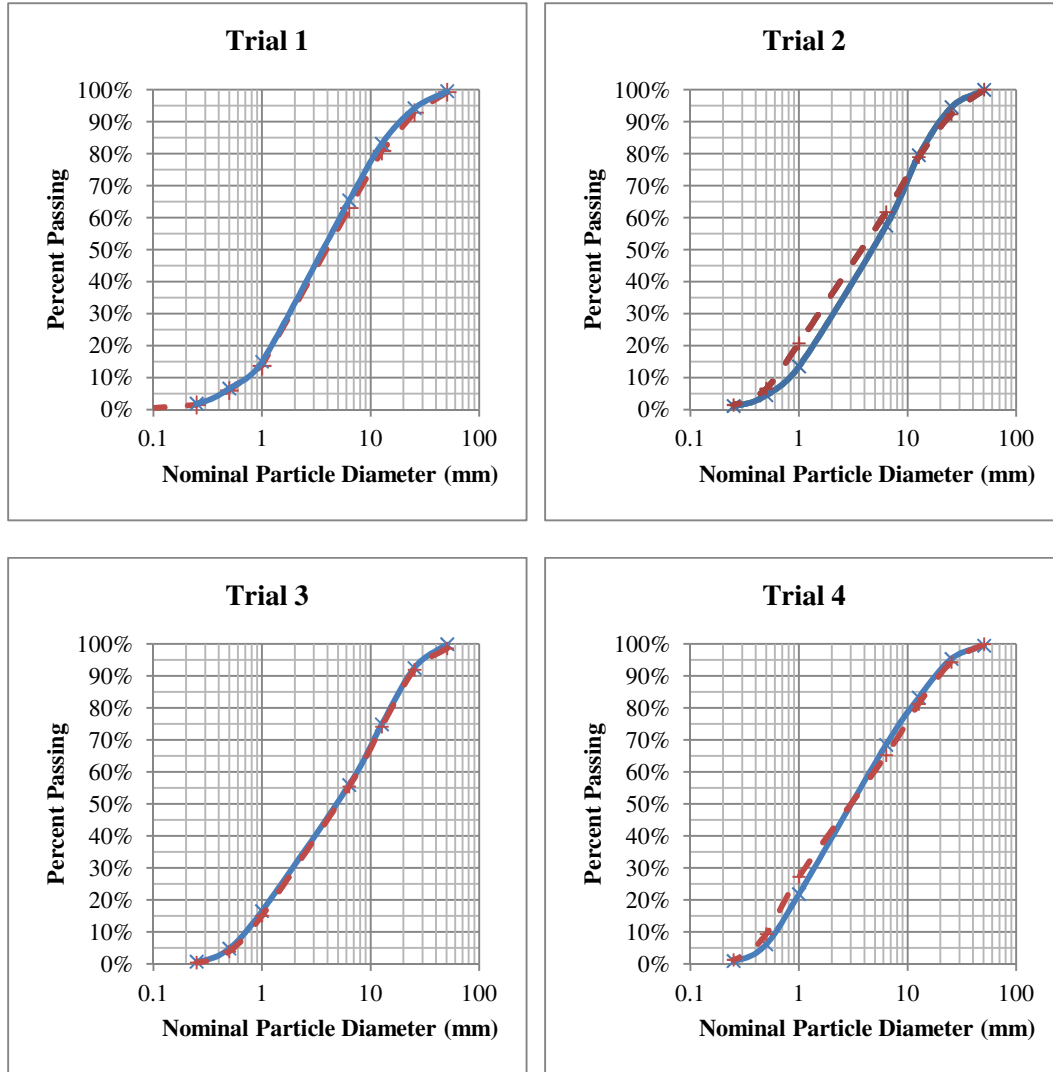
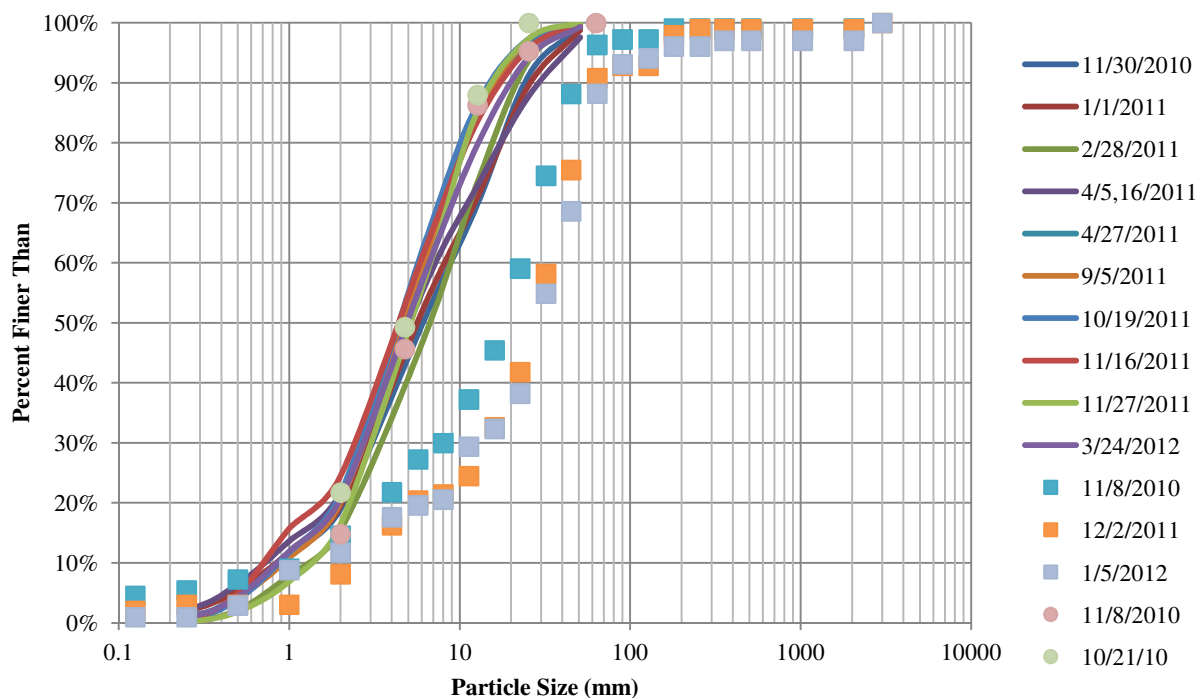


Figure II:5 – Particle size distribution of bedload material using 1:10 sub-sampling (dashed) and full-volume sampling (solid)

4. RESULTS

4.1. PARTICLE SIZE DISTRIBUTIONS OF BED AND BEDLOAD MATERIALS

The particle size distributions for each bedload event are presented in Figure II:6. Note that the particle size distribution data for the 4/5/11 and 4/16/11 events are represented by a single distribution. This reflects the fact that the 4/16/11 event occurred before the material from the 4/5/11 event was retrieved. Therefore, the material from both events was collected and sieved as a mixed pair. For reference, the particle size distribution measurements of the bed and bulk bar samples are included in Figure II:6.



Lines Represent Bedload PSDs, Squares Represent Bed PSDs, and Circles Represent Bar Sample PSDs

Figure II:6 – Particle size distribution for Little Turkey Creek bedload, bed, and bar samples

Average values for the D_{50} , D_{65} , D_{85} , and D_{90} particles for the bed surface, bar samples and bedload are summarized in Table II:2. A Pearson χ^2 test on the particle size distribution data indicate a 0% probability of similarity between the average bed PSD and both the average bar and bedload PSD, and an 86% probability of similarity between the average bar PSD and the average bedload PSD with 8 degrees of freedom in both cases.

Table II:2 – Average Particle Size Distribution Size Class
Summary, Based on Data in Figure II:6

% Finer Class	Bed Surface	Bar Sample	Bedload
D_{50}	28.3	5.3	5.4
D_{65}	39.3	8.3	8.4
D_{85}	58.8	12.3	16.4
D_{90}	68.2	16.4	21.4
D_{95}	150.6	21.5	29.4

4.2. BEDLOAD TRANSPORT RATES

The measured bedload transport rates for the 11 representative data sets are summarized in Figure II:7. Events resulting in shear values of less than 1.2 N/m^2 did not mobilize bedload material. In rare instances, larger events did not produce bedload at the pit traps due formation of a debris jam upstream where transported material deposited. The data span a range of grain shear values from approximately 1.2 to 18 N/m^2 , and transport ranges from approximately 1×10^{-6} to approximately $1 \times 10^{-2} \text{ kg/s-m}$. The plotted data suggest a critical grain shear for a mobile bed event within the range of 1 to 3 N/m^2 . Bedload transport rates increase sharply with small changes in grain shear up to about 3 N/m^2 , then follow a much less steep trend for grain shear above this value. Figures for the stage, discharge, and transport rates for individual events can be found in the Appendix.

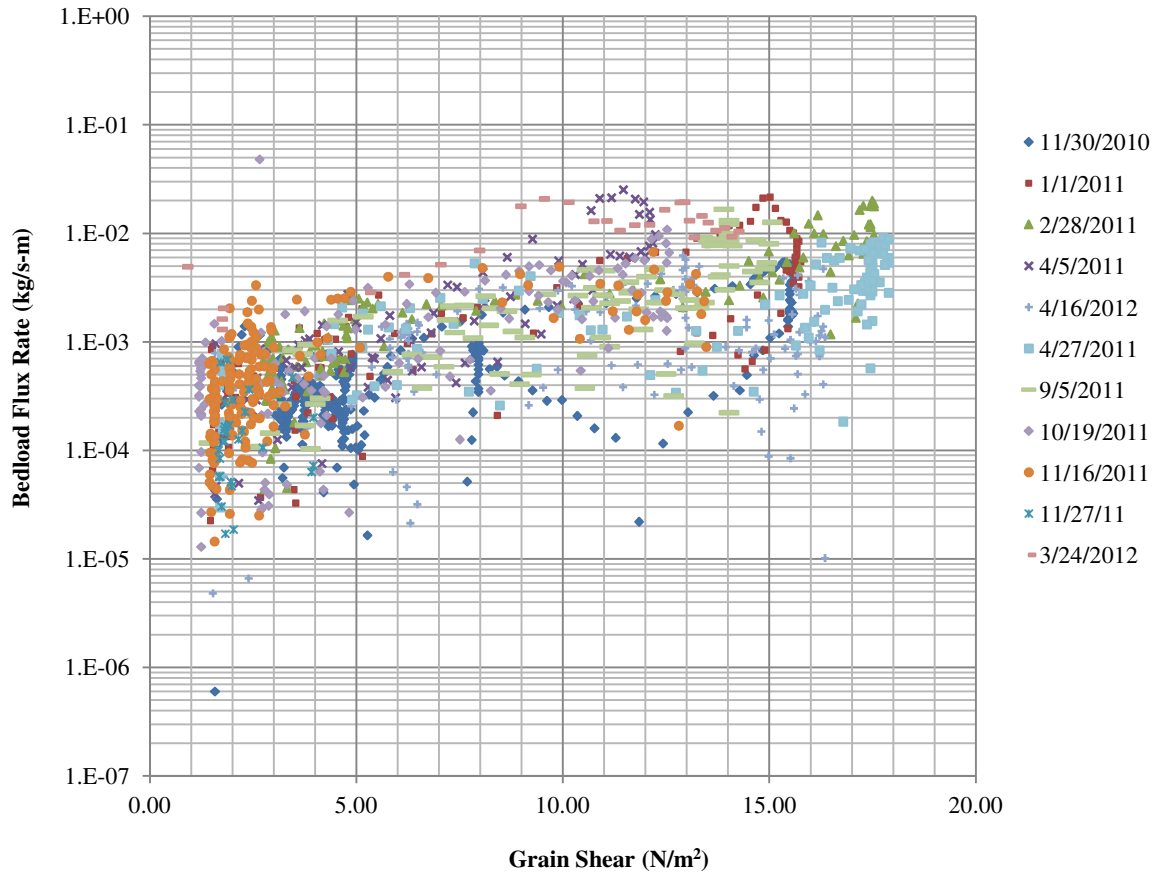


Figure II:7 – Bedload transport data for Little Turkey Creek.

4.3. QUALITATIVE COMPARISON WITH OTHER DATASETS

Bedload transport data collected at Little Turkey Creek may be compared to the data collected by Milhous (1976), Emmett (1976), and Leopold and Emmett (1976) through qualitative visual inspection in Figure II:8 and Figure II:9. The East Fork River data set was collected by Leopold and Emmett (1976) near Boulder, Wyoming. Data provided in the original publication include river discharge, flow area, mean depth, hydraulic radius, bedload transport rate and bedload D_{50} . The unit width bedload transport rates shown in Figure II:8 were calculated based on a channel width equal to the reported flow area divided by the mean depth for each event. The reach shear was calculated based on the reported hydraulic radius and a reported water surface slope of 0.0007. Leopold and Emmett note that there were no data available at the time to indicate an appreciable change in water surface slope with stage.

The Clearwater River data set was collected by Emmett (1976) in Idaho approximately 20 river kilometers above the confluence with the Snake River. Data provided in the original publication include river discharge, unit width bedload transport rate, unit stream power, mean shear stress, and bedload D_{50} . Data points for both the East Fork River and Clearwater River are presented according to the average reach shear. The data points for Little Turkey are presented for grain shear.

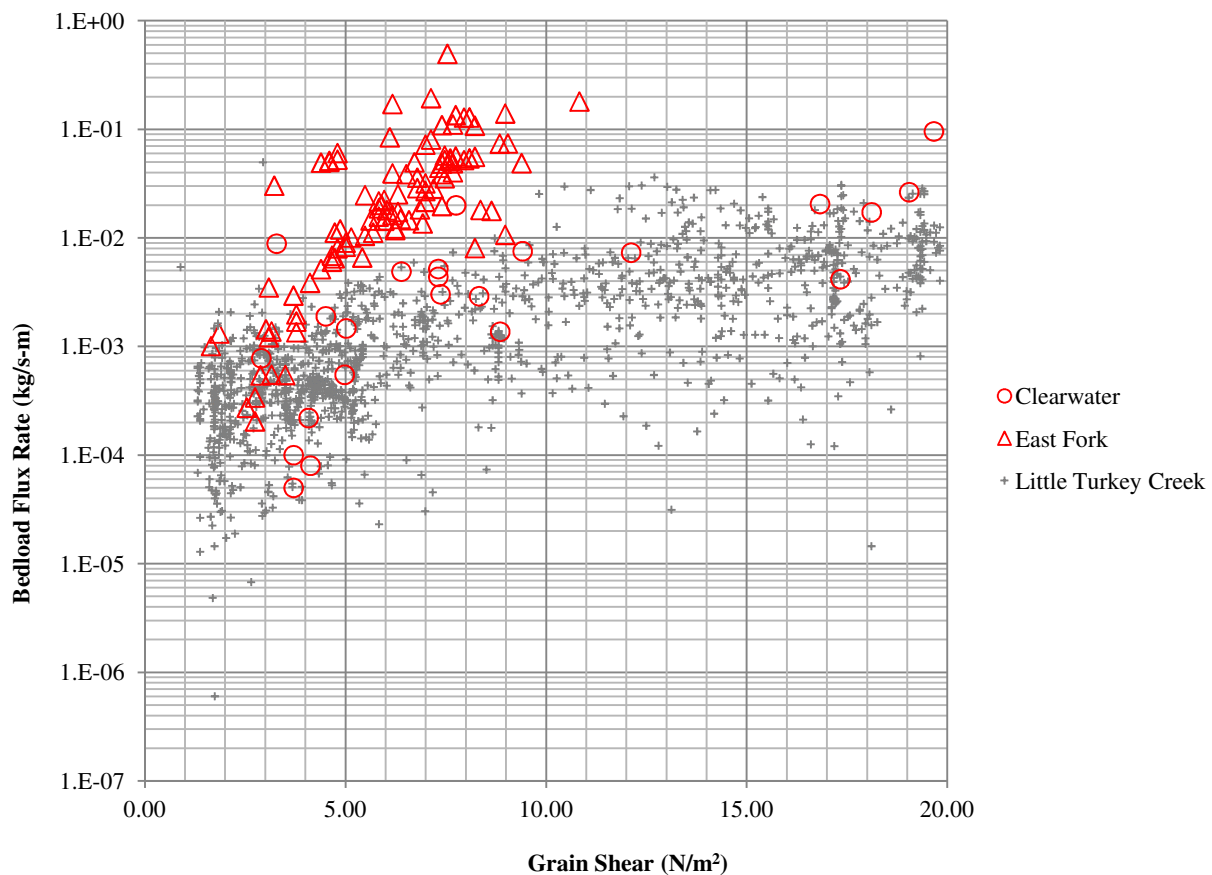


Figure II:8 – Bedload transport Data at Little Turkey Creek with respect to bedload transport data sets for the East Fork River and the Snake River.

The Oak Creek data set was collected by Milhous (1976) in McDonald State Forest near Corvallis, Oregon. Data provided in the original work by Milhous (1976) includes discharge, energy slope, bedload discharge, stream width, and bedload D_{50} . The Snake River data set was

collected by Emmett in (1976) approximately 50 river kilometers downstream of the confluence with the Clearwater River near Anatone, Washington. Data points for all three data sets presented in Figure II:9 for average reach shear.

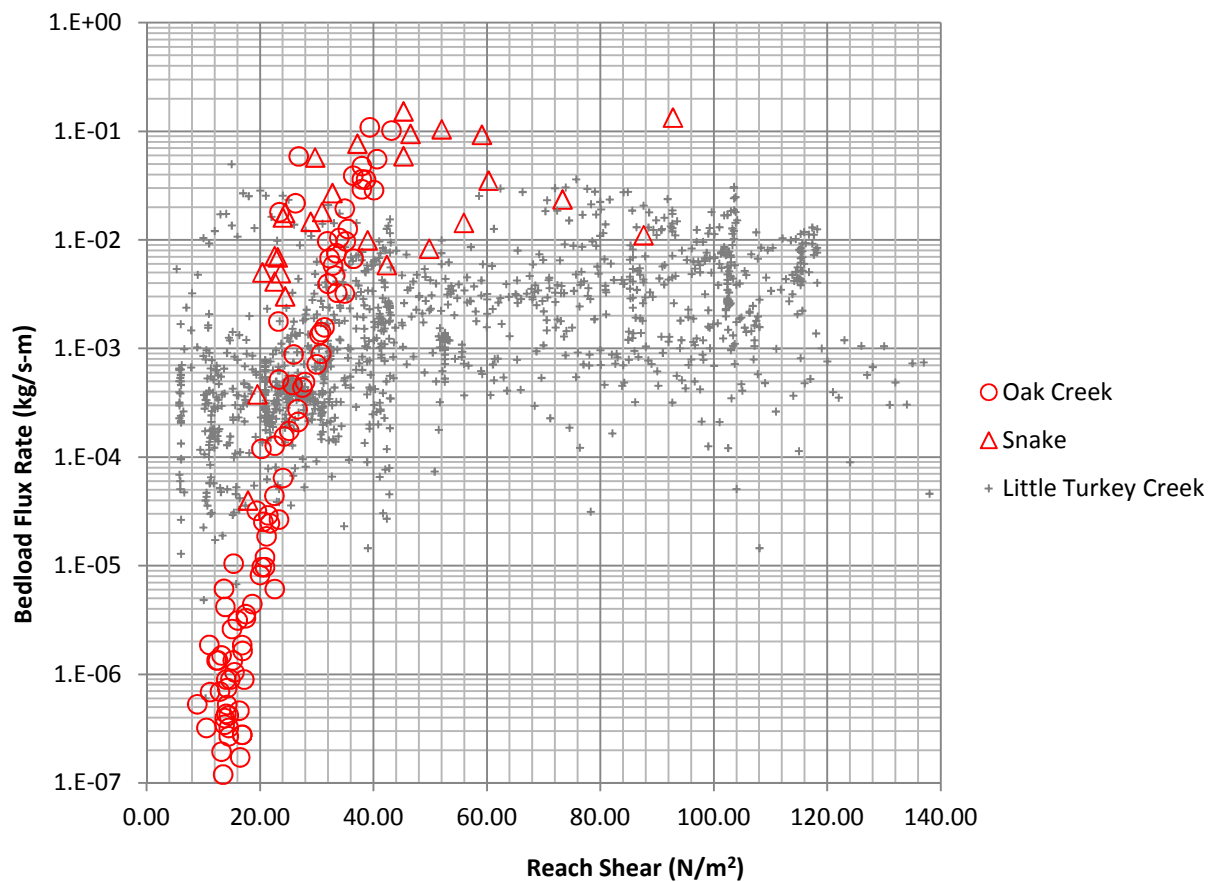


Figure II:9 – Bedload transport data at Little Turkey Creek with respect to bedload transport data sets for Oak Creek and the Snake River.

5. DISCUSSION

The range of critical shear stress values observed in Figure II:7 correspond to the approximate critical shear for a 2 to 4 mm particle according to the Shields diagram and a 6 to 20 mm particle according to the incipient motion data of Rosgen and Silvey (2005). Each of these ranges approach the median particle size of the bedload material, 4.9 mm, and the latter range includes the median particle diameter for the bed surface, 19.4 mm. Thus the critical shear stress for Little Turkey Creek falls within previously published ranges for these values. It should be noted, however, that grain shear must be considered rather than reach shear to account for the shear stress imparted on the thickly vegetated banks of Little Turkey Creek.

The sharp increase of bedload transport rates near the threshold for motion with a transition to a region of gradual increases in bedload transport for continued shear stress increase is consistent with the observations of Milhous (1973), Emmett (1976) and Leopold and Emmett (1976), as well as with the theoretical behavior predicted by Bagnold (1960, 1973) based on general physics. Bagnold's original work was with reference to stream power rather than shear, but is equally valid for shear. Further, the two and three orders of magnitude variation in measured bedload transport rates over the range of estimated shear values is consistent with the observations of others including Milhous (1973), Emmett (1976), Leopold and Emmett (1976), Gomez (1983), and others. This may reflect variation in supply during individual events, as bedload waves or pulses move through the research reach to the pit traps.

Events recorded on 11-30-2010, 1-1-2011, and 4-5-2011 clearly demonstrate a clockwise hysteresis over the course of the bedload event; transport rates on the rising limb of the hydrograph are significantly higher than the transport rates at the same discharge on the falling limb of the hydrograph (Figure II:7). This phenomenon was observed by Gaeuman (2010) during scheduled dam releases into the Trinity River in California, and notes that this type of hysteresis is commonly seen in studies considering the suspended transport of fine sediments, but is not often described in the context of bed-material transport in gravel-bed streams. Gaeuman's research suggests this phenomenon can at least be partially accounted for by changes in the hiding exposure of bed particles throughout an event, though additional research would be necessary to describe the mechanics of the hysteresis on Little Turkey Creek.

Particle size distribution data collected at the Little Turkey Creek bedload station for bedload, bed, and bar materials are consistent with the observations of Parker (1982; 2002) and Rosgen (1996), in that the distribution of the bar materials is similar to that of the bedload samples while the bed surface is notably coarser.

Finally, data summarized in Figure II:8 and Figure II:9 indicate similar trends and thresholds for the data collected at Little Turkey Creek and the East Fork River, the Clear Fork River, Oak Creek, and the Snake River for records up to approximately three times the critical shear. Figure II:8 indicates a possible agreement between the Little Turkey Creek data and the East Fork and Clear Water River data sets, given that the LTC data are expressed for grain shear and the other data sets are expressed for reach average shear. By using grain shear for the LTC data points, the impact of shear stresses acting on the forested banks can be partitioned from that acting on the bed. It is possible that this separation is less important for the East and Clear Fork River data sets because these rivers are significantly wider than LTC, so the average shear stress closely approximates the grain shear stress at the bed. The deviation of the East Fork River data from the LTC data for shear values large than about $1 \times 10^{-2} \text{ N/m}^2$ could be caused by differences in the relative fraction of sand and gravel between the two systems. In their published form, the data for the East Fork River does not contain adequate particle size distribution data to verify this assertion. However, manipulation of the Wilcock (1998) two fraction model suggests this as a possibility (further discussion of this model is presented in Chapter IV).

The data in Figure II:9 indicate possible agreement with the Oak Creek and Snake River data sets when all of the bedload transport rates are presented in terms of reach average shear stress. This might be expected for the Oak Creek data set, as Oak Creek has heavily forested banks and is

roughly similar in size to LTC. However, it is not apparent why the Snake River data set follows the LTC trend for bedload versus average reach shear. The Snake River is much wider than both LTC and Oak Creek, and is more comparable in terms of cross-section to the East Fork and Clearwater Rivers. The agreement with the LTC data may be related to armoring of the Snake River or the impact of large boulders below the surface, but the actual reason is unknown. The cause of the divergence at higher shear values is also unknown, though it is plausible that it can be attributed to much higher sand content in the other rivers as evidenced in the D_{50} values reported for these datasets, which are nearly all at or below 2 mm (Emmett 1976; Leopold and Emmett 1976; Milhous 1973).

It is noted that data collected on the Clear Fork and Snake River were collected using a Helley-Smith sampler operated from a cable bridge. The East Fork River data were collected using a battery of pit samplers and the Oak River data were collected using a cross channel vortex tube sampler. In each case, the data represent average conditions over relatively brief sampling periods. Some deviations in results may be caused by discrepancies in the methods used to collect the data.

6. NOTATIONS

D_n	Nominal particle diameter for which $n\%$ of particles in the particle size distribution are finer
K	roughness height
n	bank full Manning's roughness coefficient
n_D	Manning-Strickler roughness coefficient
R	hydraulic radius
S	energy gradient
τ'	grain shear
τ_0	reach average shear
γ	unit weight of water

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CHAPTER III USE OF 20-LITER PAIL PIT TRAPS FOR BEDLOAD CHARACTERIZATION AND MODEL CALIBRATION

CHAPTER III ABSTRACT

Non-weighing 20-liter pail pit traps have been used in bedload studies by Church et al. (1991) and in the evaluation of Helley-Smith samplers by Sterling and Church (2002). They are cited by the Maryland State Highway Administration, Structures Division as the preferred method for bedload material collection or morphological analyses. Recently, these devices have been more commonly used by design practitioners for stream restoration projects. The 20-liter pails are readily available plastic containers (5-gallon buckets) that can be found at most hardware stores. Wilcock (2001, 2004) suggests the use of 20-liter pail pit traps for data collection necessary to estimate the reference shear stresses for sands and gravels for the calibration of the Wilcock (1998) two-fraction bedload transport model. While 20-liter pail pit traps do appear in the literature, little information appears to exist to confirm that these devices indeed collect representative samples of bedload material in transport. Further, the use of these devices in the calibration of the Wilcock (1998) model has not been field tested; as Wilcock states “formal testing would be difficult because the true transport rate is never known and because reliable estimates of the transport rate are available for only a few cases and these have been used to develop the empirical transport relations used in the method.”

The research presented in this paper has two objectives: 1) to test the ability of 20-liter pail pit trap samplers to collect a bedload sample with a representative particle size distribution of the bedload in transport, as defined by the full-scale pit traps described earlier, and 2) to test the use of 20-liter pail samplers in the calibration of the Wilcock (1998) two-fraction bedload model. To address these objectives a total of twenty-two paired observations were collected from two 20-liter pail samplers on Little Turkey Creek and from the four Birkbeck installed in series across the full width of the channel downstream of the 20-liter pail samplers. Results from this study suggest that 20-liter pail samplers are capable of obtaining representative samples of bedload particle size distributions if the events are sufficiently long or intense enough to fill the pails to approximately 75% of their capacity. Further results suggest that the use of the 20-liter pail samplers for the estimation of critical shear stress for sands and gravels may not produce clear results and will require a large number of observations to achieve even approximate values. Calibrated results of the Wilcock (1998) two-fraction model are presented based on critical shear values estimated using the 20-liter pail sampler data and critical shear values estimated using the Meyer-Peter and Muller Meyer-Peter and Muller (1948) relation for critical shear stress. Results indicate that a model calibrated using the critical shear values estimated using the 20-liter pail sampler data are only modestly better than those based on the Muller Meyer-Peter and Muller (1948) relation for critical shear stress when model results are compared to the bedload transport data set for the site, measured using the large-scale pit traps.

1. INTRODUCTION

Bedload transport in gravel bed rivers is characterized by three elements that make representative sampling difficult: 1) particles of the largest mobile size class for a given flow move infrequently, 2) bedload-transport rates can span up to several orders of magnitude, and 3) bedload transport rates fluctuate considerably over time and space (Bunte et al. 2004; Gomez and Church 1989; Hayward and Southerland 1974; Hubbell 1987). Consequently, sampled transport rates may vary by orders of magnitude even during near constant flow, while 50 to 100% of the bedload transported may be concentrated within a small portion of the stream cross section (Bunte et al. 2004). This temporal and spatial variability make bedload transport difficult to quantify.

Bedload particle size distributions and transport rates may be sampled using a range of techniques including hand held devices (Helley and Smith 1971), Birkbeck pit traps (García 2008; Leopold and Emmett 1976), scour chains (Gordon et al. 1992; Leisle and Eads 1971), vortex samplers (Milhous 1973), or construction of long-term local sediment budgets from volumetric changes in the bed and banks (McLean 1980). Bunte et al. (2004) suggest that the ideal bedload sampler should be able to collect a sievable sample of bedload material for a range of flow stages, be portable to facilitate use at access limited sites, be employed without the need for excavation or construction, and have the ability to collect representative samples of gravel and cobble sized bedload material.

Table III:1 summarizes the attributes of seven bedload sampling devices commonly referenced in bedload transport related research. None of these devices combines all of the desirable properties suggested by Bunte et al (2004). However, in light of the shortcomings of the net-frame sampler, it is frequently suggested for use in non wadeable gravel bedded Western streams (Bunte 1997; Bunte et al. 2004; Bunte et al. 2008; Bunte et al. 2007; Whitaker 1997; Whitaker and Potts 1996). The strengths of the net-frame samplers include their ability to collect sievable material for a range of wadeable flows, their ability to collect samples over long durations for small events, their ability to cover 30% or more of the stream width (using multiple traps), their large opening, and their portability. A significant weakness of the net trap is the potential for it to become plugged by organic debris, resulting in a failure to collect representative bedload samples, especially in storm dominated streams in the fall (Cantrell 2009). Small non-weighing pit traps maintain many of the advantages of net samplers and are not impacted by the collection of organic material, though they do require excavation within the stream bed for installation and sievable samples cannot be collected during non-wadeable flows.

Table III:1 – Attributes of Various Bedload Samplers, (Modified from Bunte et al. (2004).

Attribute	Vortex sampler ^a	Birkbeck pit trap ^b	Non weighing pit traps ^c	Basket sampler ^d	Net-frame sampler ^e	0.076 m Pressure-difference sampler ^f	Large pressure-difference sampler ^g
Physical sample for sieve analysis	+	+/-	+	+	+	+	+
At least 20-30% width sampled	+	+	+	+	+/-	+	+
Large sampler opening	+	+	+	+/-	+/-	+	+/-
Portability	-	-	+	+/-	+/-	+	+
Use without stream excavation or construction	-	-	-	+/-	+/-	+	+/-
Ease of use	+/-	+	+/-	+/-	-	+	-

^a(Atkinson 1994; Hayward and Southerland 1974; Milhous 1973; O'Leray and Beschta 1981; Tacconi and Billi 1987)

^b(Garcia et al. 2000; Habersack et al. 2001; Powell et al. 1995; Reid et al. 1985; Reid et al. 1995; Reid et al. 1980)

^c(Bunte 1997; Church et al. 1991; Hassan and Church 2001; Powell and Ashworth 1995; Sterling and Church 2002)

^d(Engel 1981; Gao 1991; Hubbell 1964; Nanson 1974; Wilcock 2001; Xiang and Zhou 1992)

^e(Bunte 1992; Whitaker 1997; Whitaker and Potts 1996)

^f(Emmett 1976; Helley and Smith 1971; Ryan and Porth 1999; Sterling and Church 2002)

^g(Childers 1999; Duizendstra 2001; Hubbell 1987)

Non-weighing 20-liter pail pit traps have been used in bedload studies by Church et al. (1991) and in the evaluation of Helley-Smith samplers by Sterling and Church (2002). They are cited by the Maryland State Highway Administration, Structures Division as the preferred method for bedload material collection or morphological analyses (MSHA 2011). Recently, these devices have been more commonly used by design practitioners for stream restoration projects. The 20-liter pails are readily available plastic containers (5-gallon buckets) that can be found at most hardware stores. Wilcock (2001, 2004) suggests the use of 20-liter pail pit traps for data collection necessary to estimate the reference shear stresses for sands and gravels for the calibration of the Wilcock (1998) two-fraction bedload transport model. While 20-liter pail pit traps do appear in the literature, little information appears to exist to confirm that these devices indeed collect representative samples of bedload material in transport. Further, the use of these devices in the calibration of the Wilcock (1998) model has not been field tested; as Wilcock

states “formal testing would be difficult because the true transport rate is never known and because reliable estimates of the transport rate are available for only a few cases and these have been used to develop the empirical transport relations used in the method.”

The research presented in this paper has two objectives: 1) to test the ability of 20-liter pail pit trap samplers to collect a bedload sample with a representative particle size distribution of the bedload in transport, using the results from full-scale pit traps as “truth”, and 2) to test the use of 20-liter pail samplers in the calibration of the Wilcock (1998) two-fraction bedload model.

2. METHODS

2.1. STUDY DESIGN

Data collection efforts associated with this research were carried out at the continuously monitoring bedload collection station on Little Turkey Creek in Farragut, Tennessee, Figure III:1. The bedload station consists of four Birkbeck pit traps (Reid et al. 1980) in series across the channel. The proximity to the bedload station facilitates the direct comparison of particle size distributions collected in the 20-liter pail samplers and those collected by the bedload station. It also allows for comparison between the results the Wilcock (1998) two-fraction model calibrated using data from the 20-liter pit traps to bedload transport rates recorded at the bedload station for a range of flow conditions. Further information on the bedload station on Little Turkey Creek including its design and estimated efficiency can be found in Chapter I of this dissertation. For clarity, the 20-liter pail pit traps are henceforth referred to as 20-liter samplers to distinguish them from the large continuously monitoring (LCM) pit traps associated with the bedload station immediately downstream of the pails.

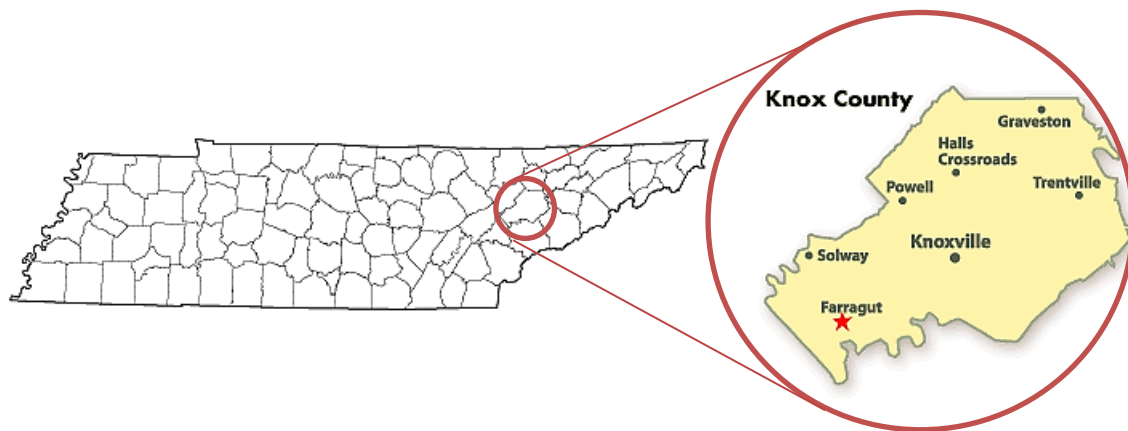


Figure III:1 – Farragut, Tennessee location map

2.2. 20-LITER PAIL PIT TRAP INSTALLATION AND USE

Two 20-liter samplers were installed at Little Turkey Creek in the riffle section approximately 5 meters upstream of the LCM pit traps (Pail A and Pail B). Pail A was installed river right of the centerline in the approximate thalweg of the riffle and Pail B was installed river left of the centerline approximately halfway between the thalweg and the top of a mid-channel bar. The 20-liter pail samplers were installed in a similar fashion to that of Sterling and Church (1991), see Figure III:2.

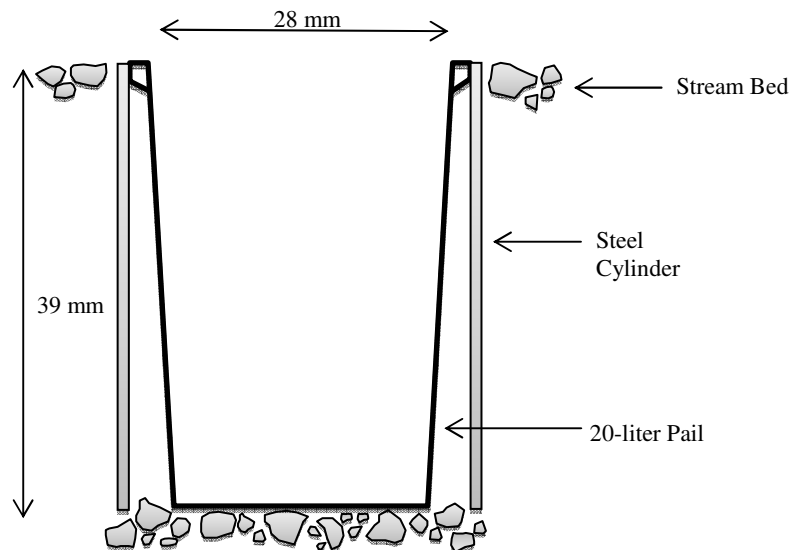


Figure III:2 – Conceptual representation of an installed 20-liter (5-gal) pail sampler recessed in the streambed.

For the installation of each sampler a steel cylinder with an inside diameter approximately equal to the outside diameter of the 20-liter pail was placed on the bed surface. Material was excavated from within the circumference of the cylinder using spade shovels and posthole diggers. As material was excavated, the steel cylinder was gently advanced into the bed using static pressure and light blows with a hammer. Excavation and cylinder advancement was carried out until the top edge of the cylinder was approximately even with the surrounding bed surface. A 20-liter pail was then installed within the steel cylinder (Figure III:2).

Following each bedload event, material was collected from each 20-liter sampler as well as from the LCM pit traps. Removal of the 20-liter pails from the steel cylinders was performed using thin pry bars and two sets of pliers. The pail would be loosened from the side walls of the cylinder with the pry bars, then lifted out of the bed with the pliers. Used sampling pails were periodically replaced with new ones when the pail rim became deformed during removal. The content of the LCM pit traps was subsampled on site at a volumetric ratio of 1:10. Sub-sampling was adopted over full volume sampling early in the project to address logistical issues related to the transport, storage and processing of full-volume samples of the bedload material. The volumetric subsampling was carried out using a round point 6.4 x 30.5 cm blade shovel. Full shovel loads were excavated from the center of the trap, depositing the first of every ten shovel loads into a 70 x 102 cm woven polypropylene sack and discarding the remaining nine shovel loads downstream. Further discussion of this procedure including its validation can be found in Chapter II of this dissertation.

Given the relative capacity and size of the pit traps associated with the bedload station, it is assumed that the presence of the 20-liter pail samplers upstream have a negligible impact on volumes collected at the station and no impact on the particle size distribution of material collected by the station.

2.3. BEDLOAD SIZE CHARACTERIZATION AND STATISTICAL COMPARISON

Material from the 20-liter pail samplers and the LCM pit traps were dried and sieved according to ASTM C136 – 06 using standard 51 mm, 25 mm, 13 mm, 6 mm, No. 18, No. 35, No. 60, and No. 200 sieve trays. From these data the D_{50} and sand fraction (as a percentage) for bedload collected from the LCM bedload traps and the trapped mass, D_{50} , and sand fraction for each 20-liter pit trap were estimated. For each 20-liter sampler the root mean square deviation (RMSD) was calculated based on the difference between the particle size distribution of the material captured in the individual 20-liter samplers and the particle size distribution captured by the LCM bedload traps. The RMSD values represent the average deviation in the percent finer values between the 20-liter pails and the LCM bedload traps for each particle size class sieved. It is calculated as follows.

$$RMSD = \sqrt{\frac{\sum_1^n (D - \bar{D})^2}{n}} \quad \text{III:1}$$

Where,

n = number of particle size classes compared

D = nominal particle diameter (mm)

\bar{D} = expected nominal particle diameter (mm)

2.4. MAXIMUM GRAIN SHEAR ESTIMATION

Water level loggers located approximately 11 m and 27 m upstream and downstream respectively were used to estimate flow depths and water surface slopes for each bedload event. From these values the peak reach average shear stress for each event was calculated. These values are used to estimate the reference shear values for transport of sands and for gravels. The peak reach average shear stress values were then used to estimate the grain shear values in order to distinguish between the shear imposed on the heavily vegetated banks and shear imposed on the bed. The Manning's equation and the Manning-Strickler relation were used to define the grain shear. This is done by reframing the Manning's equation specifically for grain roughness, Equation III:2.

$$U = \frac{C_m}{n_g} R'^{\frac{2}{3}} S_f^{\frac{1}{2}} \quad \text{III:2}$$

Where,

U = Flow velocity

C_m = Manning's constant (1.0 for SI units and 1.486 for English units)

n_g = Manning's roughness due to bed roughness

R' = Hydraulic radius due to grain shear

S_f = Friction slope

Dividing this equation by the general form of the Manning's equation, the following equation is derived.

$$\frac{R'}{R} = \left(\frac{n_g}{n} \right)^{1.5} \quad \text{III:3}$$

Where,

n = Manning's reach average roughness

R = Hydraulic radius of the channel

Rearranging Equation III:3 to solve for R and substituting the resulting form into the relation for shear stress, the following relation is derived.

$$\tau' = \tau \left(\frac{n_g}{n} \right)^{1.5} \quad \text{III:4}$$

Where,

τ' = Grain shear stress

The Manning-Strickler relation may then be used to approximate n_g as follows.

$$n_g = 0.040 k_s^{\frac{1}{6}} \quad \text{III:5}$$

Where,

k_s = Roughness height of particles on the bed.

However, this relation requires known values of n and S_f which are inherently difficult to accurately quantify in natural systems. Therefore the resistance form of the logarithmic velocity profile was used to solve for τ' , Equations III:6 and III:7 below (Pitlick et al. 2009).

$$\frac{U}{u'^*} = 2.5 \ln \left(11 \frac{R}{k_s} \right) \quad \text{III:6}$$

$$\tau' = \sqrt{\frac{u'^*}{\rho}} \quad \text{III:7}$$

Where

U = Depth-averaged velocity

u'^* = Grain shear velocity

R = Hydraulic radius

ρ = Fluid density

Channel geometry was determined through field survey efforts. The Manning's n for the channel was estimated according to water surface slope and flow measurements at bank full flow (see appendix). The bed roughness height was estimated differently for various bedload relations. As the Wilcock (1998) model was addressed in this study, the bed roughness was estimated accordingly as twice the nominal diameter of the D_{65} particle on the bed surface.

2.5. BEDLOAD TRANSPORT MODEL CALIBRATION

Calibration of the Wilcock (1998) two-fraction bedload model requires specification of the fraction of bedload in the sand size range (f_s) on the bed surface and a reference shear stress value for sand (τ_{rs}) and for gravel (τ_{rg}) in the system being modeled. The reference shear stress was used as surrogate for the critical shear stress for incipient motion. In this application, each of these values are expressed as grain shear. The relations for the Wilcock (1998) model are summarized in Equations III:8 through III:12 below.

$$Q_b = Q_{bg} + Q_{bs} \quad \text{III:8}$$

$$Q_{bg} = \frac{W_g^* f_g B u_*^3 \rho_s}{sg} \quad \text{III:9}$$

$$Q_{bs} = \frac{W_s^* f_s B u_*^3 \rho_s}{sg} \quad \text{III:10}$$

$$\phi_s = \frac{\tau}{\tau_{rs}} \quad \text{III:11}$$

$$\phi_g = \frac{\tau}{\tau_{rg}} \quad \text{III:12}$$

$$W_g^* = \begin{cases} 11.2 \left(1 - \frac{0.846}{\phi_g} \right)^{4.5} & \text{for } \phi_g < 1 \\ 0.0025 \phi_g^{14.2} & \text{for } \phi_g \geq 1 \end{cases} \quad \text{III:13}$$

$$W_s^* = 11.2 \left(1 - 0.846 \left(\frac{1}{\phi_s} \right)^{0.5} \right)^{4.5} \quad \text{III:14}$$

Where,

Q_b = Total bedload transport rate, by volume

Q_{bg} = Bedload transport rate of gravel, by volume

W_g^* = Dimensionless sediment transport rate for gravel

B = Stream width

u_* = Shear velocity

ρ_s = Sediment particle density

s = Submerged specific gravity of sediment

g = Gravitational acceleration

Q_{bs} = Bedload transport rate of sand, by volume

W_s^* = Dimensionless sediment transport rate for sand

τ = Local boundary shear stress, averaged over turbulence

3. RESULTS AND DISCUSSION

3.1. COMPARATIVE ANALYSIS OF CAPTURED BEDLOAD SIZE DISTRIBUTIONS

A total of twenty-two paired bedload observations were collected with the 20-liter samplers and the LCM pit traps between January of 2011 and May of 2012. A summary of the data for each event is provided in Table III:2. These data include the max grain shear estimated from the peak stage for each event; the D_{50} , and sand fraction (as a percentage) for bedload collected from the pit trap; and the trapped mass, D_{50} , and sand fraction for each 20-liter pit trap. The RMSD

results are also presented as the percentage difference between the fraction of sand present in the 20-liter sampler material and that present in the material collected from the LCM pit traps. Errors in the sand fraction estimation for each 20-liter pit trap are also summarized.

Figure III:3 illustrates that RMSD values range from approximately 0.15 mm to nearly 0 mm. Higher values indicate poor performance of the 20-liter sampler with regard to its ability to collect a representative bedload particle size distribution. The data points suggest that the 20-liter sampler produced similar results regardless of location. The data further suggest that the most representative data were obtained when the mass of material collected by the 20-liter sampler for a single event is approximately 22 kg. This mass corresponds to about 75% of the capacity of a 20-liter sampler. Beyond this capacity, RMS values rise slightly. This is likely due to the fact that the samplers only collected material for a portion of the event before becoming filled with material.

The poor performance of the of the 20-liter samplers for smaller samples is thought to be a result of partial transport occurring over only a portion of the channel width (Bunte 2006; Parker 2008). Thus the 20-liter samplers may be partially bypassed by material while the pit traps still collect a representative sample due to their size relative to the channel width. Conversely, for larger events bedload transport occur over nearly the full width of the channel bed allowing the 2-liter samplers and the pit traps to each collect representative samples.

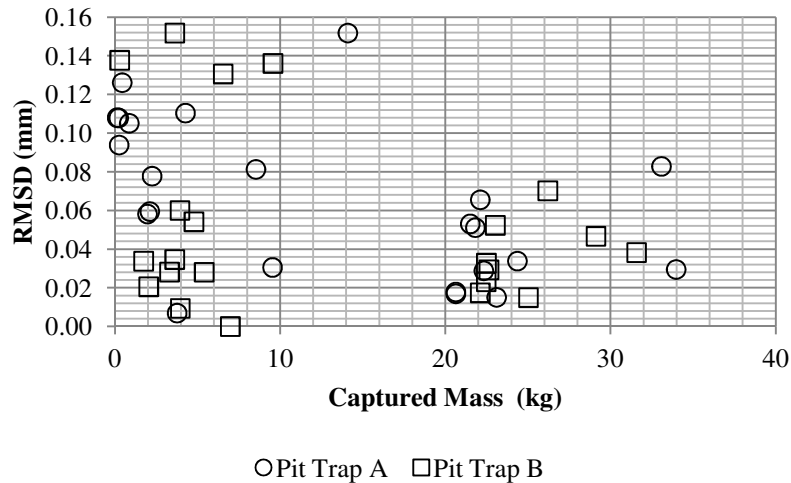


Figure III:3 – Mass captured by the 20-liter samplers vs. root mean squared deviation

Table III:2 – Summary of Bedload Transport Characteristics per Collection Event for LCM
Bedload

Event Date	Max Grain Shear	LCM Bedload Station			20-liter Pit Trap A				20-liter Pit Trap B				
		D ₅₀ (mm)	Sand Fraction	Trapped Mass (kg)	D ₅₀ (mm)	Sand Fraction	RMSD (mm)	Sand Fraction Error	Trapped Mass (kg)	D ₅₀ (mm)	Sand Fraction	RMSD	Sand Fraction Error
1/1/2011	15.8	5.9	19%	0.13	1.9	50%	3.8	32%	2.80	3.9	0.33	2.9	14%
1/26/2011	1.9	5.2	18%	1.96	6.9	16%	3.6	-2%	3.30	5.5	0.17	0.3	-1%
2/28/2011	17.6	6.8	15%	22.11	5.1	21%	1.3	6%	23.02	5.6	0.20	1.2	4%
4/16/2011	16.3	5.5	21%	22.32	5.6	21%	0.3	0%	22.63	5.5	0.21	0.2	0%
4/27/2011	17.6	4.3	28%	3.76	4.2	29%	0.1	1%	3.95	4.0	0.31	0.4	3%
6/21/2011	3.3	5.3	30%	4.26	3.0	40%	21.8	10%	6.55	2.7	0.42	23.6	12%
8/4/2011	4.0	6.1	23%	2.10	3.8	35%	6.5	12%	3.93	4.6	0.26	5.1	3%
9/5/2011	15.1	5.1	20%	21.81	4.3	31%	1.0	11%	22.47	4.9	0.24	1.2	4%
10/19/2011	19.6	5.2	20%	21.50	3.8	31%	1.5	11%	22.11	5.1	0.21	0.7	1%
11/16/2011	13.6	4.9	21%	20.63	4.7	24%	0.2	3%	22.48	4.4	0.32	0.5	11%
11/21/2011	4.1	4.9	21%	20.63	4.5	24%	0.5	3%	6.98	4.6	0.32	1.6	11%
11/22/2011	5.0	4.0	34%	0.22	0.5	70%	6.0	37%	9.56	3.9	0.26	4.1	-8%
11/27/2011	13.9	4.9	24%	23.10	5.4	21%	0.6	-4%	25.03	5.2	0.24	0.5	0%
12/6/2011	4.0	3.1	38%	24.36	3.2	35%	0.8	-3%	4.78	2.6	0.45	0.4	7%
12/16/2011	5.0	3.1	38%	0.86	0.9	67%	2.7	28%	2.04	3.7	0.32	2.9	-6%
12/22/2011	6.9	3.6	34%	9.53	3.7	30%	0.5	-4%	5.40	3.0	0.39	1.2	5%
1/9/2012	3.2	10.7	17%	0.43	1.0	57%	6.5	39%	0.28	0.9	0.64	6.6	47%
2/3/2010	17.7	3.8	34%	2.24	4.5	19%	1.9	-15%	3.61	3.7	0.32	1.9	-2%
2/10/2012	4.2	3.9	30%	0.25	3.3	40%	7.1	10%	1.73	3.5	0.32	0.7	2%
2/31/2012	4.6	7.1	15%	33.97	6.3	16%	0.7	0%	26.20	5.3	0.15	1.7	0%
3/24/2012	14.5	5.5	16%	8.53	3.3	35%	2.0	19%	29.11	6.1	0.16	2.0	0%
4/11/2012	18.5	5.5	19%	33.08	8.5	12%	2.0	-7%	31.57	6.8	0.14	1.1	-5%
5/20/2012	18.0	4.9	22%	14.09	4.4	27%	3.1	5%	3.62	5.5	0.18	6.5	-4%

The data summarized in Figure III:4 indicate a weak correlation between the mass of the captured samples and the magnitude of the maximum grain shear for the event. This suggests that even when partial transport occurs, if the event is of sufficient duration the buckets may collect a representative sample for low stage events.

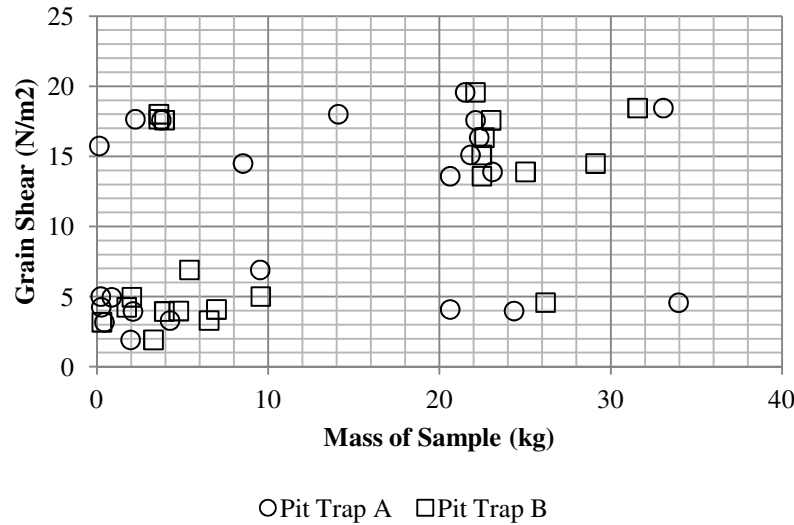


Figure III:4 – Mass captured by the 20-liter samplers vs. maximum event grain shear

The data in Figure III:5 show a trend similar to that in Figure III:3. The largest errors in the sand fraction data are for samples smaller than 2 kg. Samples between 2 and 15 kg are in the $\pm 20\%$ range and samples larger than 15 kg are in the $\pm 10\%$ range. It is further observed that the sand fraction data appear to be less impacted by traps becoming completely filled, as sand fraction errors for events filling more than 75% of the 20-liter pit traps actually appear to improve. Finally, Figure III:6 presents data points for the fraction of sand collected by the 20-liter samplers and the maximum shear recorded for each event. These values were applied in an effort to determine the relative reference grain shear stress for sands and gravels in the following subsection.

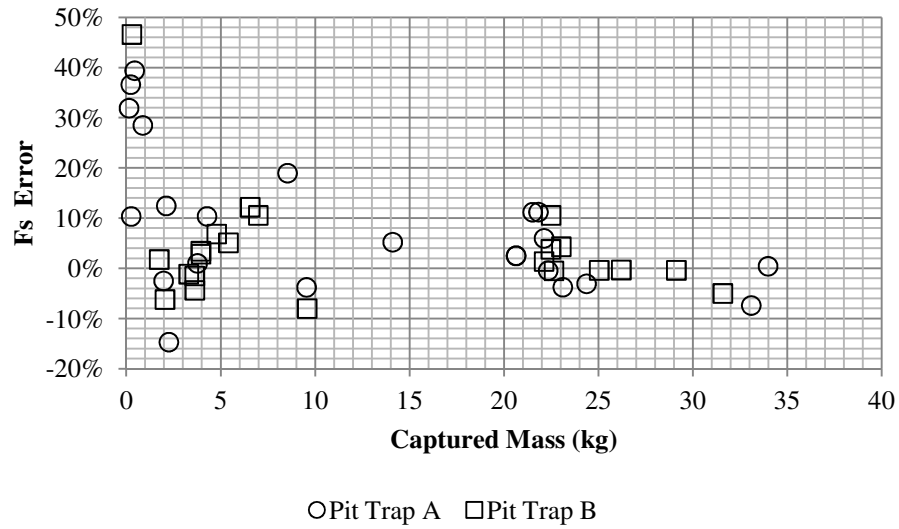


Figure III:5 – Mass captured by the 20-liter samplers vs. sand fraction error

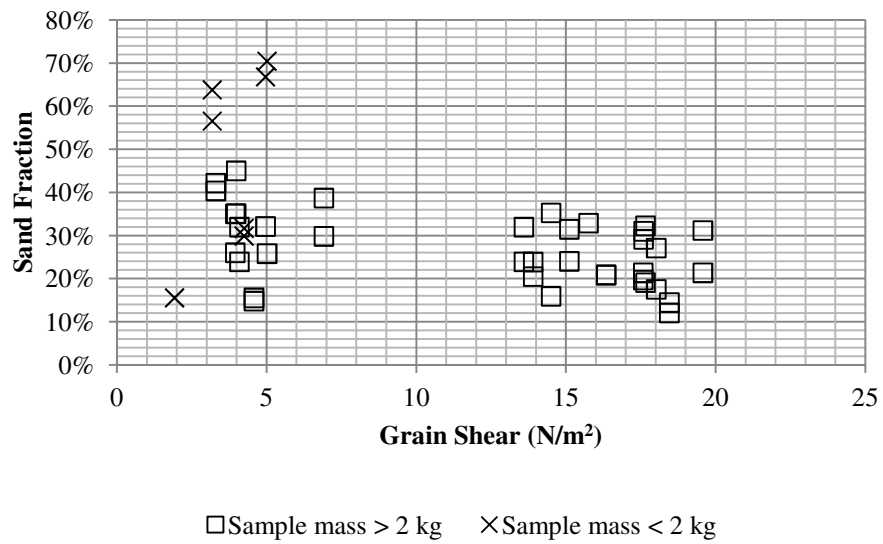


Figure III:6 – Peak grain shear vs. sand fraction from 20-liter samplers

3.2. CALIBRATION OF THE WILCOCK (1998) TWO-FRACTION MODEL

The grain shear versus sand fraction data presented in Figure III:5 was applied to calibrate the Wilcock (1998) two-fraction model. Figure III:5 includes all sand fraction estimates from the 20-liter pit samples. The data points are presented in two classes, one for data from samples larger than 2 kg and one for samples smaller than 2 kg. These data do not clearly indicate a reference shear value for sands, as all samples were at least 50% gravel. Further, because all of the samples contain at least 50% gravel they do not clearly indicate a reference shear for gravel. This is due in part to the fact that these data points represent material collected over the full hydrograph for a bedload event with a range of shear stress values up to the maximum value reported. The data do however show that the sand fraction becomes less scattered for events with a maximum grain shear of more than approximately 10 N/m². This value was therefore chosen to approximate the reference shear for the gravel fraction. The reference shear for sand was approximated as 1.9 N/m². This is the lowest maximum grain shear for which any material was collected in the 20-liter samplers. Note that the sand fraction for this sample may be in error as suggested by the data in Figure III:5. However, this is of little importance to the task of estimating the reference shear for sands.

With regard to these reference shear estimates, the Meyer-Peter and Muller (1948) relation for critical shear stress for bedload particles is used as a basis for comparison. According to their relation (Equation III:15), the critical shear for a 2 mm gravel/sand particle is 1.5 N/m² which is very close to the value estimated using the 20-liter samplers for the sand reference shear value.

$$\tau_{cr} = 0.047(\rho_s - \rho)gd \quad \text{III:15}$$

Where,

τ_{cr} = Critical shear stress for initiation of bedload movement

ρ_s = Sediment particle density

ρ = Fluid density

g = Gravitational acceleration

d = Nominal particle diameter

The critical shear for a medium gravel particle (11 mm) is 8.4 N/m², which falls well within the range of values shown in Figure III:6 and approximated as 10 N/m². The results of the Wilcock (1998) model prediction calibrated using data from the 20-liter samplers as well as from estimations of the sand and gravel reference shear stress values made using the Meyer-Peter and Muller (1948) relation are shown in Figure III:7 as Calibration I and II respectively along with measured bedload transport rates collected at the same site. In both calibrations the value for the fraction of sand on the bed surface was estimated to be 15% based on pebble count data collected at the riffle.

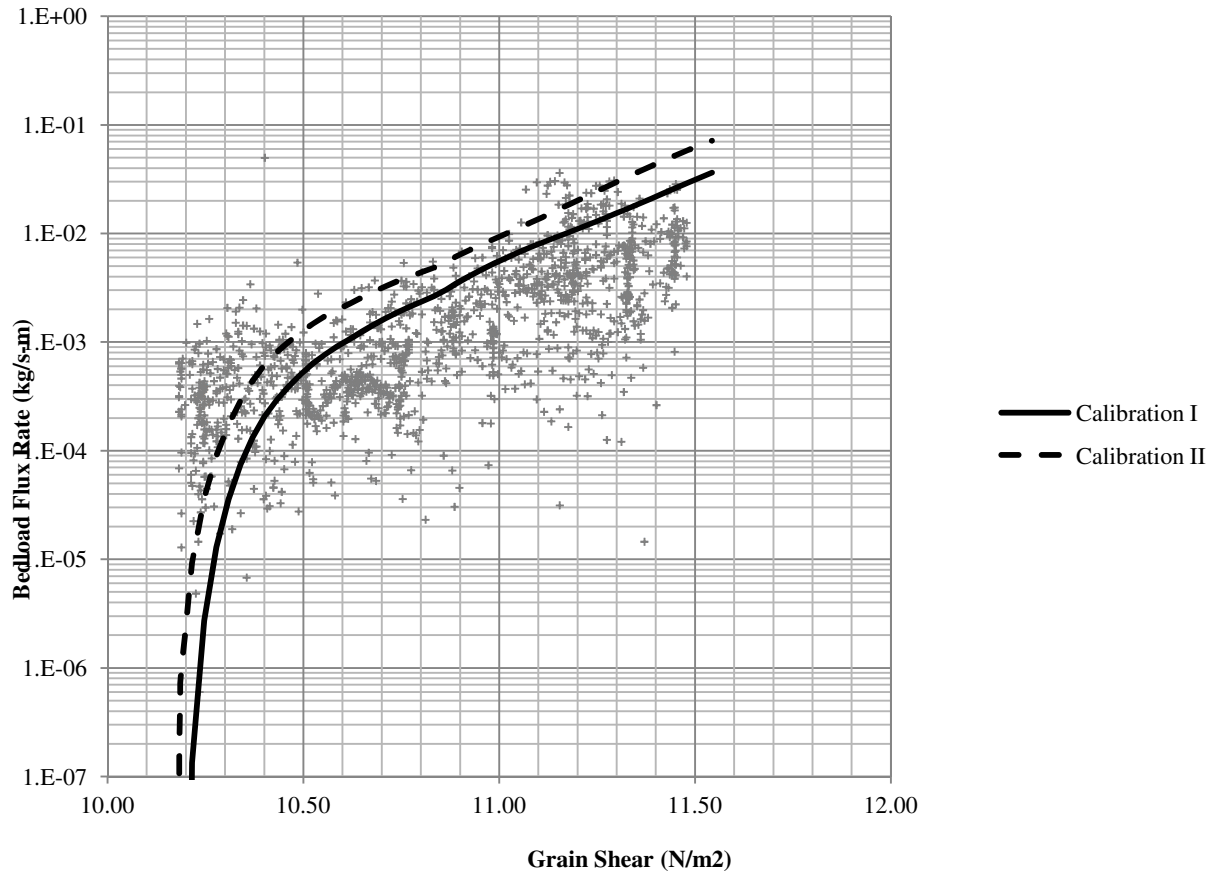


Figure III:7 – Results of the Wilcock (1998) two-fraction model calibrated using 20-liter sampler data presented with measured bedload transport rates for Little Turkey Creek

The calibrated model prediction shown in Figure III:7 falls within an order of magnitude of the central tendency of the bedload transport data collected at the same reach. The predicted values trend closest to the lower measurements of bedload transport observations for data in the 10.1 to 10.5 m stage range and trend towards the higher bedload transport observations in the shear range beyond approximately 10.4 m. Considering the seemingly rough approximations for the reference shear values that were obtained from the 20-liter samplers, the agreement of the model results with the bedload data is surprisingly close. The results of each calibration shown in Figure III:7 suggest only a marginal difference between Calibration I and Calibration II with regard to the spread in the bedload transport data, though it may be put forth that Calibration I is superior as it falls closer to the middle of the range of observed transport rates.

4. SUMMARY

The results of this research suggest that 20-liter samplers are capable of collecting representative particle size distribution data from bedload transport events if the events are sufficiently long or intense enough to fill the samplers to approximately 75% or more of their capacity. It appears that similar results may be obtained by either locating the 20-liter sampler in the thalweg of the riffle or halfway between the thalweg and the top of a mid-channel bar. However, a separate study may be needed to determine if placement in the cross-section can be optimized based on both location and number of 20-liter samplers placed in the cross-section.

In this research setting, the 20-liter pit samplers performed only marginally well at the task of collecting samples that clearly demark the reference shear for gravels. In this system, the approximations obtained through review of 20-liter pit sampler data are close to those obtained using the Meyer-Peter and Muller (1948) relation for critical shear stress. Model results calibrated using data from the 20-liter pit samplers fall closer to the middle of the range of observed transport rates than results based on the Meyer-Peter and Muller (1948) relation. However, given the level of effort and time necessary to collect sufficient samples using the bucket samplers to approximate the reference shear values, acceptable application of the Meyer-Peter and Muller (1948) relation for model calibration may be suitable in applications where error within an order of magnitude are deemed acceptable.

5. NOTATIONS

B	stream width
C_m	Manning's constant (1.0 for SI units and 1.486 for English units)
\bar{D}	expected nominal particle diameter (mm)
D	nominal particle diameter (mm)
d	nominal particle diameter
g	gravitational acceleration
k_s	roughness height of particles on the bed.
n	reach averaged Manning's roughness
n_g	Manning's roughness due to bed roughness
\mathbf{n}	number of particle size classes compared
Q_b	total bedload transport rate, by volume
Q_{bg}	bedload transport rate of gravel, by volume
Q_{bs}	bedload transport rate of sand, by volume
R	hydraulic radius
R'	hydraulic radius due to grain shear
s	submerged specific gravity of sediment
S_f	friction slope
U	depth averaged velocity
u_*	shear velocity
W_g^*	dimensionless sediment transport rate for gravel
W_s^*	dimensionless sediment transport rate for sand

τ	local boundary shear stress, averaged over turbulence
τ'	grain shear stress
τ_{cr}	critical shear stress for initiation of bedload movement
u'^*	grain shear velocity
ρ_s	sediment particle density
ρ	fluid density

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**CHAPTER IV UNCERTAINTY IN SELECTED BEDLOAD
TRANSPORT MODELS: SUPPORT FOR STREAM
RESTORATION DESIGN IN THE SOUTHERN
APPALACHIAN RIDGE AND VALLEY REGION**

CHAPTER IV ABSTRACT

Successful stream restoration designs on alluvial systems in part require knowledge of or the ability to predict bedload transport rates over the range of flows capable of mobilizing and or sustaining bedload flux. Site specific bedload transport measurements over the full range of anticipated channel flows are rarely available for a given site, so designers must choose from available standard bedload transport models to make predictions. However, estimates of bedload transport rates developed from models are notoriously inaccurate. While the physics of particle motion in all alluvial systems are conceptually the same, there can be wide variation between the critical conditions for incipient motion in a given system due to the combined effects of cohesive materials, vegetation, and the relative fraction of sand and gravel. Most bedload transport models can be adjusted to account for this by changing the “stock” reference shear stress (a surrogate for critical shear stress) in the formulae.

Calibration of a given bedload transport model by adjusting the reference shear stress certainly improves the potential for a model predictions, but it does not prevent model prediction errors due to uncertainty in other input parameters, such as the channel roughness, particle diameter, and energy slope. Errors in these input parameters can result in large errors in model predictions, and the combined effect of even small simultaneous errors in all input parameters for a given model can result in order of magnitude errors in model predictions. This is a troubling notion, as many bedload transport relations require specification of values including slope and Manning’s roughness; these values are known to vary with stage and are inherently difficult to specify without some degree of uncertainty. This study demonstrates the result of error and uncertainty in input parameters for three different bedload models: 1) a modified form of the Meyer-Peter Muller (1948) model, 2) a modified form of the Parker, Klingeman, and McLean (1983) model, and 3) the Wilcock (1998) model.

The impact of input errors was assessed for discrete variables and the impact of uncertainty was assessed for uniform uncertainty in all independent variables. The independent variables examined in this study are energy slope, Manning’s n , reference shear, and the model specific grain diameter. The result of error and uncertainty in the input parameters for these models is presented in comparison to the bedload transport data set collected at Little Turkey Creek, in Farragut, Tennessee. With regard to discrete errors in these models, they are most sensitive to Manning’s n , followed closely by slope. Errors as high as 50% still result in model estimates that are within the range of observed bedload transport rates at Little Turkey Creek. Errors due to the other independent input parameters show markedly less sensitivity in most instances. The impact of uniform uncertainty associated with model input parameters suggests that even modest levels of uncertainty up to 20% translate to 95% confidence intervals for model results that can span an order of magnitude or more. Finally, the results of this research suggest that the modified Meyer-Peter Muller model provides the most robust estimate for bedload transport on Little Turkey Creek. However, the Wilcock (1998) model is also relatively robust and did not require calibration through modification of model coefficients to achieve agreement with the bedload data collected at Little Turkey Creek.

1. INTRODUCTION

In alluvial rivers, bedload transport is the fundamental process maintaining a dynamically stable channel geometry in response to both the quantity and timing of water and the volume and character of coarse material delivered from the watershed (Emmett and Wolman 2001; Leopold et al. 1964). Engineering and conservation efforts aimed at restoring the form and function of riverine ecosystems increasingly recognize the importance of bedload transport. Specifically, with regard to the plan and profile of proposed restoration designs and the ability of the proposed dimensions to maintain a dynamic equilibrium within the restored reach (Barry et al. 2008; Goodwin 2004; Wilcock 2004). Restoration requires knowledge or the ability to predict bedload transport rates over the range of flows capable of mobilizing and/or sustaining bedload flux.

Site specific bedload transport measurements over the full range of anticipated in channel flows are rarely available for a given site. In this instance stream restoration designers must choose from available standard bedload transport models to make predictions. However, estimates of bedload transport rates developed from models are notoriously inaccurate (Bravo-Espinosa et al. 2003; Goodwin 2004; Wilcock 2001; Yang and Huang 2001). While the physics of particle motion in all alluvial systems are conceptually the same, there can be wide variation between the critical conditions for incipient motion in a given system due to the combined effects of cohesive materials, vegetation, and the relative fraction of sand and gravel. Most bedload transport models can be adjusted to account for this by changing the “stock” reference shear stress (a surrogate for critical shear stress for initiation of particle motion) in the formulae (Wilcock 2001).

Considerable effort has been spent over the years in comparing the accuracy of various transport formulas. These comparisons suffer from the lack of known transport rates with which to compare model results for a given site. Wilcock (2001) asserts that such studies divert attention from the primary source of error in calculated transport rates, which he claims are due to uncertainty in the boundary conditions rather than to model selection. While this may be true in some instances, it is noted in this study that modification of the Meyer-Peter Muller (1948) and Parker, Klingeman, and Mclean (1983) models is necessary to provide agreement with the data set at Little Turkey Creek, while no modification is necessary for the Wilcock (1998) model. Given that all three models are based on the same boundary conditions, it is recognized that model selection may indeed be important where a range of measured transport data points are not available. This observation notwithstanding, the work presented in this study is concerned with the effect of error and uncertainty in model input parameters for relations that are anticipated to perform well at a given site given an absence of error and uncertainty in the input parameters.

Calibration of a given bedload transport model by adjusting the reference shear stress certainly improves the potential for model predictions, but it does not prevent model prediction errors caused by uncertainty in other input parameters such as the channel roughness, particle diameter, and energy slope (Pitlick et al. 2009). Errors in these input parameters can result in large errors in model predictions, and the combined effect of even small simultaneous errors in all input parameters for a given model can result in order of magnitude errors in model predictions (Pitlick et al. 2009; Wilcock et al. 2008; Wilcock 2004). This is a troubling notion, as many bedload transport relations require specification of values including slope and Manning’s

roughness; these values are known to vary with stage and are inherently difficult to specify without some degree of uncertainty.

The objective of this study is to illustrate the result of error and uncertainty in input parameters for three different bedload models: 1) a modified form of the Meyer-Peter Muller (1948) model (MPM), 2) a modified form of the Parker, Klingeman, and Mclean (1983) model (PKM), and 3) the Wilcock (1998) model (W98). The result of error and uncertainty in the input parameters for these models is presented in comparison to the bedload transport data set collected at Little Turkey Creek, in Farragut Tennessee (see Chapter II).

2. STUDY DESIGN AND METHODS

The bedload transport data used to compare the results of error and uncertainty in the selected models were collected over the course of two years and include bedload rate observation collected at 5 minute intervals for 11 bedload transport events up to a total collected volume of approximately 1.6 m³ of material. Bedload observations were collected in concert with water surface elevation and water surface slope data referenced to a locally established datum collected on 15-minute intervals. For a thorough discussion of the means and methods used in collection of this data and a description of the study reach the reader is referred to Chapter II. The results of this study are specific to a single study site in the Southern Appalachian Ridge and Valley Region, although the bedload transport data used in this study are comparable with other data sets from Western US streams and rivers.

The models selected for review in this study initially also included the Parker and Klingeman (1982), Parker(1990), Wilcock and Crowe(2003). However, results of both the Parker and Klingeman (1982) and the Parker (1990) models are strikingly similar for Little Turkey Creek to those for the PKM model. Therefore, the model with the simplest form was selected. The Wilcock and Crowe (2003) model was eliminated from consideration because preliminary results of this model poorly described the data at Little Turkey Creek, and those results could not be improved through calibration. Details on the models included in this study are provided in the following sections. Input variables selected for the assessment of error and uncertainty were based on their independence from other parameters and are summarized in Table VI:1. The impact of input errors was assessed for discrete variables, and the impact of uncertainty was assessed for uniform uncertainty in all independent variables. Further details on these methods are provided in proceeding sections.

Table IV:1 – Individual Parameter Error Ranges from the Known Value Evaluated for each Model

Parameter	Model	Range
Slope (S)	All Models	$\pm 50\%$
Manning's n (n)	All Models	$\pm 50\%$
Mean Substrate Particle (D_{50s})	PKM	$\pm 50\%$
Mean Bed Particle (D_{90b})	MPM	$\pm 50\%$
Mean Bed Particle (D_{65b})	W98	$\pm 50\%$
Reference Shear (τ_r)	MPM and PKM	$\pm 50\%$, 100%, -99%
Reference Shear Stress for Sand (τ_{rs})	W98	$\pm 50\%$, 100%, -99%
Reference Shear Stress for Gravel (τ_{rg})	W98	$\pm 50\%$, 100%, -99%
Bedload Sand Fraction (f_s)	W98	50% to 95%*

2.1. MODELS TESTED

Figure IV:1 illustrates results of the MPM, PKM, and W98 models for Little Turkey Creek using the same relative input data for each model. It can be seen in this figure that the stock form of the MPM and PKM models poorly describe the bedload transport versus stage relationship for Little Turkey Creek. The underestimation of bedload transport by the MPM model is consistent with the observations of Gomez and Church (1989) and the three orders of magnitude overestimation of bedload transport by the PKM model is consistent with the observations of Weinhold (2001). In the following sections describing each model, coefficient modifications to the PKM and MPM model are presented that align the predictions of these models more closely with the data for Little Turkey Cree. It is possible, that these modifications are suitable for use in other Southern Appalachian Ridge and Valley Streams, though additional research is warranted to evaluate this possibility.

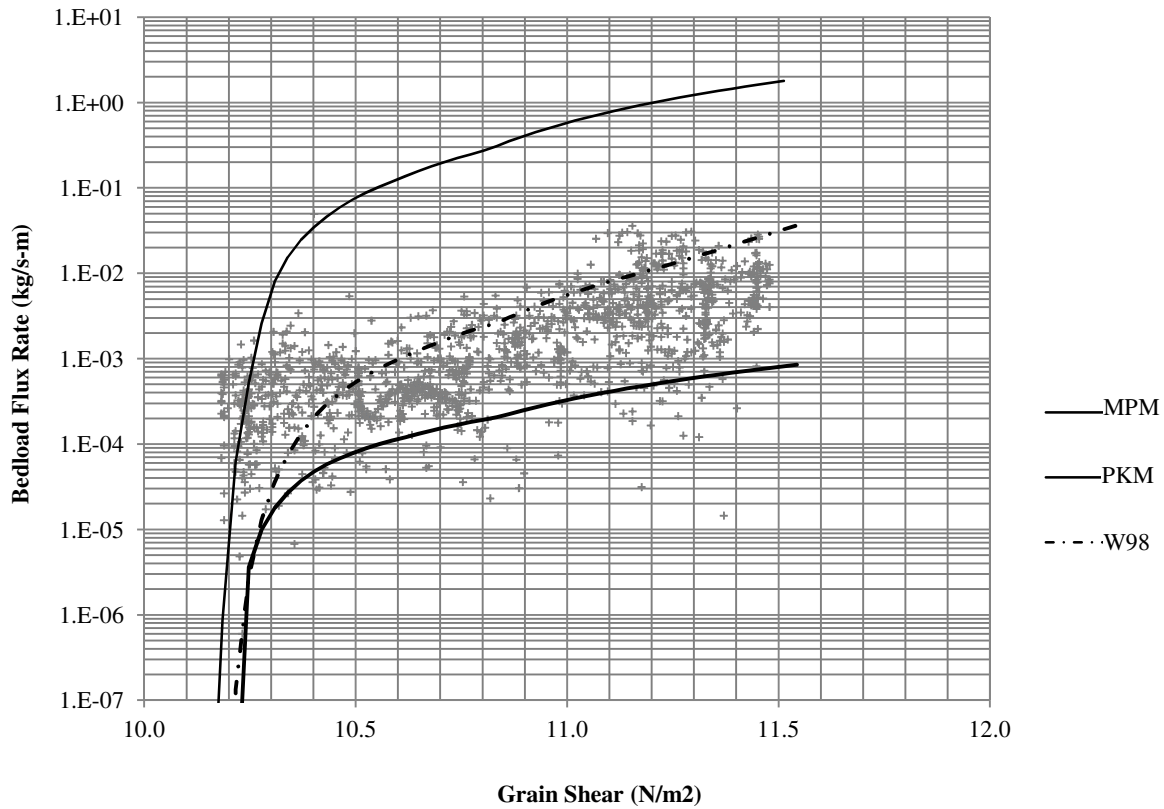


Figure IV:1 Comparison of stock bedload transport models to Little Turkey Creek bedload data

2.1.1. Meyer-Peter and Muller [MPM] Model

The MPM model was developed according to laboratory observations of bedload transport for a range of particle sizes, gradations, flow stages, specific gravities, and energy slopes (Meyer-Peter and Muller 1948). The model expresses dimensionless bedload transport rate in terms of two variables, the critical dimensionless shear stress for particle motion and the dimensionless shear stress in the channel. The model is summarized below in Equations IV:1 through IV:3

$$Q_b = \frac{W^* B u_*^3 \rho_s}{(s - 1)g} \quad \text{IV:1}$$

$$u_* = \sqrt{\tau/\rho} \quad \text{IV:2}$$

$$W^* = 8(\tau^* - \tau_c^*)^{3/2} \quad \text{IV:3}$$

Where,

τ = Local boundary shear stress

τ^* = Grain shear stress

τ_c^* = Critical grain shear stress

ρ = Density of water

Q_b = Total bedload transport rate by volume

W^* = Dimensionless sediment transport rate,

B = Stream width

u_* = Shear velocity

ρ_s = Density of the sediment particle(s)

s = Density of bedload particles / Density of fluid

g = Acceleration of gravity

Modification of the MPM model for Little Turkey Creek was achieved through the alteration of coefficients in Equation IV:3. The resulting modification is summarized in Equation IV:4.

$$W^* = 64(\tau^* - \tau_c^*)^{3/2} \quad \text{IV:4}$$

2.1.2. Modified Parker, Klingeman and Mclean (1982)[PKM] Model

The modified PKM model included in this study is identical in form to the original PKM bedload model which is based on data collected by Milhous on Oak Creek and Hollingshead on the Elbow River (Hollingshead 1968; Milhous 1973). The original form of the PKM model is summarized in Equations IV:5 through IV:8 (Parker et al. 1982). The relationship for W^* presented in Equation IV:6 for $0.95 < \phi_{50} < 1.65$ was developed based on a “by-eye” curve fit of data points for Oak Creek and the Elbow River. Parker et al. (1990) extended their model to address values for which $\phi_{50} > 1.65$ using modifications of Einstein’s model (1950) and the previous work of Parker (1978; 1979) to address values for which $\phi_{50} > 1.65$. The relation for values for which $\phi_{50} < 0.95$ was added by Pitlick et al. (2009).

$$Q_b = \frac{W^* B u_*^3 \rho_s}{(s - 1)g} \quad \text{IV:5}$$

Where,

Q_b = Total bedload transport rate by volume

B = Stream width

ρ_s = Mass density of the sediment particle(s)

s = Specific gravity; density of bedload particles / density of fluid

g = Acceleration of gravity

u_* = Shear velocity, see Equation IV:2

W^*

$$= \begin{cases} 11.2 \left(1 - \frac{0.822}{\Phi_{50}} \right)^{4.5} & \Phi_{50} > 1.65 \\ 0.0025 e^{[14.2(\Phi_{50}-1) - 9.28(\Phi_{50}-1)^2]} & 0.95 \leq \Phi_{50} \leq 1.65 \\ 0.0025 \Phi_{50}^{14.2} & 0.95 < \Phi_{50} \end{cases} \quad \text{IV:6}$$

Where,

Φ_{50} = Normalized dimensionless shear stress, formulated using the median grain size of the substrate, as given by Equation IV:7.

$$\Phi_{50} = \frac{\tau_{50}^*}{\tau_{r50}^*} \quad \text{IV:7}$$

Where,

τ_{r50}^* = Reference dimensionless shear stress, computed by Parker et al. to be 0.0876

τ_{50}^* = Dimensionless shear stress formulated in terms of the median grain size of the substrate, as given by Equation IV:8.

$$\tau_{50}^* = \frac{u_*^2}{(s-1)gD_{50s}} \quad \text{IV:8}$$

Where,

D_{50s} = Median grain size of the substrate

Modification of the PKM model was achieved through the alteration of coefficients in IV:6 through trial and error to produce a model prediction that approximates the median of transport observations on Little Turkey Creek. The resulting modification to IV:8 is summarized in IV:9.

$$W^* = \begin{cases} 0.062 \left(1 - \frac{0.822}{\Phi_{50}}\right)^{4.5} & \Phi_{50} > 1.65 \\ 1.39 \times 10^{-5} e^{[14.2(\Phi_{50}-1)-9.28(\Phi_{50}-1)^2]} & 0.95 \leq \Phi_{50} \leq 1.65 \\ 1.39 \times 10^{-5} \Phi_{50}^{14.2} & 0.95 < \Phi_{50} \end{cases} \quad \text{IV:9}$$

2.1.3. Wilcock [W98] Model

The W98 model was derived to frame the bedload transport rate in terms of a gravel and sand fraction according to laboratory observations in a recirculating flume (Wilcock 1998) as well as field observations (Emmett 1980; Kuhnle 1992; Myrick et al. 1980). The W98 model is summarized in IV:10 through IV:14 below.

$$Q_b = Q_{bg} + Q_{bs} \quad \text{IV:10}$$

Where,

Q_{bg} = Total bedload transport rate for the gravel fraction, by mass

Q_{bs} = Total bedload transport rate for the sand fraction, by mass

$$Q_{bg} = \frac{W_g^* f_g B u_*^3 \rho_s}{(s-1)g} \quad \text{IV:11}$$

$$Q_{bs} = \frac{W_s^* f_s B u_*^3 \rho_s}{(s-1)g} \quad \text{IV:12}$$

Where,

W_g^* = Dimensionless bedload transport range for the gravel fraction, IV:15

W_s^* = Dimensionless bedload transport range for the sand fraction, IV:16

f_g = Fraction of gravel in the bedload material

f_s = Fraction of sand in the bedload material

$$\phi_g = \frac{\tau}{\tau_{rg}} \quad \text{IV:13}$$

$$\phi_s = \frac{\tau}{\tau_{rs}} \quad \text{IV:14}$$

$$W_g^* = \begin{cases} 11.2 \left(1 - \frac{0.846}{\phi_g} \right)^{4.5} & \text{for } \phi_g < 1 \\ 0.0025 \phi_g^{14.2} & \text{for } \phi_g \geq 1 \end{cases} \quad \text{IV:15}$$

$$W_s^* = 11.2 \left(1 - 0.846 \left(\frac{1}{\phi_s} \right)^{0.5} \right)^{4.5} \quad \text{IV:16}$$

Where,

τ_{rg} = Reference shear for gravel

τ_{rs} = Reference shear for sands

2.2. MODEL INPUT PARAMETERS

Each model was applied using particle size distribution data and geometric parameters collected at the Little Turkey Creek bedload research station, and according to guidelines provided by the original authors as well as guidance provided by Wilcock et al. (2008) and Pitlick et al. (2009). A summary of input parameters for each model is provided in Table IV:2. In all model calculations, the grain shear was estimated and used in place of the reach average shear in order to partition the effects of shear stress on the vegetated banks from that on the bed surface. For the modified MPM and PKM models grain shear was estimated using Equation IV:17 through Equation IV:19. For the W98 model the grain shear was estimated using Equation IV:17 and Equation IV:20 in accordance with the guidelines specified by Wilcock (1998).

$$u'^* = \sqrt{\frac{\tau'}{\rho}} \quad \text{IV:17}$$

$$\tau' = \tau \left(\frac{n_g}{n} \right)^{1.5} \quad \text{IV:18}$$

$$n_g = 0.040 k_s^{\frac{1}{6}} \quad \text{IV:19}$$

Where,

u'^* = Grain shear velocity
 τ' = Grain shear stress
 τ = Reach average shear stress
 n = Manning's coefficient
 k_s = Roughness height of particles on the bed

$$\frac{U}{u'^*} = 2.5 \ln \left(11 \frac{R}{k_s} \right) \quad \text{IV:20}$$

Where,

U = Depth-averaged velocity
 u'^* = Grain shear velocity
 R = Hydraulic radius
 ρ = Fluid density

Note that Equation IV:19 is the Manning-Strickler relation, where k_s has been assumed to be 10.7 times the nominal diameter of the D_{50} particle of the bed substrate (Pitlick et al. 2009). In Equation IV:20, k_s has been assumed to be twice the nominal diameter of the D_{65} particle on the bed surface (Pitlick et al. 2009). Information on how the reach average shear stress and Manning's coefficient and other hydraulic parameters were estimated for the study site is in Chapter II of this dissertation.

Table IV:2 – Input Parameters for the Selected Bedload Transport Models

Model	Slope (S)	Manning's n (n)	Bed Width (B)	Bed Roughness Height [□] (k_s)	Mean Substrate Particle Diameter (D_{50s})	Reference Shear Stress (τ_r)	Mean Bed Surface Particle Diameter (D_{50b})	Reference Shear Stress for Sand (τ_{rs})	Reference Shear Stress for Gravel (τ_{rg})	Bedload Sand Fraction (f_s)
			(m)	(m)	(mm)	(N/m ²)	(mm)	(N/m ²)	(N/m ²)	
MPM	0.01	0.1	4.7	2*D _{90b}	N/A	2	18	N/A	N/A	N/A
PKM	0.01	0.1	4.7	10.7*D _{50s}	5.3	N/A	N/A	N/A	N/A	N/A
W98	0.01	0.1	4.7	2*D _{65b}	N/A	N/A	N/A	2	10	0.15

2.3. ERROR AND UNCERTAINTY IN INPUT PARAMETERS

2.3.1. Discrete Parameter Error

To illustrate the effect of individual error in input parameters for each model a series of model predictions was made fixing all but a single input parameter to the known value and varying the degree of error in individual parameters to the minimum and maximum degrees summarized in Table IV:3. The range limits were selected such that resulting prediction errors fall within the range of measured variability in bedload transport observations at Little Turkey Creek study site.

Table IV:3 – Ranges of Uniform Uncertainty Applied to Each Model

Model	Range
PKM	10-20%
MPM	10-20%
W98	10-15%

2.3.2. Simultaneous Parameter Uncertainty

The effect of simultaneous parameter uncertainty was assessed through the use of Monte Carlo simulation of the selected bedload transport relations, as suggested by Wilcock (2008; 2004). Input parameters for the MPM and PKM model were evaluated for two ranges of uniform uncertainty in all input parameters, $\pm 10\%$ and $\pm 20\%$. The W98 model was evaluated to a uniform range of $\pm 10\%$ and $\pm 15\%$ uncertainty in all input parameters. These ranges are chosen in an effort to illustrate resulting uncertainties that fall at the margins of the observations collected at Little Turkey Creek. The Monte Carlo analysis of each model assumes the uncertainty within these ranges is normally distributed with a standard deviation of one fourth of the uncertainty range (Wilcock 2001). In reality, the distribution of the uncertainty in the input parameters may be non-parametric. However, parametric distributions were applied here for the sake of illustration. Monte Carlo analyses were run for $N=1,000$ simulations each for the full range of in channel flow stages for Little Turkey Creek using Visual Basic for Applications, Figure IV:2. Channel stages analyzed in each simulation include base flow and bank full flow with intermediate stages included every 0.31 meters. The resulting distributions were used to define the 95% confidence intervals on the resulting bedload transport estimates. The plotted confidence intervals were then visually compared to the range of observed bedload transport observations collected at the field study site on Little Turkey Creek.

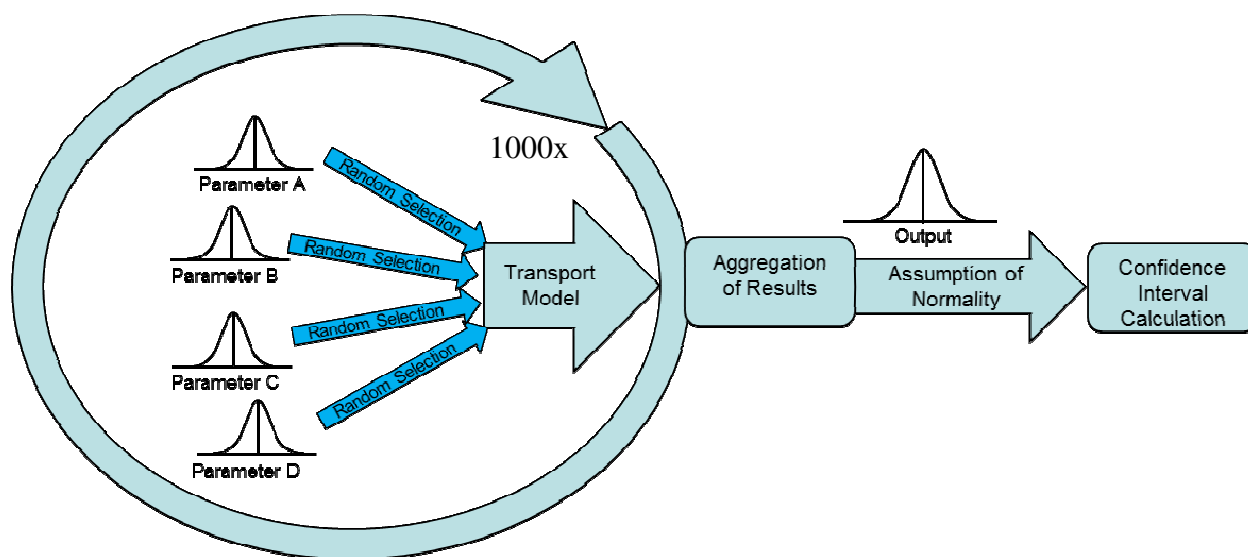


Figure IV:2 Conceptual illustration of the Monte Carlo simulation process used

3. RESULTS AND DISCUSSION

3.1. CALIBRATED MODEL RESULTS

The results of the calibrated Modified MPM, Modified PKM, and W98 models using the input data presented in Table IV:2 are presented in Figure IV:3. The results of the calibrated unmodified MPM (1948) and PKM (1984) models are provided for reference. Note that the uncalibrated models bound the Little Turkey Creek data set but do not scale well to the bedload transport rates measured at Little Turkey Creek. By comparison, the Modified MPM, modified PKM, and W98 relations appear to describe the mean of the data rather well. The results in Figure IV:3 also illustrate the variability of the measured transport rates about the model estimates. The spread suggests that even for models that are specified carefully and correctly, the results still represent an average condition over which individual transport rates may vary as much as two orders of magnitude. This observation is consistent with the observation of Pitlick et al. (2009) with regard to model predictions, and with many others with regard to the variability observed in bedload transport rates (Bunte et al. 2007; Emmett 1976; Goodwin 2004)

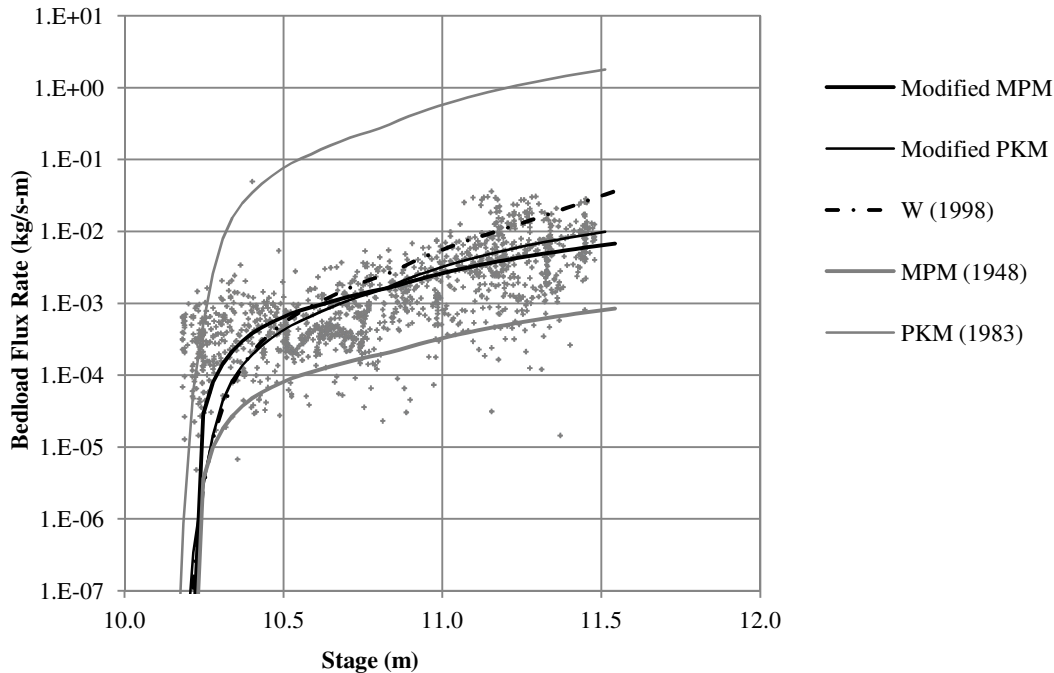


Figure IV:3 – Modified bedload transport model predictions compared to field data collected from Little Turkey Creek, Tennessee (2010-2011).

3.2. EFFECT OF ERRORS AND UNCERTAINTY

3.2.1. Discrete Errors

Modified Meyer-Peter Muller Model

The effect of discrete errors in individual model input parameters is illustrated in Figure IV:4 within the context of variability of the bedload transport measurements at Little Turkey Creek for the modified MPM model. Note that the parameters with the greatest discrete influence are the estimate of Manning's n and the energy slope (S). The MPM model estimates increase with low estimates of Manning's n and decrease with low estimates of slope. In each instance, the model is more sensitive to low estimates for these parameters rather than high estimates, and errors greater than 50% may result in estimates that fall outside of the measured variability in bedload transport rates at the Little Turkey Creek. Discrete errors for the reference shear value appear to have little impact at higher channel stages. Compared to the effect of errors in either S or n , model results of the modified MPM model are overall less sensitive to errors in the reference shear stress. Finally, the model is least sensitive to errors in the estimate of the D_{90} particle on the bed surface (D_{90b}).

Modified Parker Klingeman and McLean Model

The effects of discrete errors in the modified PKM model are similar to those in the modified MPM model, Figure IV:5. Once again, the parameters with the greatest discrete influence are the estimates of n and S . Again, low estimates in n result in elevated bedload transport estimates, and low estimates in slope result in low estimates for bedload transport. Also, the discrete effect of errors in the particle size used in the model has the smallest impact on model performance. The modified PKM model is however more sensitive to the estimate of reference shear than was the modified MPM model.

Wilcock (1998) Model

The W98 model incorporates a wider range of input parameters than the modified MPM and PKM models, yet it appears to be the most sensitive to discrete errors in input parameters, as shown in Figure IV:6. For instance, the effect of high Manning's n estimate results in approximately two orders of magnitude error in bedload transport estimates, far greater than does the same degree of error for Manning's n in the other models. The effects of errors in the slope parameter and particle size used by the model are comparable to the impacts of those errors on the modified MPM and PKM models. Unlike the other models, the W98 model addresses the reference grain shear for the sand fraction separately from that of the gravel fraction. For the data at Little Turkey Creek, errors in the reference shear for the gravel fraction appear to have a larger impact on results than do errors in the reference shear for the sand fraction. The individual sensitivity at a given site may be related. For interpreting the general sensitivity of these parameters at a given site, it was observed that the W98 model is at least as sensitive if not more sensitive to errors in the reference shear values than are the modified PKM and MPM models.

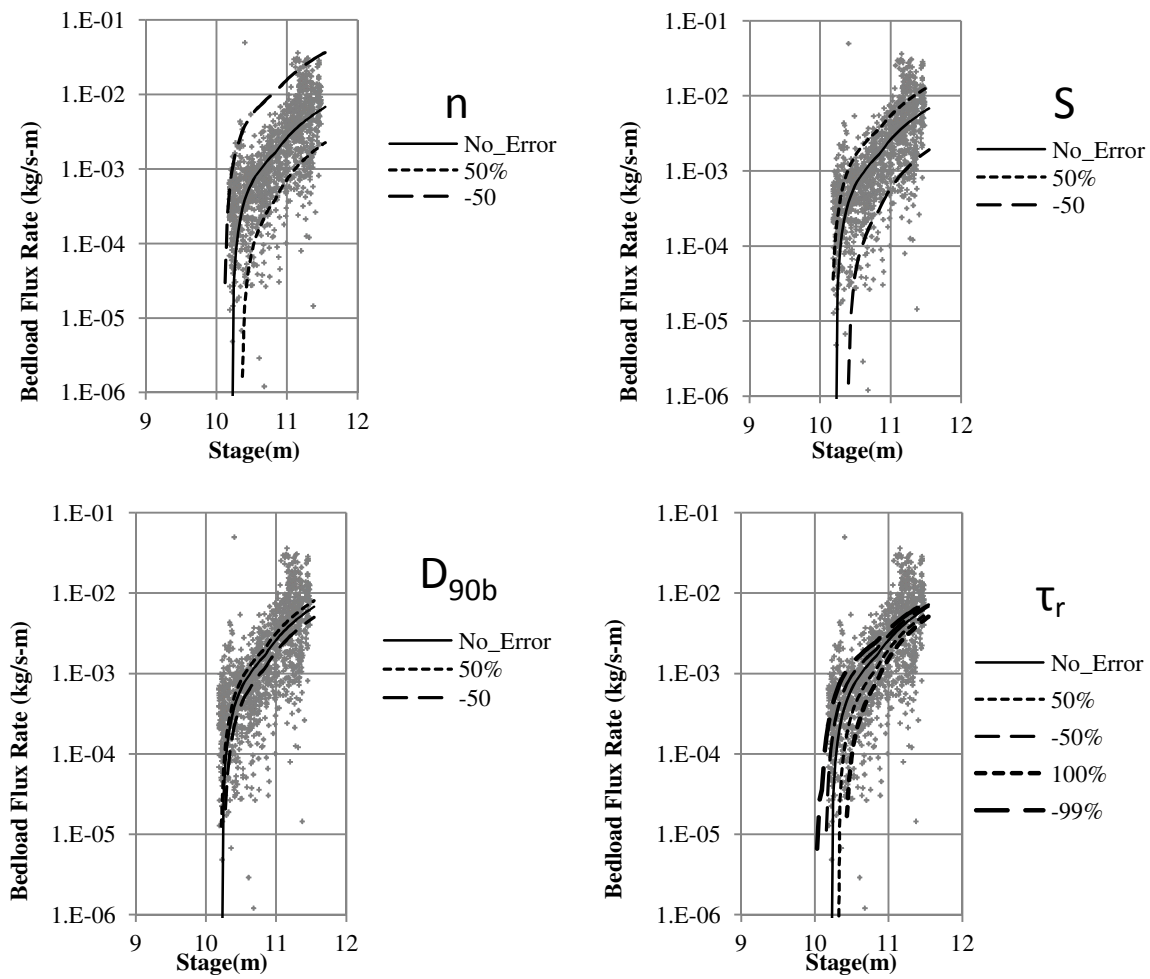


Figure IV:4 – Effect of discrete errors in Manning's n (n), slope, (S), particle diameter (D_{90b}) and reference shear (τ_r) for the modified MPM model and comparison to Little Turkey Creek bedload data

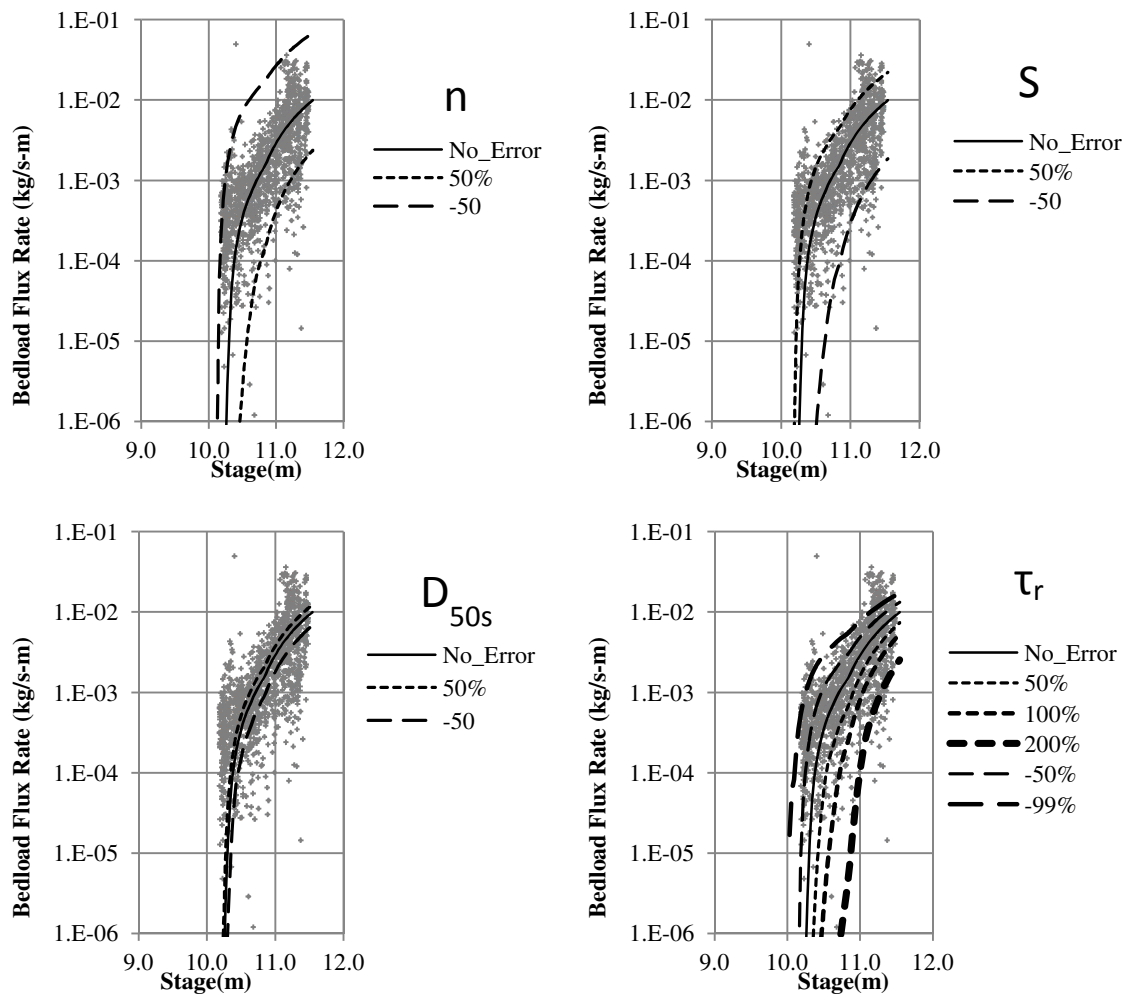


Figure IV:5 – Effect of discrete errors in Manning's n (n), slope, (S), particle diameter (D_{50s}) and reference shear (τ_r) for the modified PKM model and comparison to Little Turkey Creek bedload data

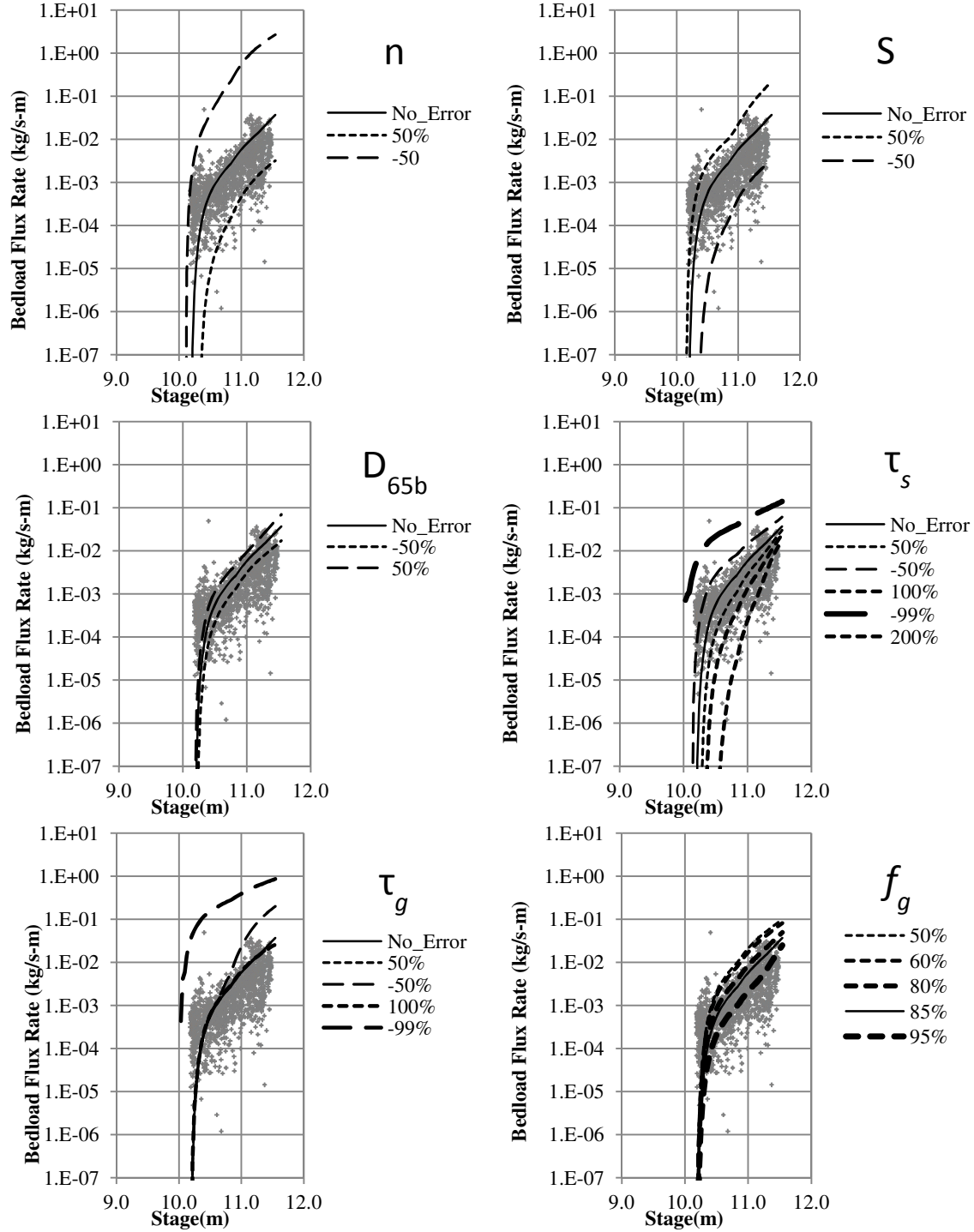


Figure IV:6 – Effect of discrete errors in Manning's n (n), slope, (S), particle diameter (D_{65b}) and reference shear for sand (τ_{rs}), reference shear for gravel (τ_{rg}), and gravel fraction (f_g) for the W98 model and comparison to Little Turkey Creek bedload data

The impact of the gravel fraction error in the W98 model appears relatively small given the variability in the bedload transport data. Note that values expressed in the plot for the gravel fraction are values of the sand fraction itself rather than variation from the known value of 15%.

Discrete Errors Discussion

The effects of discrete errors in all three of the models reviewed in this study illustrate significant general trends. All of the models are most strongly influenced by errors in the Manning's n parameter and the energy slope parameter, and all models are least sensitive to the dimension of the reference particle diameter. This suggests that the largest return on model accuracy may be obtained through rigorous field efforts to accurately define values for Manning's n and energy slope rather than reference shear stress or particle size distributions. Reference shear values may plausibly be estimated using the Meyer-Peter Muller reference shear relation for modeling purposes, and approximations of particle diameters can be made with only a small investment in field work.

3.2.1. Cumulative Variable Uncertainty

The 95% confidence intervals for model predictions of bedload transport for each model are summarized in Figure IV:7. The confidence intervals are presented for uniform levels of error in all model input parameters of 10 and 20% for the modified MPM and PKM models and for 10 and 15% for the W98 model. These results suggest that for model predictions to be considered even modestly better than a best guess, uncertainty in the input parameters for that model may be no more than a modest 20%.

This result assumes that distribution of the uncertainty of each variable is normal and that uncertainty is equal for each variable. In practice, it is plausible that the uncertainty for some variables may be nonparametric and related to the potential bias of a given field method. Further, in practice it is unlikely that each input parameter would be assigned the same level of uncertainty. However, the results of these analyses do offer some insights. In regards to robustness, the modified MPM appears to be the most resilient to uncertainty in input parameters, followed by the W98 model and the Modified PKM, as indicated by the relative range of values within the 95% confidence intervals illustrated in Figure IV:7. Further, for uniform uncertainty in input variables, the W98 model appears to have an upper limit to the 95% confidence interval that is within the range of the measured bedload transport rates. Finally, it is noted that a 10, 15 or 20% error may be considered large for input parameters that describe channel geometry, but given available field methods they are very modest for errors in parameters that describe the reference shear value, the Manning's n value, and even the energy slope value (Wilcock et al. 2008).

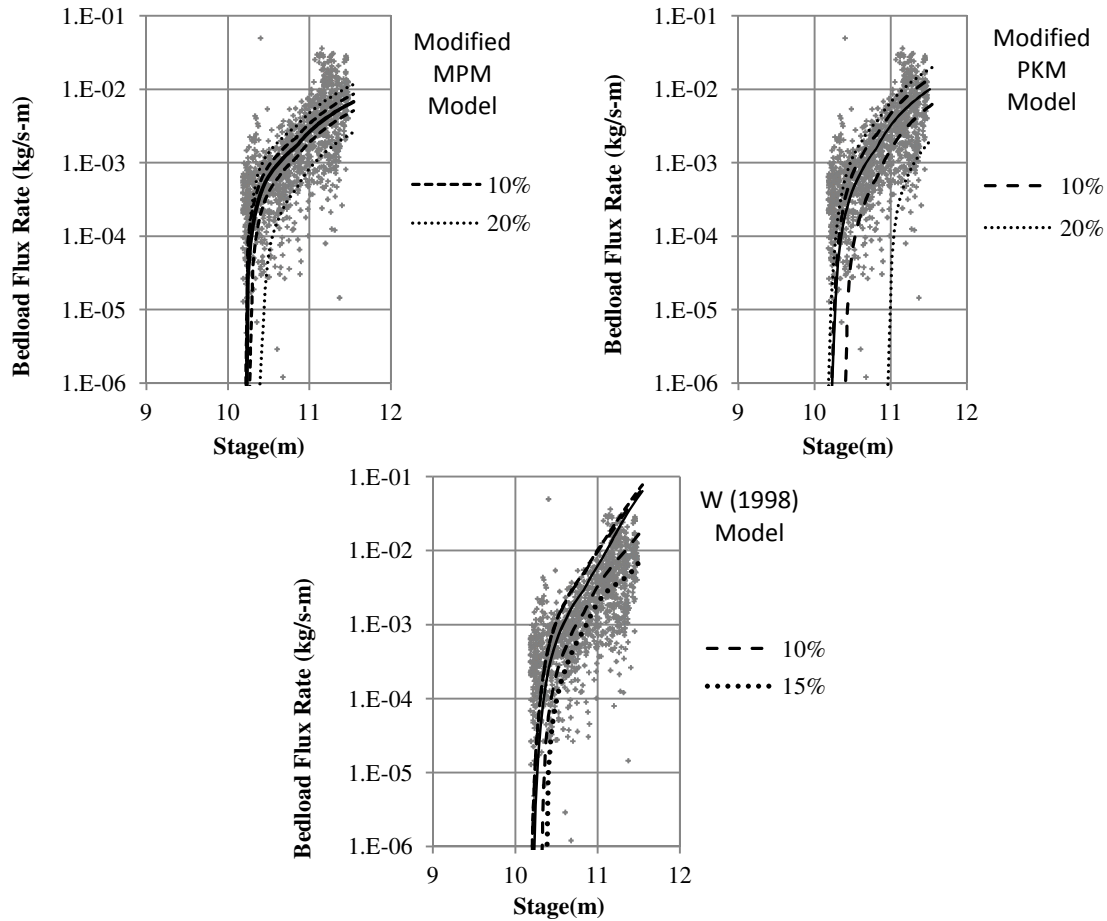


Figure IV:7 – 95% Confidence intervals for 10% and 20% uniform uncertainty in input parameters for the modified MPM and PKM models and 10% and 15% for the W98 model

4. SUMMARY

The potential quality of bedload transport estimates made using uncalibrated models is generally accepted to be very low (Bravo-Espinosa et al. 2003; Goodwin 2004; Wilcock 2001; Yang and Huang 2001). Calibration of a given bedload transport relation for a local estimate of the reference shear value provides a degree of improvement in model predictions, and in the case of the Wilcock (1998) model, is the only calibration necessary to produce bedload transport estimates that fall within measured rates at the same site. In the case of the MPM and PKM models in this study, site specific calibration of some models must be further calibrated using field measurements of bedload transport rates. For models that are anticipated to be well suited to a given site without the need to provide further calibration based on measured transport rates, great care is warranted in the selection of model input parameters. Of the most significant importance are the parameters for the Manning's n and energy slope value. Discrete errors in

these parameters greater than 50% from the true value can produce errors that are outside of even the measured maximum variability for bedload transport rates over time. This suggests that the largest return on model accuracy may be obtained through rigorous field efforts to accurately define average values for these parameters rather than conducting field studies that focus more strongly on estimating the reference shear stress or particle size distributions.

The potential impact of uniform uncertainty associated with model input parameters suggests that even modest levels of uncertainty up to 20% translate to confidence intervals for model results that can span an order of magnitude or more. Errors of this size may be considered relatively small with regard to parameters that describe channel geometry, but are rather modest for the most sensitive input parameters for the models reviewed. Finally, the results of this research suggest that the modified MPM model provides the most robust estimate for bedload transport on Little Turkey Creek. However, the W98 model is comparatively robust and did not require calibration through modification of model coefficients to achieve agreement with the bedload data collected at Little Turkey Creek.

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SUMMARY OF CHAPTERS I-IV

The work summarized in the preceding chapters include: 1) an evaluation of the collection efficiencies of the Birkbeck pit samplers used at the bedload monitoring station at Little Turkey Creek, 2) a new bedload data set characterizing the relationship between grain shear and transport rates on a Southern Appalachian Ridge and Valley stream, 3) an evaluation of the use of 20-liter pit traps for characterizing bedload particle size distributions and collecting reference shear observations for calibration of the Wilcock (1998) model, and 4) and evaluation of the effect of errors and uncertainty in selected bedload transport models with regard to the observed variation in bedload transport measurements at Little Turkey Creek.

The work presented in Chapter I provides a qualitative assessment of the pit traps collection efficiencies for the bedload monitoring station at Little turkey Creek. It also provides additional information and a new approach for other researchers to base their own pit trap efficiency assessments. The results of this research suggest that the pit traps at Little Turkey Creek, this suggests trap efficiency is at or near 100% until the traps become approximately 75% full. This result is applied in Chapter II to truncate bedload transport observations to include only those collected when the pit traps are less than or equal to 75% full. The findings are in contrast to the frequent assumption that the efficiency of pit traps is at or acceptably near 100% (Garcia et al. 2000; Hubbell 1987; Kuhnle et al. 1988; Laronne et al. 1992; Powel et al. 1998; Reid et al. 1995; Wilcock 2001).

The work presented in Chapter II provides the bedload transport research and stream restoration design community with the first dataset of this scale for bedload transport rates on a Southern Appalachian Ridge and Valley stream. This research also provides a qualitative comparison between bedload transport characteristics shown in the well-known data sets of Milhous (1973) on Oak Creek, Emmett (1976) on the East Fork River and Leopold and Emmett (1976) on the Snake and Clear Fork Rivers. These data also support the relatively recent observations of Gaeuman (2010) on the Trinity River in California suggesting that there may be a hysteresis effect in bedload transport rates during the passage of a given hydrograph. The work presented in Chapter II is applied in Chapter III to the evaluation of 20-liter pail pit samplers and Chapter IV in the evaluation of uncertainty in the selected bedload transport models.

The work presented in Chapter III provides researchers and practitioners with some bases with which to evaluate the potential use of 20-liter pail pit samplers for collection of bedload particle size distribution data and reference shear observations as suggested by Wilcock (2001) and others (Church et al. 1991; MSHA 2011; Sterling and Church 2002). Results from this study suggest that 20-liter pail samplers are capable of obtaining representative samples of bedload particle size distributions given that events are sufficiently long or intense enough to fill the pails to approximately 75% of their capacity. Further results suggest the use of the 20-liter pail samplers for the estimation of critical shear stress for sands and gravels may not produce clear results and require a significant number of observations to achieve even approximate values.

The work presented in Chapter IV illustrates the impact of error and uncertainty in the independent input parameters for slope, Manning's n , reference shear, and the particle size on the modified Meyer-Peter (1948) model, the modified Parker, Kingeman and Mclean (1982) model,

and the Wilcock (1998) model. This research shows that the slope and Manning's n are most sensitive to discrete errors with errors greater than 50% resulting in model predictions that fall outside of the observed variability in bedload transport rates collected at Little Turkey Creek. The models are markedly less sensitive to errors in the other independent input parameters in most instances. The impact of uniform uncertainty associated with model input parameters suggests that even modest levels of uncertainty up to 20% translate to 95% confidence intervals for model results that can span an order of magnitude or more. Finally, the results of this research suggest that the modified Meyer-Peter Muller model provides the most robust estimate for bedload transport on Little Turkey Creek. However, the Wilcock (1998) model is comparatively robust and did not require calibration through modification of model coefficients to achieve agreement with the bedload data collected at Little Turkey Creek.

While there may be varied applications for these findings presented in each chapter, the cumulative body of work is presented to provide stream restoration design professionals with specific background information to inform bedload transport measurements and predictions on streams in the Southern Ridge and Valley Region.

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APPENDIX

VITA

Patrick L. McMahon was born on August 24, 1979 in Chattanooga, Tennessee. He graduated from the University of Tennessee with a Bachelor of Science degree in Civil Engineering in 2004 and with a Master of Science degree in Environmental Engineering in 2005. He spent the following years working as a civil engineer in Alaska and Tennessee. In 2013, he completed the requirements for the Doctor of Philosophy in Civil Engineering from the University of Tennessee, Knoxville.