TECHNICAL MEMORANDUM

STATISTICAL EVALUATION OF TRINITY RIVER POINT BAR BED MOBILITY AND BED SCOUR DURING ANNUAL SPRING ROD RELEASES FOR WY 2009 – 2013

Prepared for:

Trinity River Restoration Program
P.O. Box 1300
Weaverville, CA 96093

Prepared by:

Hoopa Valley Tribal Fisheries Department
P.O. Box 417
Hoopa, CA 95546

Geoff Hales, Andrea Hilton, Scott McBain
McBain Associates
980 7th Street
Arcata, CA 95521

Shay Howlin
Western EcoSystems Technology, Inc.
415 W. 17th Street, Suite 200
Cheyenne, WY 82001

February 13, 2020

ABSTRACT

Bed mobility and scour are fundamental TRRP objectives for physical processes. Field-based monitoring of bed mobility and scour accurately documents bar response to annual flows, allowing comparisons with physical process management objectives in the ROD (i.e., were Trinity River Flow Evaluation bed mobility and scour objectives met in any particular water year by winter flood or ROD releases?). However, field monitoring requires annual resources and does not provide a quantitative prediction of bar mobility and scour response to various flows. Recently improved 2-D hydraulic models can be used to provide deterministic predictions of bar response, but historic application of these models has shown modest performance, and results are specific to every bar due to unique hydraulic conditions.

The objective of this analysis was to determine if a statistical model, using all bed mobility and scour data collected since 2009 across multiple WY types, could be developed to predict bed mobility and scour on point bars in the restoration reach. Statistical models were developed from a population of 111 sites with bed mobility experiments and 114 sites with bed scour experiments, to determine (a) the probability of a site having >80% bed mobility, and (b) the probability of a site achieving >1.0 D_{84} scour, across a range of flows and specific inundation zones. Results can allow managers to use predicted values, with associated confidence, to evaluate management actions relative to the predicted probability of mobility and scour, and then integrate management decisions and anticipated outcomes across disciplines.

This page intentionally left blank.

TABLE OF CONTENTS

1 Introduction.....1
2 Objective.....2
3 Approach and Methods.....2
3.1 Inundation zones.....3
3.2 Analytical Variables.....4
3.2.1 Dependent variables.....4
3.2.2 Independent variables.....7
3.3 Statistical methods.....9
3.3.1 Data included/excluded from analysis.....9
3.3.2 Summary of statistical test applied.....10
4 Results and Conclusions.....13
5 Summary and Recommendations.....21
5.1 Summary of Findings-Best Fit Models.....22
5.2 Summary of Findings-Model Performance.....22
5.3 Model Application.....22
5.4 Recommended next steps-review model performance.....23
6 References.....23

LIST OF FIGURES

Figure 1. Conceptual planform illustration of bed mobility and bed scour experiment placement....3
Figure 2. Conceptual planform illustration of marked rock and scour chain placement....................4
Figure 3. Location of bars where marked rock and scour chains were used to monitor bed mobility from WY 2009 – 2013...6
Figure 4. Illustration showing the 2m buffer area over which spatial estimates of boundary shear stress is computed from SRH-2D model computational nodes. 8
Figure 5. Predicted percentage of rocks moved, with 95% prediction interval across the range of maximum daily average flow while holding Shields parameter constant.........................14
Figure 6. Predicted average relative scour, with 95% prediction interval, across the range of maximum daily average flow 15
Figure 7. Predicted percentage of rocks moved, with 95% prediction interval across the range of Shields parameter while holding maximum daily average flow constant.........................17
Figure 8. Predicted probability of sites exhibiting greater than or equal to 80% mobility, with 95% prediction interval, across the range of maximum daily average flow 18
Figure 9. Predicted probability of sites exhibiting greater than or equal to 1 relative scour, with 95% prediction interval, across the range of maximum daily average flow....................19

LIST OF TABLES

Table 1. Flow related geomorphic peak releases and duration, with water year class and management objectives related to bed mobility and scour 1

Table 2. Summary of bed mobility and bed scour experiments conducted during the Spring ROD release, WY 2009 –2013........ 5

Table 3. Summary of variables used in the statistical analysis........ 5

Table 4. Sample size for each model after data exclusion........ 10

Table 5. Response, predictor variables, and random effects with respective units........ 12

Table 7. The results of the best fit models for percent rocks moved and average relative scour over the three inundation zones. 14

Table 8. AIC statistics and ranking for top mobility and scour models parameterized as binary outcomes........ 16

Table 9. The results of the best fit models for the binary outcomes of mobility and scour over the three inundation zones.. 17

Table 10. Mobility model predictions at maximum daily average flows across the range of flows observed during the experiment with 95% confidence interval for each of the inundation zone........ 20

Table 11. Scour model predictions at maximum instantaneous flow or maximum daily average flow across the range of flows observed during the experiment........ 21

1 INTRODUCTION

Bed mobility and scour of alluvial bar surfaces between Lewiston Dam and the North Fork Trinity River (restoration reach) are objectives of the Record of Decision (ROD) flows and are essential processes to restoring a scaled-down, dynamic alluvial channel as required by the ROD (DOI 2,000). Bed mobility and scour monitoring has been conducted since 1991 to evaluate geomorphic effectiveness as a function of peak flow in the restoration reach, including relationships between flow magnitude, shear stress, and bed mobility and scour (e.g., Wilcock 1992; Wilcock et al. 1995; Hales 1999; May et al. 2009). While these analyses showed encouraging relationships, results were largely site-specific and their applicability as a predictive management tool for the restoration reach was limited due to small sample sizes (few observations and/or few study sites) and a narrow range of monitoring flow events, and hydraulic models that were of poorer resolution than is available now.

Since 2006, bed mobility and scour experiments have been used to evaluate whether annual ROD flow releases are achieving corresponding bed mobility and scour objectives for each of five designated water year (WY) types (Table 1). In 2009, the Trinity River Restoration Program (TRRP) initiated a monitoring framework (Integrated Assessment Plan, or IAP) that included bed mobility and scour monitoring as well as fisheries, vegetation, and additional geomorphic monitoring. Bed mobility and bed scour monitoring continued under this framework through 2014.

Until now, 2009 – 2014 bed mobility and bed scour reporting has been limited to data summaries from annual monitoring (e.g., McBain & Trush and HVT 2012, 2013, 2014 and McBain Associates and HVT 2014). While these annual reports have been successful at evaluating whether bed mobility and scour objectives specific to each water year type were met, results were evaluated only within the context of their respective water year class and not evaluated inter-annually.

Table 1. Flow related geomorphic peak releases and duration, with water year class and management objectives related to bed mobility and scour (from USFWS and HVT 1999).

Water Year Type	Peak Release (cfs)	Duration (days)	Bed Mobility and Scour Objectives
Critically Dry	1,500	36	None
Dry	4,500	5	Channelbed surface mobilization of in-channel alluvial features (e.g. spawning gravel deposits)
Normal	6,000	5	Mobilization of matrix particles (D_{84})* on general channelbed surfaces and along flanks of alternate bar surfaces Channel bed scour greater and redeposition of gravels
Wet	8,500	5	Mobilization of matrix particles (D_{84}) on alternate bar surfaces Channelbed scour greater than 1 D_{84} depth and redeposition of gravels on face of alternate bars
Extremely Wet	11,000	5	Mobilization of matrix particles (D_{84}) on alternate bar surfaces Channelbed scour greater than 2 D_{84} depth and redeposition of gravels on face of alternate bars

*D_{84} is the particle size in a cumulative distribution for which 84 percent is finer. This is a common particle size used in sediment transport equations and is commonly assumed to represent the alluvial “framework”.

More advanced hydraulic models than those used in previous studies (e.g., May et al. 2009) are now available, which can be used to improve bed mobility and scour predictions in the restoration reach and provide deterministic predictions of bar response. This analysis uses output from the most current Trinity River hydraulic model, combined with the large amount of available empirical bed mobility and scour data, to investigate whether a statistical model can be developed to predict systemic or reach-specific bed mobility and scour. Such a predictive model would provide an important tool for future flow management and for the TRRP's Decision Support System (DSS) effort.

2 OBJECTIVE

The objective of this analysis is to determine if a statistical model, using data collected from WY 2009 through WY 2013, can be developed to predict bed mobility and scour on point bars in the restoration reach during the annual Spring ROD release.

3 APPROACH AND METHODS

Beginning in WY 2006, paired measurements of bed mobility and scour data were collected through annual monitoring within the restoration reach. Starting in WY 2010, a Generalized Random Tessellation Stratified (GRTS) sampling protocol was adopted by the TRRP to select monitoring sites, which was applied to annual bed mobility and scour data collection through 2014. Although post-ROD bed scour and mobility data collection began in 2006, this analysis uses only data obtained from WY 2009 – 2013. Data prior to 2009 were excluded due to sampling inconsistencies, and 2014 (Critically Dry) results were excluded because similar results for Dry WYs (2009 and 2013) were already well represented in the data population. WY 2014 results showed no mobility or scour for all experiments, and it was determined that including WY 2014 results would not contribute to or otherwise strengthen the model's prediction of mobility thresholds.

To determine if an acceptably accurate bed mobility and scour model can be developed using the empirical data, bed mobility and scour data (dependent variables) from WY 2009 – 2013 were evaluated relative to several independent variables, including geomorphic reach type, streamflow, cross sectional average boundary shear stress, and Shields parameter. Next, statistical modeling was performed to evaluate if single variables or covariates accurately predict bed mobility and scour. Modeling was performed using bed mobility and scour results from three different portions of bar surfaces, described in Section 3.1.

Bed mobility and scour experiments were installed and monitored using a consistent methodology across all sites. Bed mobility was monitored using painted tracer rock sets and bed scour was monitored with scour chains. Bed mobility was measured using groups of individually-labeled, brightly-marked tracer rock sets installed along the cross sections. Each group contained sets of two sizes of rocks, representing D_{50} and D_{84} size classes determined by measuring the substrate particle size distribution, where the D_{50} and the D_{84} represent the median and the 84^{th} percentile grain size, respectively. D_{50} and D_{84} pairs were set at regular intervals along each monitoring cross section spanning the exposed bar surface and extending into the low-water channel (Figure 1). Where placed, each tracer rock was set on the bed surface so that its exposure mimicked that of the surrounding rocks by removing a similar sized rock from the bed and setting the tracer rock in its place. This technique allowed the tracer rocks to reasonably approximate natural bed surface conditions and avoid unnatural over- or under-exposure. The cross sections were revisited to determine which tracer rocks moved following peak flow events.

Bed scour and deposition was measured using scour chains installed on each cross section. Scour chains were placed within or adjacent to the tracer rock sets. Each scour chain consisted of a 15 mm-link brass chain, a duckbill-type earth anchor affixed on one end, and a stainless steel nut affixed to the other end to aid in relocation. The chain was driven vertically into the channel substrate to a minimum depth of approximately 0.6 m, and a short (10 – 30 cm) length of chain was left lying flat on the bed surface. To measure scour and deposition, the chain location was reoccupied, its elevation surveyed, and the bed surface carefully excavated by hand until the chain was found. Differences in pre-and post-high flow chain length and changes in surveyed bed surface elevations documented scour and deposition depths.

A full description of bed mobility and scour experiments, including field and analytical methods, are detailed in annual data reports for WY 2009 – 2013 (McBain & Trush and HVT 2012, 2013, 2014, McBain Associates and HVT 2014).

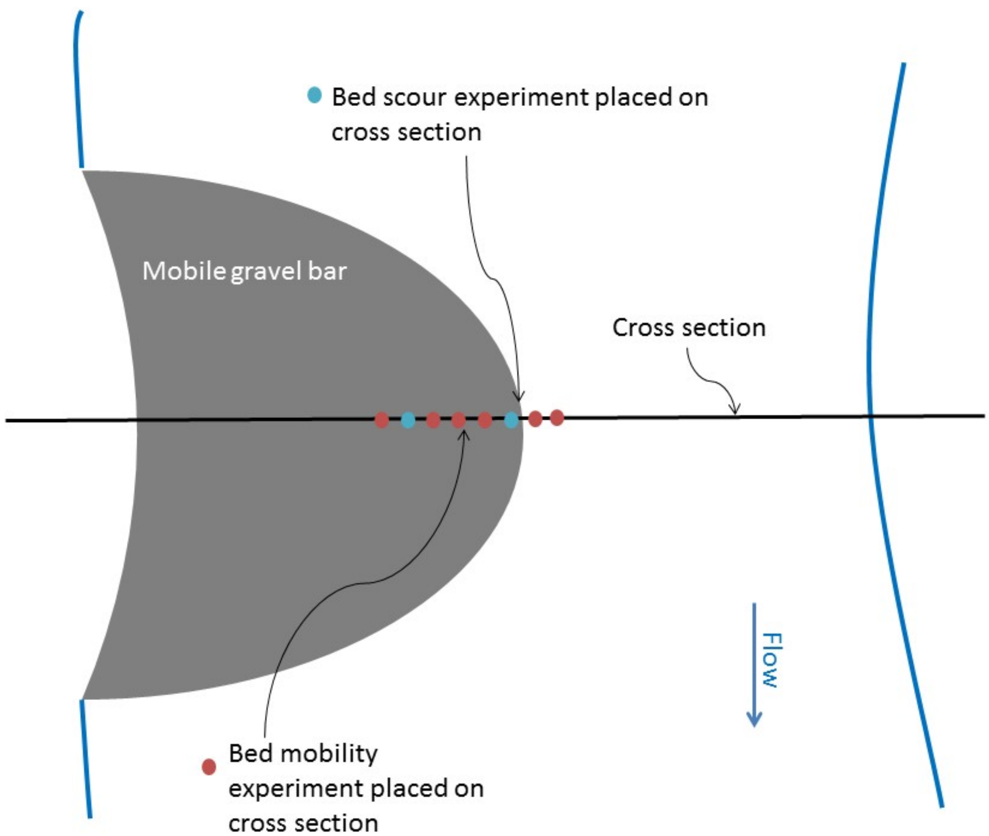

Figure 1. Conceptual planform illustration of bed mobility and bed scour experiment placement across a gravel bar. Bed mobility experiment (marked rocks) shown in orange, bed scour experiments (scour chains) shown in blue, co-located with marked rocks.

3.1 Inundation zones

Past annual monitoring reports presented bed mobility and scour results in two ways: (1) for the total experiment (number of rocks moved relative to the total number of rocks in the experiment), and (2) as a subset of the total experiment specific to the portion of the bar that was located within the 450 cfs to 2,000 cfs zone, called the "riparian encroachment risk zone" (McBain & Trush and HVT 2012, 2013, 2014 and McBain Associates and HVT 2014). This 450 – 2,000 cfs subset was reported to support riparian vegetation work being conducted concurrently at these monitoring sites to evaluate whether specific riparian scour objectives were being met. For this analysis, results include the total experiment and 450 – 2,000 cfs inundation zone (as per previous annual reports), as well as a third range that narrows results to the 450 – 1,000 cfs zone (Figure 2).

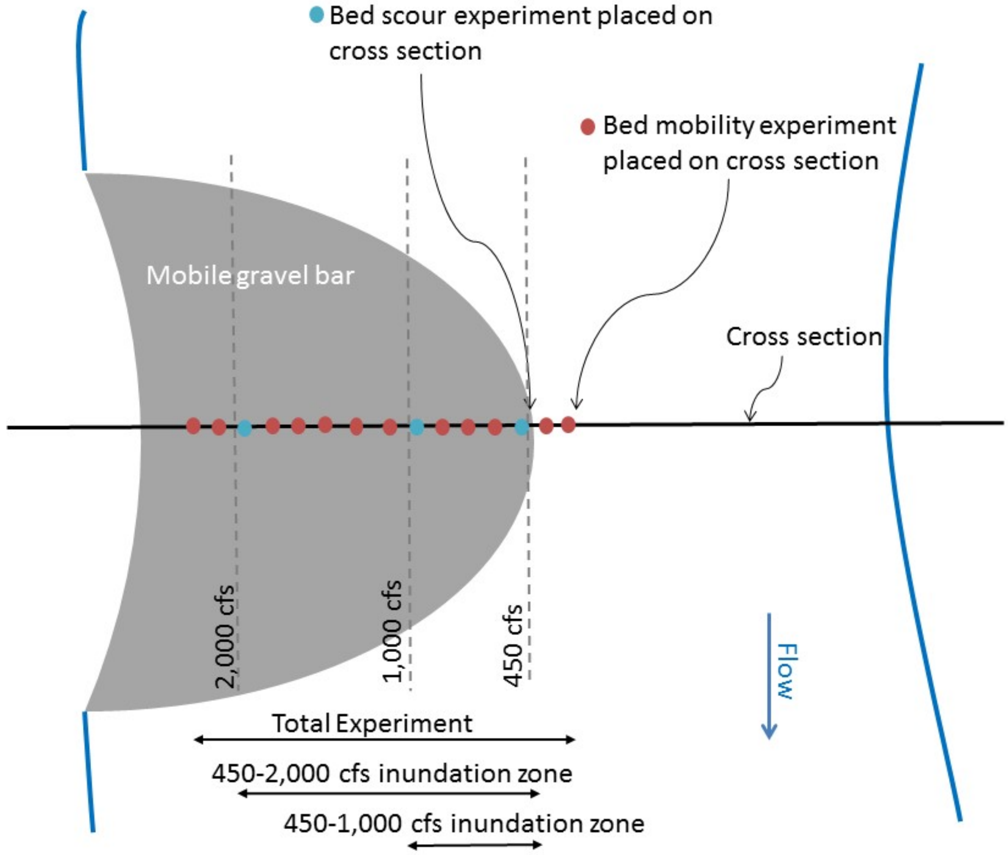

Figure 2. Conceptual planform illustration of marked rock and scour chain placement across a bar, showing the three inundation zones evaluated for mobility: (1) "Total experiment" for when the bar is completely submerged, (2) the portion of the experiment between the 450 cfs and 2,000 cfs inundation zone, and (3) the portion of the experiment between the 450 cfs and 1,000 cfs inundation zone.

3.2 Analytical Variables

The dependent variables for this analysis are bed mobility and bed scour, which have data available for 111 and 114 sites, respectively (Table 2 and Figure 3). Independent variables include maximum daily average streamflow, maximum 15-minute instantaneous streamflow, shear stress, and Shields parameter (Table 3). Data were further stratified by geomorphic feature type (point bar, medial bar, or island). In addition, maximum daily average streamflow and maximum instantaneous streamflow were distinct variables in the model. Shear stress (and thus Shields parameter) was computed using maximum daily average streamflow.

3.2.1 Dependent variables

Dependent variables in the statistical analysis are bed mobility and scour on bar features, as measured in the three inundation zones.

3.2.1.1 Bed mobility

Bed mobility results are based on the percentage of rocks within each experiment that moved. These results have historically been presented in Trinity River annual monitoring reports as one of three classifications: no mobility (< 20% tracer rocks moved), partial mobility (20-80% moved), and full mobility (> 80% moved) (M&T and HVT 2012, M&T and HVT 2013, M&T and HVT

2014, McBain Associates and HVT 2014). For this analysis, bed mobility results were simplified to a binary outcome, where statistical modeling placed results into either “no mobility” or “partial mobility” categories. As part of the analysis, the outcome was assigned a “1” if the mobility percentage was greater than or equal to 80%, and a “0” if the mobility percentage was less than 80% (additional discussion in Section 3.3.2). The use of a binary outcome to differentiate sites that are fully mobile is potentially more useful to TRRP managers compared to the prior three-category designation used in the 2009 – 2013 annual monitoring reports (meeting objectives can be assessed as a yes or no answer). In addition, if the percentage of tracer rocks that moved in either the 450 cfs to 1,000 cfs or 450 cfs to 2,000 cfs inundation zones contained less than 80% of the tracer rocks used in the total experiment, results were excluded due to insufficient experiment coverage.

Table 2. Summary of bed mobility and bed scour experiments conducted during the Spring ROD release, WY 2009 –2013. Bed mobility and scour experiments are co-located, but in some cases, results are available for only a single experiment. The maximum daily streamflow at Trinity River at Lewiston (USGS 11-525500) and the Trinity River above the North Fork (USGS 11-526400) indicate the range of flows experienced at monitoring sites during the ROD release due to tributary accretion.

Water year	**Water year type**	**Maximum daily average ROD release at USGS Trinity River at Lewiston (cfs)**	**Maximum daily average streamflow at USGS Trinity River Above North Fork Trinity River (cfs)**	**Number of sites with bed mobility experiment results**	**Number of sites with bed scour experiment results**
2009	Dry	4,410	7,120	8	3
2010	Normal	6,440	7,710	12	14
2011	Wet[1]	11,600	12,000	35	36
2012	Normal	6,080	6,770	32	36
2013	Dry	4,420	4,670	24	25
			Total:	**111**	**114**

[1]Although 2011 was a Wet water year, the annual ROD hydrograph had a peak release with a planned duration similar to an Extremely Wet water year, albeit with a shorter duration (three versus five days).

Table 3. Summary of variables used in the statistical analysis.

Variable	**Independent or dependent**
Bed mobility in a given inundation zone on bar	Dependent
Bed scour at a particular location on bar	Dependent
Maximum daily average flow at monitoring site	Independent
Maximum instantaneous peak flow at monitoring site	Independent
Average shear stress over the experiment	Independent
Computed Shields parameter over the inundation zone	Independent

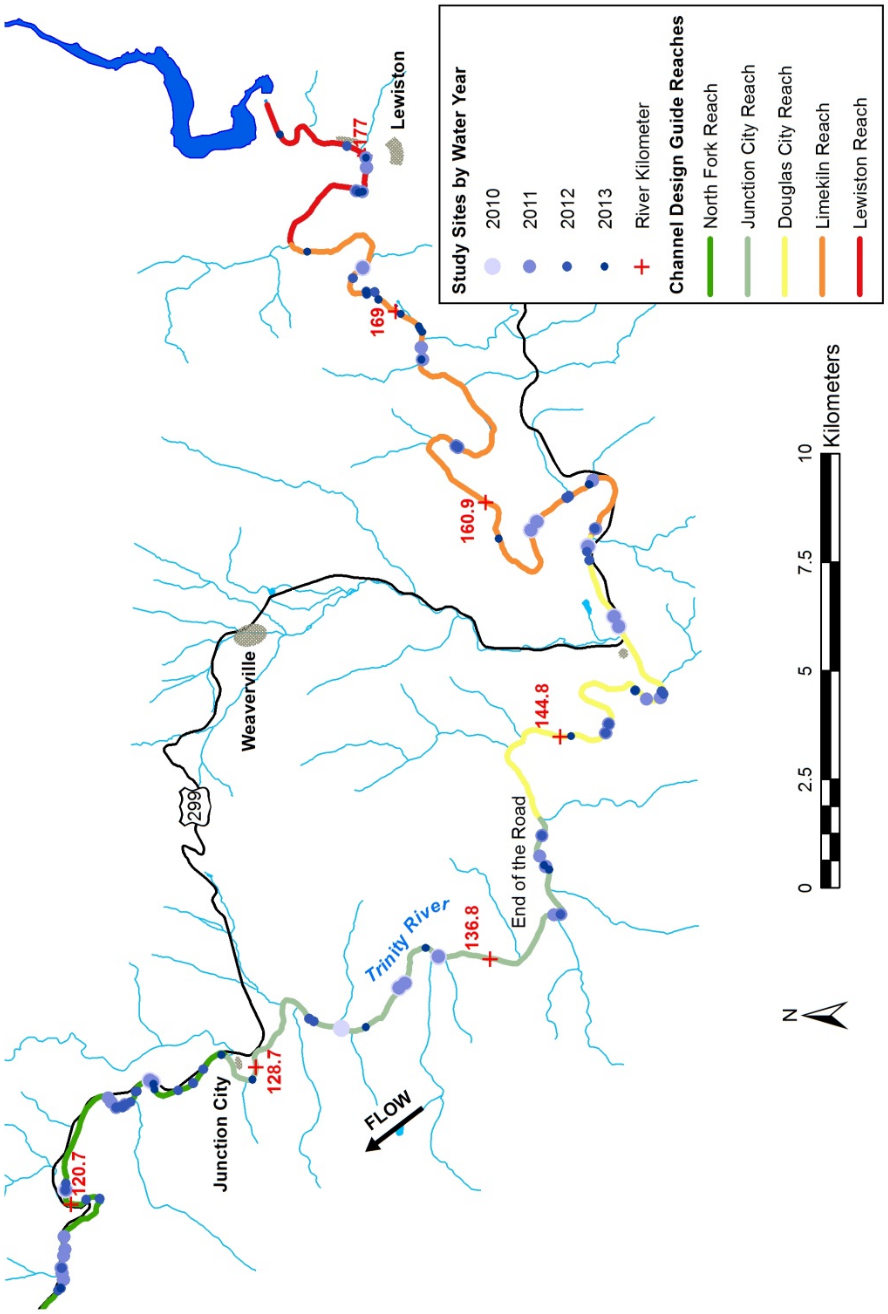

Figure 3. Location of bars where marked rock and scour chains were used to monitor bed mobility from WY 2009 – 2013. Colored river lines indicate Trinity River geomorphic reaches established in the Channel Design Guide (HVT et al. 2011).

3.2.1.2 Bed scour

Results are reported as both actual scour depth and relative scour, which is a dimensionless ratio defined as scour depth/D_{84}. Historically results have been grouped into one of three categories: <1.0, 1.0 to 2.0, or >2.0, which correspond directly to ROD scour objectives (M&T and HVT 2012, M&T and HVT 2013, M&T and HVT 2014, McBain Associates and HVT 2014). Similar to the bed mobility results, bed scour data for this analysis was assigned a binary value, where 1.0 indicated the average scour depth was ≥1.0 and ”0” if < 1.0. (additional discussion in Section 3.3.2).

3.2.2 Independent variables

Independent variables include boundary shear stress, Shields parameter, and streamflow (maximum daily average and maximum instantaneous peak). The value for each independent variable, with the exception of shear stress, was considered to be representative across all three inundation zones and thus the same value was used (Figure 2). For shear stress, values were computed by inundation zone.

3.2.2.1 Boundary shear stress

At cross sections where bed mobility and scour were monitored, local boundary shear stress was estimated using the most recent TRRP SRH-2D hydraulic model (Bradley 2018). This was done by establishing an area around the experiment from which a representative shear stress can be assumed. An area was defined using the total experiment width along the monitoring cross section and extending a zone 1 m up- and downstream, thereby creating a 2 m “buffer” (Figure 4). The 2 m buffer was chosen to account for inherent natural hydraulic variability to offset potential error resulting from averaging predicted shear stress only along the monitoring cross section. The 2 m buffer is assumed to provide a representative boundary shear stress at a scale that reduces local variability but is also representative of the overall experiment.

For each experiment, SRH-2D shear stress values were extracted from within the buffer and then averaged to generate a single shear stress value at each experiment. This was done for a range of modeled index streamflows: 1,500 cfs, 2,500 cfs, 4,500 cfs, 5,500 cfs, 6,000 cfs, 8,500 cfs, 11,000 cfs, and 14,000 cfs (these index flows were selected because they coincide with available SRH-2D model results). Linear interpolation was used to determine the average shear stress value that corresponded with the site-specific maximum daily average streamflow from which bed mobility and scour result was reported. The same shear stress value was used for each of the three inundation zones analyzed (i.e., shear stress was not further segregated into distinct values for the different inundation zones).

The SRH-2D hydraulic model was developed using 2016 channel topography, however the bed mobility and scour results were from 2009 – 2013. This temporal separation creates a limitation on combining these data for comparison (i.e., comparing shear stress results based on 2016 site topography with empirical mobility and scour data from 3 to 7 years prior). Error is introduced if topographic changes occurred from the time the experiment was monitored to when the topography was collected for the hydraulic model. To reduce this error potential, experiment cross sections were reviewed individually for geomorphic changes. Several sites were identified that had experienced significant morphological change over the experiment zone between their monitoring date and 2016. For example, in some instances, the channel had migrated such that the experiment location in 2016 was completely wetted and below 450 cfs. In other cases, channel rehabilitation construction had entirely reworked the channel topography. Based on the case by case review, 26 sites were removed from the data set due to what were determined to be significant topography differences.

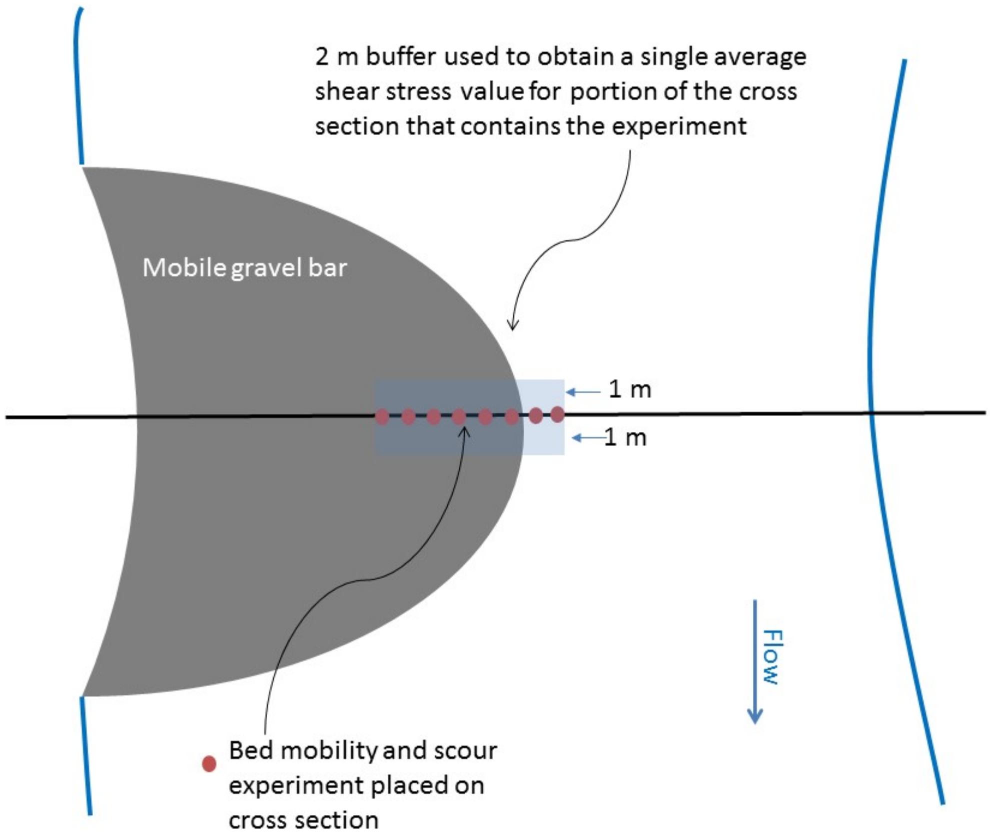

Figure 4. Illustration showing the 2m buffer area over which spatial estimates of boundary shear stress is computed from SRH-2D model computational nodes (Bradley 2018). Model results from within the buffer are averaged to generate a single average shear stress value for each inundation zone across the cross section for each index flow.

3.2.2.2 Shields parameter

Shields parameter (τ^*) is a dimensionless ratio of the modeled hydraulic mobility force to the particle resisting force:

$$\tau^* \approx \frac{\text{mobility force}}{\text{grain resisting force}}$$

which can be expressed as the following equation:

$$\tau^*_{D_{84}} = \frac{\tau_b}{(\rho_s - \rho_w) g D_{84}}$$ *Equation 1*

Where:

τ^*_{D84} = Shields parameter for the D_{84} particle size;

τ_b = average boundary shear stress (Pa), obtained from SRH-2D hydraulic model (Bradley 2018) computed as a single averaged value within the 2 m buffer surrounding each experiment;

ρ_s = sediment density (2,800 kg/m^3, from Hales 1999);

ρ_w = water density (1,000 kg/m^3 at 0^{o}C)

g = gravitational acceleration (9.81 m/sec^2);

D_{84} = particle diameter in a cumulative distribution of which 84% is finer. A weighted average particle size was used where experiments spanned multiple facies and more than one D_{84} size was used for monitoring.

Using Equation 1, a single Shields parameter value was computed for each experiment. Bed mobility and bed scour results were evaluated relative to these computed Shields parameter values.

3.2.2.3 Maximum daily average and instantaneous streamflow at the site

Maximum daily average streamflow and maximum instantaneous streamflow was computed for each site using published USGS records for the gage nearest the site during the water year which the experiment occurred, as reported in annual monitoring reports (McBain & Trush and HVT 2012, 2013, 2014 and McBain Associates & HVT 2014). Flow estimates for each monitoring site were calculated using the closest upstream USGS mainstem gaging station and included flow from tributary gaging stations where applicable; no additional adjustments were made to scale flows from the gaging stations to the monitoring sites (e.g., by using drainage area accretion estimates).

3.3 Statistical methods

The objective of statistical models is to develop the best statistical relationships between model output (dependent variables) and primary driving variables (independent variables). Based on observed data, the statistical analysis followed the following steps:

1. Review data that should be excluded from analysis due to sampling differences, different geomorphic units, or other logical factors;
2. Explore best fit models to identify which independent variables explained more variance observed in dependent variables; and
3. Develop statistical models between these primary independent and dependent variables.

The following sections summarize the methods used for these three steps.

3.3.1 Data included/excluded from analysis

To reduce variance associated with differing bar features, observations associated with the “medial bar” or “island” geomorphic feature types were removed, and only observations associated with the “point bar” geomorphic feature type were used, which represented the majority (92 percent) of all experiments.

Although each monitoring cross section contained 2-5 scour chains, relative scour results were averaged over each individual cross section for a given year and inundation zone. By averaging scour, the dataset was limited to one response for each cross section and year combination. This step was consistent with treating the GRTS site as the sample unit in the analysis and ensured independence in the data. Data from the scour analysis which had D_{84} values that were less than 20 mm (n=6) were also excluded; these represent locations where scour chains were set in a predominantly sandy matrix, where likely preferential scouring resulted in in abnormally high relative scour values that added excessive variance to the results.

The modeling process removes observations from model fitting if a given observation does not contain data for the response or any of the predictor variables. This results in smaller sample sizes than the raw dataset if there are missing data for the responses or predictors. The sample sizes for scour are also variable depending on the inundation zone considered (Table 4).

Table 4. Sample size for each model after data exclusion.

Model and inundation zone	Sample size (n)
Mobility: total experiment	74
Mobility: 450-2,000 cfs inundation zone	70
Mobility: 450-1,000 cfs inundation zone	66
Scour: total experiment	72
Scour: 450-2,000 cfs inundation zone	61
Scour: 450-1,000 cfs inundation zone	38

3.3.2 Summary of statistical test applied

General and generalized linear mixed models (GLMMs; Zuur et al. 2009) were used to analyze mobility and scour data. The models contained a combination of fixed and random effects, with the random effects of monitoring site and water year incorporated to account for these sources of random variability. GLMM models allow a response that does not exhibit a normal distribution to be related to a linear combination of a set of predictor variables. Mobility at a site was initially modelled as a binomial probability with the number of rocks moved per the number of rocks set in the experiment as the response. A GLMM was fit with a binomial distribution to the mobility and predicted the percentage of rocks moved. Relative scour at a site was initially modelled as a normally distributed random variable, with the distributional assumptions improved after a log transformation of the relative scour values. A general linear mixed model was fit to the log transformed values and predicted average scour after exponentiation of the model predictions. Averages over multiple scour experiments were made to ensure assumptions of independence were met.

After initial modeling efforts for both scour and mobility, the response was converted to follow a binomial distribution. This change allowed users to interpret the model results as the probability of a site being mobile or scoured, or the number of sites that are mobile or scoured for a given experiment. For both mobility and scour to be modelled this way, thresholds were defined to characterize sites as mobile and scoured (discussed in Section 3.2.1). A binary outcome was developed for mobility by assigning a one if the percent of rocks moved at a given inundation zone and year was equal to, or greater than, eighty percent (≥80%), and a zero if the number of rocks moved was less than eighty percent (≤80%). The percent of rocks moved was determined by dividing the number of D_{84} rocks moved by the total number of rocks along a given cross section within a given inundation zone.

For bed scour, a binary outcome of one was assigned if the average relative scour for a location was ≥ 1.0 and a zero if average relative scour was < 1.0. Because the binomial model does not allow for a third outcome, average relative scour > 2.0 was simply lumped in with the >1.0 (i.e., not analyzed separately). We did investigate the possibility of an additional model that split the binary outcome at a 2.0 threshold, but the high number of zero values precluded the model from convergence when fit with the independent variables.

A GLMM with a binomial distribution was fit to each of the binary mobility and scour responses in separate models. Due to the large range of values among the independent variables, each independent variable was standardized to a normal variate prior to modeling. A logit linking function was used to relate the linear predictors to each response (Equation 2). The inverse function was determined to transform the predictions from the fitted models to values that fell within the (0,1) bounds of the binomial distribution (Equation 3). These predictions can be interpreted as the probability of a site achieving a given response level. For mobility, the prediction represents the probability of a site achieving at least 80% mobility, while for relative scour the prediction represents the probability of a site achieving scour of at least 1.0. If the predictions were multiplied by one hundred, the response can be interpreted as the proportion of sites that will achieve a given response level.

$$ln\left(\frac{\mu_i}{1-\mu_i}\right) = X_i\beta = \eta_i$$ *Equation 2*

where μ_i is the expected value of the response, X_i are the predictors associated with the i^{th} site, β is the vector of fixed effect regression coefficients for the GLMM.

$$\mu_i = \frac{exp(\eta_i)}{1+exp\ (\eta_i)}$$ *Equation 3*

where η_i is the linear predictor defined above as a function of predictor variables and regression coefficients. Predictions were graphed across the range of the independent variable, while holding all other variables in the model constant.

Separate models were developed for each of three inundation zones: 450 cfs to 1,000 cfs inundation zone, 450 cfs to 2,000 cfs inundation zone, and the total experiment for both mobility and scour. R statistical software (R Core Team, 2013) was used for all data management and statistical analyses.

There were five explanatory variables identified as potentially impacting either mobility or scour and two random effects (Table 5). A model selection process was conducted to determine which combination of variables was most useful in predicting the response. A final model was selected by comparing the model covariates that yielded a model with the lowest Akaike Information Criterion value (AIC, Burnham and Anderson 2003). The AIC method assesses the quality of a statistical model by considering both the fit of the model and the number of covariates in the model. More specifically, AIC represents the best fit given the number of parameters in the model. Since log likelihoods are maximized during fit, and the AIC is derived from the residual log likelihood, the lower numbers indicate a better fit. Pairwise correlation coefficients were calculated to determine if any of the variables were correlated with one another and did not allow highly correlated variables to enter the model together. As expected, maximum daily average flow (MDAF) and maximum instantaneous peak flow (IPF) were very highly correlated with one another (correlation coefficient > 0.99), as was shear stress (SS) and Shields parameter (LSP) (correlation coefficient = 0.71). The discrete categorization of water year was correlated with MDAF and IPF as can be seen in figures of flow variables color-coded by year (e.g. Figure 5). The model selection process using the information theoretic approach guided the inclusion of the random effects that were most likely given the data.

Table 5. Response, predictor variables, and random effects with respective units.

Variable	Type	Units
Bed mobility	Response	# of D_{84} rocks moved*
Bed scour	Response	Scour (mm) / D_{84} (mm)*
Maximum daily average flow	Predictor	Cubic feet per second (cfs)
Maximum instantaneous peak flow	Predictor	Cubic feet per second (cfs)
Shear stress	Predictor	Pascal (pa)
Shields parameter	Predictor	Dimensionless
Distance from dam	Predictor	Kilometer
Water year	Random effect	Year
Monitoring Site	Random effect	Dimensionless

*Variables modified as described in Statistical methods section

After identifying the best fit models, predictions across the range of the covariates in the models were estimated. This analysis provided a graphical display of the modelled relationship between the predictor variables and the response. In addition to the covariates in the best fit models, response functions were developed for mobility and scour when shear stress and Shields parameter were included in the model. The 95% confidence intervals for the response functions were developed through a normal approximation with the fixed effect standard error. Overdispersion was evaluated for the top models using a ratio of the sum of the squared residuals to the residual degrees of freedom (McCullaugh and Nelder 1989). All models presented have a ratio of near or below 1, indicating no overdispersion issues in the model fit.

4 RESULTS AND CONCLUSIONS

Initial statistical modeling of mobility and scour indicated maximum daily average flow to be the most important predictor variable (Table 7). Maximum daily average flow was a statistically significant predictor, at the alpha equal to 0.01 level of significance, in all six models for mobility and scour in each inundation zone. In addition, each of the six models exhibited a lower AIC than a random intercepts model, indicating a parsimonious selection of covariates. Consistent with expectations, all of the regression coefficients on flow were positive (Table 7), indicating a positive curvilinear relationship between flow and each response. The model results indicate increased flows were associated with a larger percentage of rocks moved and higher average relative scour across all three inundation zones. All models exhibited a positive slope for mobility (Figure 5) and scour (Figure 6) across the flow variables in the model.

Table 6. AIC statistic and ranking for top mobility and scour models as originally parameterized. Models with the lowest AIC were selected for presentation. DeltaAICc gives an indication of how far a model is from the top model based on the AIC statistic.

Inundation Zone	Rank	Model	AICc	deltaAICc
Percent of Rocks Moved				
Total Experiment	1	Shields Param. + Max. daily avg. flow + Site	398.25	0.00
	2	Shields Param. + Max. daily avg. flow + RiverKM + Site	400.30	2.05
	3	Shields Param. + Inst. peak flow + RiverKM + Site	405.35	7.10
450-2,000 cfs	1	Shields Param. + Max. daily avg. flow + Site	264.39	0.00
	2	Shields Param. + Max. daily avg. flow + RiverKM + Site	266.23	1.83
	3	Shields Param. + Inst. peak flow + Site	267.24	2.85
450-1000 cfs	1	Max. daily avg. flow + Site	164.92	0.00
	2	Shields Param. + Max. daily avg. flow + Site	165.30	0.37
	3	Shields Param. + Max. daily avg. flow + RiverKM + Site	165.47	0.55
Average Scour >1 *D84*				
Total Experiment	1	Max. daily avg. flow + Site	185.21	0.00
	2	Shields Param. + Max. daily avg. flow + Site	186.21	1.01
	3	Inst. peak flow + Site	187.13	1.92
450-2,000 cfs	1	Max. daily avg. flow + Site	207.92	0.00
	2	Inst. peak flow + Site	208.63	0.72
	3	Shear stress + Max. daily avg. flow + Site	209.9	1.98
450-1000 cfs	1	Max. daily avg. flow + Site	126.13	0.00
	2	Inst. peak flow + Site	126.18	0.05
	3	Max. daily avg. flow + RiverKM + Site	128.55	2.42

Table 7. The results of the best fit models for percent rocks moved and average relative scour over the three inundation zones. The significance level of each covariate is demonstrated by the asterisks next to the covariate. The absence of an asterisk indicates that the covariate was not significant at an alpha level of 0.05.

Model and inundation zone	**Intercept**	**Maximum daily average flow**	**Shields Parameter**
Mobility: total experiment	0.986 ***	1.465 ***	0.902 ***
Mobility: 450-2,000 cfs	0.582	2.018 ***	0.571 *
Mobility: 450-1000 cfs	1.729 ***	2.149 ***	---
Scour: total experiment	0.734 ***	0.553 ***	---
Scour: 450-2,000 cfs	0.729 ***	0.568 ***	---
Scour: 450-1000 cfs	0.742 **	0.373 *	---

Significance codes: '***' 0.001 '**' 0.01 '*' 0.05

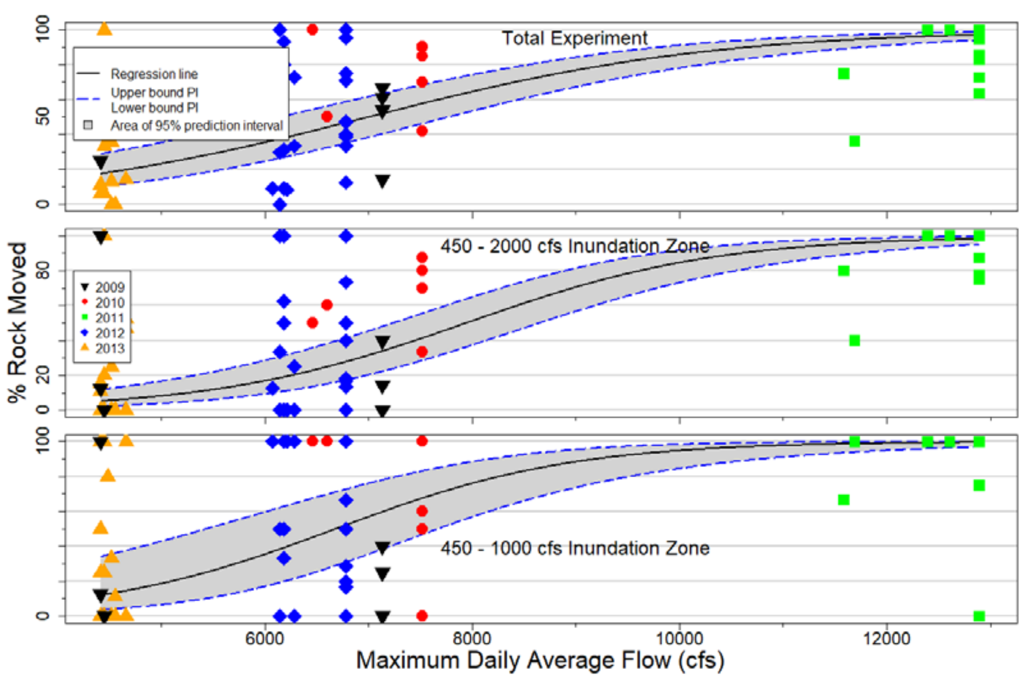

Figure 5. Predicted percentage of rocks moved, with 95% prediction interval across the range of maximum daily average flow while holding Shields parameter constant. Data used to fit the model is color-coded by year. As an example, the predicted percentage of rocks moved when the maximum daily average flow was 8,500 cfs is 71% for the total experiment (95% prediction interval was 61 to 80%). Recall that for statistical modeling, results are converted to follow a binary outcome with 80% representing the total mobility threshold (please see Section 3.3.2 for more detailed discussion).

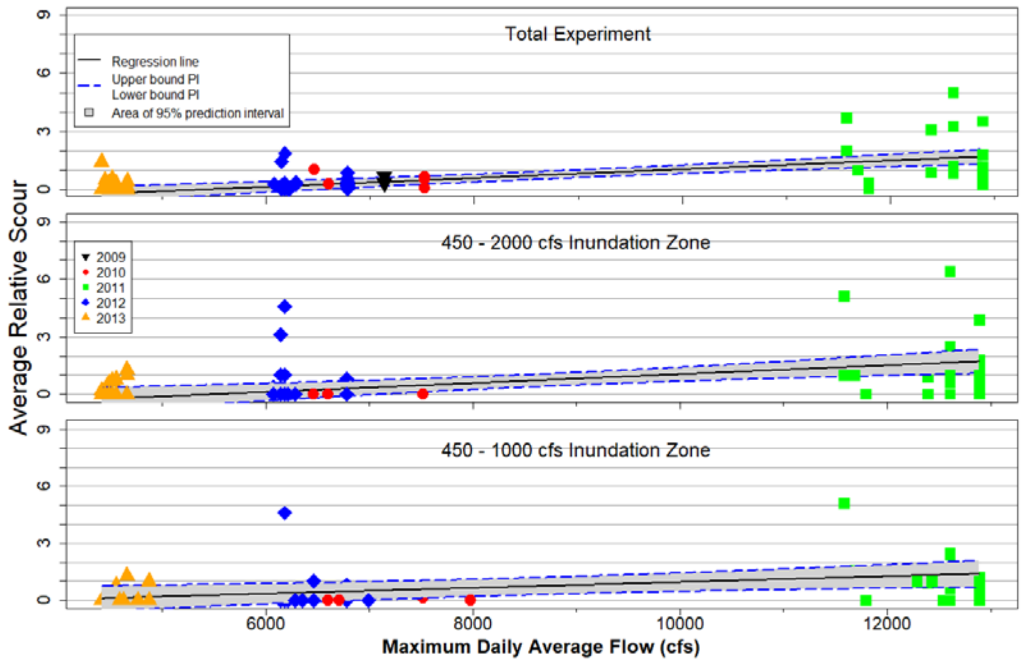

Figure 6. Predicted average relative scour, with 95% prediction interval, across the range of maximum daily average flow. Data used to fit the model is color-coded by year. As an example, the predicted average relative scour when the maximum daily average flow was 8,500 cfs is 0.70 for the total experiment (95% prediction interval was 0.50 to 0.90). Recall that for statistical modeling, results are converted to follow a binary outcome (one was assigned if the average relative scour for a location was ≥ 1.0 and a zero if average relative scour was < 1.0; please see Section 3.3.2 for more detailed discussion).

In addition to flow, the random effect of site was included in all 6 of the models based on the results of the AIC statistic. This result represents the different levels of mobility or scour throughout the sites of the experiment and is predominantly driven by the variation in the individual sites in the experiment. Including this effect in the model enabled the random variability of sites to be accounted for as a source of variation and improves the predictions of the relationship with flow. The random effect of water year did not end up in the top models for mobility and scour. In general, when the random effect of water year was present, the models with flow variables were singular due to the quasi-complete separation of water year and flow. All models with singularity issues were removed from consideration in the ranking of models by AIC.

Shields parameter was included as a model covariate for the mobility model across the total experiment and 450-2,000 cfs inundation zone. Shields parameter may be a better predictor than shear stress alone because (1) Shields parameter is computed using shear stress, and (2) it incorporates grain size. The modelled relationship showed increased mobility (percentage of rocks moved) with larger values of the Shields parameter (p=0.002 for the total experiment and 0.029 for the 450-2,000 cfs inundation zone; Figure 7).

After modifying the bed mobility and bed scour to binary variables for the sake of alternate interpretations, the model results corroborated the importance of flow through statistically significant parameter estimation. Maximum daily average flow came into every model and was significant at the alpha equal to 0.05 level of significance in five of the six models (Table 8). Again, the regression coefficients for flow were positive indicating a positive curvilinear relationship between flow and each response (Table 9). The modelled relationships indicate that increased flows were associated with greater mobility (Figure 8) and scour (Figure 9) responses.

Table 8. AIC statistics and ranking for top mobility and scour models parameterized as binary outcomes. Models with lowest AIC were selected, with the exception of scour in the 450-2,000 cfs inundation zone where the 2nd model had an AIC statistic within 2 of the top model (deltaAICc) but was more parsimonious.

Inundation Zone	**Rank**	**Model**	**AICc**	**deltaAICc**
Mobility >= 80%				
Total Experiment	1	Max. daily avg. flow + Site	73.72	0.00
	2	Shields Param. + Inst. peak flow + RiverKM + Site	74.23	0.51
	3	Inst. peak flow + Site	75.10	1.38
450-2,000 cfs	1	Max. daily avg. flow + Site	66.00	0.00
	2	Inst. peak flow + Site	67.48	1.48
	3	Shear stress + Max. daily avg. flow + Site	67.79	1.79
450-1000 cfs	1	Max. daily avg. flow + Site	84.77	0.00
	2	Max. daily avg. flow + RiverKM + Site	85.89	1.12
	3	Inst. peak flow + Site	86.04	1.27
Scour >= 1 D_{84}				
Total Experiment	1	Max. daily avg. flow + Site	64.43	0.00
	2	Inst. peak flow + Site	64.77	0.34
	3	Shields Param. + Max. daily avg. flow + Site	65.22	0.79
450-2,000 cfs	1	Shear stress + Max. daily avg. flow + Site	53.06	0.00
	2	Max. daily avg. flow + Site	53.10	0.04
	3	Inst. peak flow + Site	53.41	0.35
450-1000 cfs	1	Max. daily avg. flow + Site	39.03	0.00
	2	Inst. peak flow + Site	39.05	0.02
	3	Max. daily avg. flow + RiverKM + Site	40.92	1.89

Again, the presence of the random effect of site was supported by the AIC statistic for all 6 models. The presence of the random effect of site was retained in these models to account for the spatial variation of individual sites.

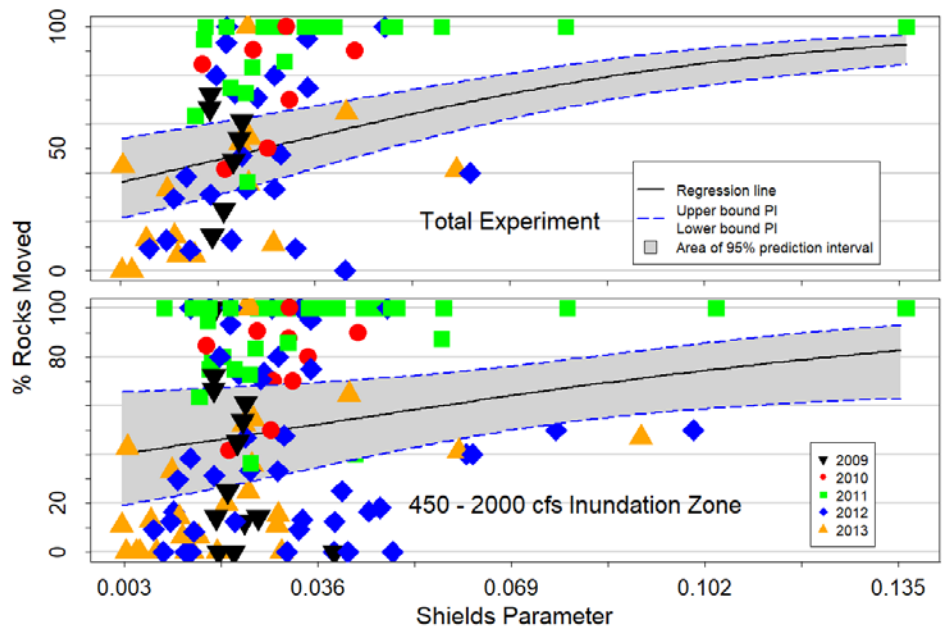

Figure 7. Predicted percentage of rocks moved, with 95% prediction interval across the range of Shields parameter while holding maximum daily average flow constant. Data used to fit the model is color-coded by year.

Table 9. The results of the best fit models for the binary outcomes of mobility and scour over the three inundation zones. The significance level of each covariate is demonstrated by the asterisks next to the covariate. The absence of an asterisk indicates that the covariate was not significant at an alpha level of 0.05.

Model and inundation zone	**Intercept**	**Maximum daily average flow**
Mobility: total experiment	-0.660	2.264 *
Mobility: 450-2,000 cfs	-0.759	1.903 **
Mobility: 450-1000 cfs	0.165	1.182 **
Scour: total experiment	-1.622 **	1.500 **
Scour: 450-2,000 cfs	-2.123 **	1.258 *
Scour: 450-1000 cfs	-2.002 *	1.016

Significance codes: '***' 0.001 '**' 0.01 '*' 0.05

From the six models, 95% prediction intervals were developed for each response function (Figure 8 and 9). For scour, the prediction interval area increases slightly as the physical area of consideration gets smaller due to the smaller sample size (i.e. the area of the 95% confidence interval is larger for the 450 – 1,000 cfs inundation zone than for the total experiment area). In addition, confidence intervals are wider at the extremes of the flow covariate, and smaller in the middle range of the covariate. As seen in the scour predictions across the range of the Shields parameter, the confidence intervals increase in width as the amount of data is reduced in the upper ranges of Shields parameter.

As an example of model predictions, the predicted probability of at least 80% mobility at a maximum daily average flow of 10,000 cfs ranged from 0.474 to 0.639 across the inundation zones (Table 10). Predicted probability of scour greater than 1.0 at a maximum instantaneous peak flow of 10,000 cfs ranged from 0.156 to 0.249 across the inundation zones (Table 11).

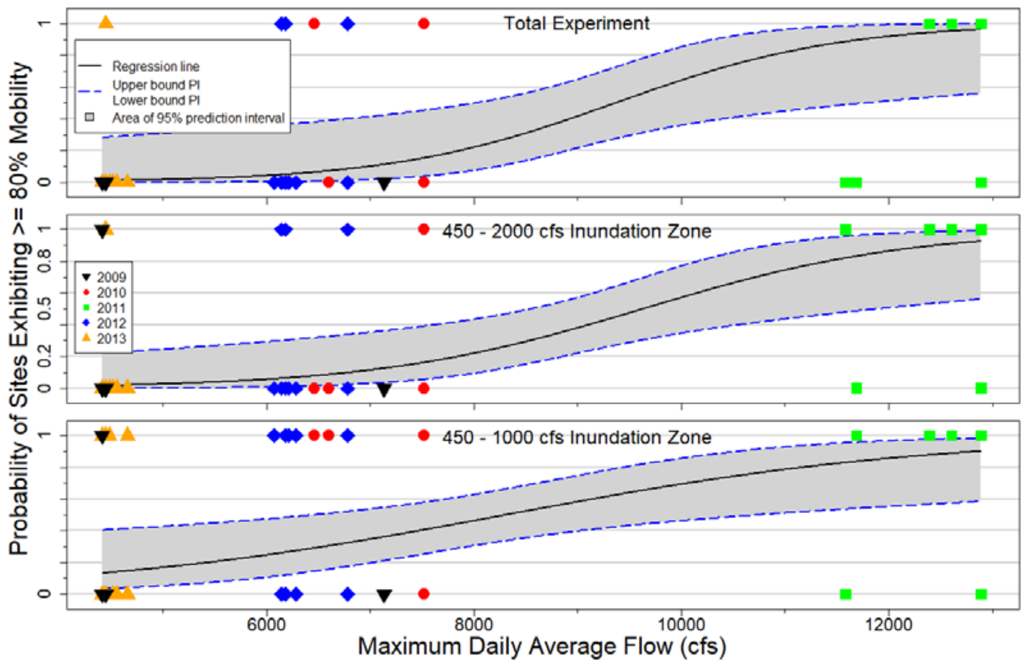

Figure 8. Predicted probability of sites exhibiting greater than or equal to 80% mobility, with 95% prediction interval, across the range of maximum daily average flow. Data used to fit the model is color-coded by year. As an example, the predicted probability of sites exhibiting ≥ 80% mobility when the maximum daily average flow was 8,500 cfs is 0.23 for the total experiment (95% prediction interval was 0.12 to 0.54).

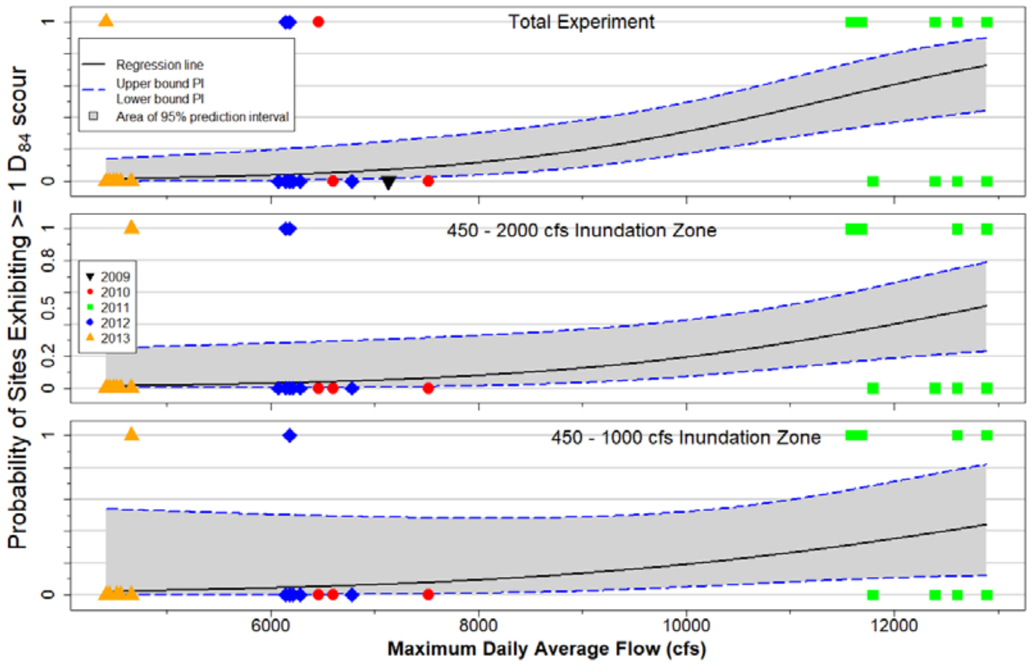

Figure 9. Predicted probability of sites exhibiting greater than or equal to 1 relative scour, with 95% prediction interval, across the range of maximum daily average flow. Data used to fit the model is color-coded by year. As an example, the predicted probability of sites exhibiting ≥ 1.0 scour when the maximum daily average flow was 8,500 cfs was 0.142 for the total experiment (95% prediction interval was 0.05 to 0.33).

Table 10. Mobility model predictions at maximum daily average flows across the range of flows observed during the experiment with 95% confidence interval for each of the inundation zone.

Flow	**Inundation zone**	**Predicted probability of a site with >80% mobility**	**Lower confidence interval**	**Upper confidence interval**
4,410 cfs	total experiment	0.022	0.001	0.320
	450 to 2,000 cfs	0.033	0.003	0.257
	450 to 1,000 cfs	0.188	0.064	0.439
6,000 cfs	total experiment	0.065	0.008	0.382
	450 to 2,000 cfs	0.079	0.016	0.319
	450 to 1,000 cfs	0.292	0.145	0.500
8,500 cfs	total experiment	0.283	0.117	0.542
	450 to 2,000 cfs	0.272	0.133	0.475
	450 to 1,000 cfs	0.506	0.342	0.669
10,000 cfs	total experiment	0.530	0.294	0.753
	450 to 2,000 cfs	0.474	0.287	0.668
	450 to 1,000 cfs	0.639	0.432	0.805
11,500 cfs	total experiment	0.763	0.419	0.935
	450 to 2,000 cfs	0.685	0.406	0.874
	450 to 1,000 cfs	0.754	0.494	0.906
12,000 cfs	total experiment	0.894	0.493	0.987
	450 to 2,000 cfs	0.831	0.485	0.962
	450 to 1,000 cfs	0.835	0.539	0.957

Table 11. Scour model predictions at maximum instantaneous flow (total experiment and 450 cfs to 1,000 cfs inundation zone) or maximum daily average flow (450 cfs to 2,000 cfs inundation zone) across the range of flows observed during the experiment with 95% confidence interval for each inundation zone.

Flow[1]	**Inundation zone**	**Predicted probability of a site with scour > 1.0 D_{84}**	**Lower confidence interval**	**Upper confidence interval**
4,410 cfs	total experiment	0.024	0.003	0.169
	450 to 2,000 cfs	0.021	0.001	0.267
	450 to 1,000 cfs	0.032	0.001	0.520
6,000 cfs	total experiment	0.049	0.010	0.218
	450 to 2,000 cfs	0.038	0.004	0.290
	450 to 1,000 cfs	0.052	0.003	0.497
8,500 cfs	total experiment	0.142	0.053	0.328
	450 to 2,000 cfs	0.093	0.020	0.342
	450 to 1,000 cfs	0.107	0.015	0.482
10,000 cfs	total experiment	0.249	0.126	0.432
	450 to 2,000 cfs	0.156	0.050	0.393
	450 to 1,000 cfs	0.161	0.035	0.501
11,500 cfs	total experiment	0.398	0.237	0.586
	450 to 2,000 cfs	0.248	0.105	0.481
	450 to 1,000 cfs	0.235	0.068	0.563
12,000 cfs	total experiment	0.557	0.340	0.755
	450 to 2,000 cfs	0.361	0.169	0.612
	450 to 1,000 cfs	0.321	0.099	0.670

[1] Non-sequential flow values are a result of the difference between maximum daily average flow and maximum instantaneous flow for similar flow thresholds, depending on the specific model and associated inundation zone. Statistical models for scour across the total experiment and 450 cfs to 1,000 cfs inundation zone relied on maximum instantaneous flow, while statistical models for scour across the 450 cfs to 2,000 cfs inundation zone relied on maximum daily average flow. Results for both are included above, resulting in non-sequential flow values for the middle (450 cfs to 2,000 cfs) inundation zone.

5 SUMMARY AND RECOMMENDATIONS

The objective of this analysis was to determine if a statistical model, using all of the data collected since 2009 across multiple WY types, can be developed to predict bed mobility and scour on point bars in the restoration reach resulting from the annual Spring ROD release. The analysis first focused on predictions of specific bed mobility and scour depth and showed considerable variability. The analysis was adjusted to simplify the dependent variables towards metrics more useful for managers (probability of a site having >80% bed mobility, probability of a site with >1.0 D_{84} scour). This second analysis was more useful in a management context, and is discussed below, along with recommended next steps.

5.1 Summary of Findings-Best Fit Models

The best fit statistical models to predict bed scour and mobility relied most heavily on maximum daily average streamflow. The models did not rely on other potential independent variables (local boundary shear stress or Shields parameter), though the effect to account for individual variation in sites was included. Average boundary shear stress or Shields parameter should be a better predictor of bed mobility and scour than streamflow, as those are indices of force on the bars that cause bed mobility and scour. The poor performance of shear stress or Shields parameter may be a result of inherent decisions within the analysis and resulting data simplifications (Figure 4). In the real world, each marked rock and individual scour chain experience unique shear stress and not a uniform condition; however, topographic data and computational node spacing is coarser than rock placement, so extracting node-specific shear stress values from the SRH-2D model may not accurately represent local forces and turbulence at the experiments. The effect of this data simplification could be quantified with future efforts in SRH-2D model validation, comparing physical measurements with computed model outputs for specific locations along the total experiment cross section over a single bar feature.

5.2 Summary of Findings-Model Performance

While using streamflow rather than shear stress or Shields parameter is a better model to predict bed mobility and scour (Table 10 and 11), the streamflow variables do not consistently predict bed scour and mobility well. First, the models typically under-predict what would be expected for bed mobility and scour across multiple streamflow thresholds based on TRFE hypotheses. For example, during a 6,000 cfs Normal water year release, the probability of a site having 80% bed mobility (full mobility) is predicted to be 6% for the total experiment and the probability of a site having bed scour > 1.0 is predicted to be 5%. Similarly, the probability of full mobility for the total experiment and > 1.0 scour for a 8,500 cfs Wet water year release is 28% and 14% (respectively), and for an 11,000 cfs Extremely Wet water year release (modeled flow was 11,500 cfs) is 76% and 40% (respectively). Current TRRP management actions are based on the assumption that spring ROD release flows will result in a much higher probability of bed mobility and scour (USFWS and HVT 1999). While the statistical models show increases in bed mobility and scour with increases in streamflow, predictions consistently fall below TRFE hypotheses for streamflow management actions.

Second, the models often predict that scour for the total experiment will be greater than the other two inundation zones (Table 11). At high flows, this pattern can be observed in the bed mobility predictions as well (Table 10). While seemingly counterintuitive (because increased bed mobility and scour is anticipated closer to the thalweg), the result may be partially explained with total experiment placement, which often extends below the 450 cfs inundation elevation into the mainstem channel where bed mobility and scour is likelier to be greater (Figure 2). Bed mobility predictions are correctly higher for the 450 cfs to 1,000 cfs inundation zone as compared to corresponding 450 cfs to 2,000 inundation zone predictions for all streamflows (Table 10). In addition, the statistical model for bed scour agreed with intuitive bed scour relationships with larger predictions for the 450 cfs to 1,000 cfs inundation zone as compared to the corresponding 450 cfs to 2,000 cfs inundation zone for streamflows below approximately 11,000 cfs (Table 11).

5.3 Model Application

The statistical models provide the ability to use predicted values, with associated confidence, to allow TRRP managers to decide if a management action is worthy based on the predicted probability of mobility and scour. While the statistical model results under-predict TRFE expectations by WY class, TRRP managers can use the model results to guide expectations of the probability that mobility and scour targets will be achieved for a particular flow release. For example, using Table 10, a Wet WY release of 8,500 cfs has a 28% chance of meeting ROD bed mobility objectives for an entire gravel bar (the total experiment) but a 51% chance for the portion of the bar in the 450 – 1,000 cfs zone). What may be considered a poor flow effectiveness probability for the total experiment allows managers to evaluate options for better achieving bed mobility and scour targets changes with streamflow. This can help managers during annual flow release planning where hydrograph adjustments can be proposed to improve the likelihood of meeting certain goals (both physical and biological) at either the restoration reach or at site-specific scales, as well as targeting full or partial mobility, or scour, in the different zones.

5.4 Recommended next steps-review model performance

This analysis focused on using 2009 – 2013 field data because a consistent GRTS sampling scheme was used during the 2010 – 2013 period, while 2009 was added to increase the breadth and range of the flow variables (measurement methods were the same, but site selection was not GTRS-based). There are considerably more mobility and scour data available that could be added to the analysis, particularly prior to 2009. However, based on these model methods and results, we are unsure that a larger sample size or adjusted field methods will improve model accuracy. While the models are indeed usable predictive tools, resulting relationships presented herein between bed mobility, scour, and streamflow should still be validated with monitoring between sites (i.e., past monitoring has shown that not all sites responded similarly to nearly identical flows).

Recent improvements in predictive accuracy of 2-D hydraulic models may now enable them to be a comparable or better tool for predicting bed mobility and scour than a statistical model, and thus reduce the need for annual field-based assessments. While making a careful comparison between 2-D model and statistical model predictions with measured field results was outside the scope of this project, we encourage this comparison to be made to evaluate and compare the accuracy of the two modeling approaches on predicting bed mobility and shear stress for any given location. If the results of this comparative analysis conclude that 2-D hydraulic models and statistical models are still too coarse for flow management activities, annual field-based assessments for Normal and wetter water year types should be continued to assess whether ROD geomorphic objectives are being achieved.

6 REFERENCES

Andrews, E.D. 1983. *Entrainment of gravel from naturally sorted riverbed material*. Geological Society of America Bulletin, v. 94, p. 1225-1231.

Bradley, N. 2018. Trinity River 40 Mile Hydraulic Model: Update with 2016 Topography, Technical Report No. SRH-2018-11, Prepared for Trinity River Restoration Program, March 2018

Burnham, K. P., and D. R. Anderson. 2002. Model selection and multimodel inference, 2nd Edit. Springer, New York.

Hales, G. M. 1999. *Bed scour as a function of Shields parameter: Evaluation of a predictive model with implications for river management*. Master's Thesis. Humboldt State University, Arcata, CA. 136 p.

Hoopa Valley Tribe, McBain & Trush, Inc., and Northern Hydrology & Engineering. 2011. *Channel Rehabilitation Design Guidelines for the Mainstem Trinity River.* Prepared for the Trinity River Restoration Program. Hoopa, CA.

May, C.L., Pryor, B.S., T. Lisle, and M. Lang. 2009. *Coupling hydrodynamic modeling and empirical measures of bed mobility to predict the risk of scour and fill of salmon redds in a large regulated river*. Water Resources Research, 45, W05402, doi:10.1029/2007WR006498

McBain & Trush, Inc. (M&T) and Hoopa Valley Tribe (HVT). 2012. *WY 2010 Geomorphic and Riparian Monitoring Results.* Administrative Review Draft. Prepared for the Trinity River Restoration Program, Weaverville, CA.

McBain & Trush, Inc. (M&T) and Hoopa Valley Tribe (HVT). 2013. *WY 2011 Geomorphic and Riparian Monitoring Results.* Prepared for the Trinity River Restoration Program, Weaverville, CA.

McBain & Trush, Inc. (M&T) and Hoopa Valley Tribe (HVT). 2014. *WY 2012 Geomorphic and Riparian Monitoring Results.* Prepared for the Trinity River Restoration Program, Weaverville, CA.

McBain Associates and Hoopa Valley Tribe (HVT). 2014. *WY 2013 Geomorphic and Riparian Monitoring Results.* Prepared for the Trinity River Restoration Program, Weaverville, CA.

McCullaugh, P. and J.A. Nelder FRS. 1989. Generalized Linear Models 2nd Edition. Chapman and Hall, New York.

Parker, G., P. C. Klingeman, and D.G. McLean, 1982. Bedload and size distribution in paved gravel-bed streams, *Journal of the Hydraulics Division, Proceedings of the American Society of Civil Engineers*, Vol. 108, No. HY4, 544-571.

R Core Team. 2013. R: A language and environment for statistical computing. R Foundation for Statistical Computing, Vienna, Austria. URL http://www.R-project.org/.

Wilcock, P. R. 1992. *Experimental investigation of the effect of mixture properties on transport dynamics*. In, Wilcock, P. R., Kondolf, G.M., Barta, A.F., Matthews, W.V.G., and Shea, C.C. 1995. Spawning gravel flushing during trial reservoir releases on the Trinity River: Field observations and recommendations for sediment maintenance flushing flows. Center for Environmental Design Research. Report 05-95. University of California.

Wilcock, P.R., Kondolf, G.M., Barta, A.F., Matthews, W.V.G., and Shea, C.C. 1995. *Spawning gravel flushing during trial reservoir releases on the Trinity River: Field observations and recommendations for sediment maintenance flushing flows.* Center for Environmental Design Research. Report 05-95. University of California.

U.S. Department of Interior (USDOI). 2,000. *Record of Decision Trinity River Mainstem Fishery Restoration EIS/EIR*. Washington, D.C.

United States Fish and Wildlife Service (USFWS) and Hoopa Valley Tribe (HVT). 1999. Trinity River Flow Evaluation Final Report. U.S. Fish and Wildlife Service, Arcata Fish and Wildlife Office, Arcata, CA and Hoopa, CA.

Zuur, A., Ieno, E.N., Walker, N., Saveliev, A.A. and Smith, G.M., 2009. *Mixed effects models and extensions in ecology with R.* Springer Science & Business Media.