Trinity River Restoration Program

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Sediment Transport in the Trinity River, CA: Data Synthesis 2004-2015

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Contents

Abstract

Sediment transport data collected in the Trinity River over a 12 year period are used to identify temporal and spatial patterns in how sediment fluxes have responded to flow and sediment management, evaluate potential causes of changes in the sediment transport regime, and to assess which components of the sediment monitoring program are most valuable for guiding management decisions. Most sediment monitoring results have thus far been presented only in year-specific reports, and the data is distributed among hundreds of separate spreadsheets. A major objective of this report is to synthesize these data into a coherent summary of what is known about sediment transport in the Trinity River has how it has changed in response to management.

Fine bed material loads at the four sediment monitoring locations along the Trinity River between Lewiston Dam and the North Fork Trinity River increases with downstream distance from the Dam. Gravel loads at the monitoring location nearest the dam, however, exceed the loads at the next two locations downstream by about 35%. The elevated gravel loads at the most upstream location can be attributed to gravel augmentations that have been implemented upstream from that location on a nearly annual basis over the past decade. Transport data suggests that gravel augmentations are affecting gravel supplies at the second monitoring location downstream from the dam, but not at the third location. The largest gravel loads are observed at the most downstream of the four monitoring locations.

To first-order, sediment transport rates are controlled by the magnitude of water discharge in the river. But numerous secondary factors strongly influence relationships between stream flow and transport rate, leading to large fluctuations in sediment transport characteristics over time. Temporal variations in the transported loads of fine bed material and gravel follow broadly similar patterns, suggesting that the availability of fine bed material exerts a strong control the transport rates of both sediment types. Changes in channel geometry or substrate composition may also have altered transport rates at some locations. Overall, the transport rates of both the coarse and fine bed material fractions appear to have decreased over the past decade at three of four monitoring locations. Comparisons with sediment loads determined from year-specific measurements confirm that this temporal variability renders long-term composite rating curves ineffective for quantifying annual sediment loads. As TRRP management is explicitly intended to change the rate and character of sediment transport processes in the river, existing sediment transport data are of little use for detecting the effects of management actions on future transport rates.

Bedload sample data from individual monitoring sites show some evidence of hysteresis over annual flow releases in about 60% of the datasets evaluated. Clockwise hysteresis is by far the most common type, especially for fine bedload at the two most upstream monitoring locations. In most cases, the fine and coarse bedload fractions display similar types of hysteresis or lack thereof. We hypothesize that changes in the availability of fine bedload during a flow event determines the degree of hysteresis observed in the transport rates of both size fractions. Nearly all instances of anticlockwise hysteresis occur at the most downstream sediment monitoring location. This is likely due to the greater distance of that monitoring location from upstream sediment sources. It appears that, rather than depleting

upstream supplies of fine bed material, extended periods of high flow may allow fine sediment derived from sources far upstream to reach the monitoring location.

Gravel monitoring results from 2015 indicate that gravel augmentations slightly exceeded the gravel flux past the most downstream sediment monitoring location that year, demonstrating that the current method for determining gravel augmentation quantities met its intended target. Gravel budget calculations through water year 2015 show that gravel storage has continued to increase in the reaches downstream from Lewiston Dam. Estimates of gravel deliveries from Rush Creek and Indian Creek for water years 2012-2015 were obtained from repeated topographic surveys of tributary confluences. Continued topographic monitoring of these confluences is recommended, as tributary gravel inputs estimated from long-term composite rating curves were found to be highly inaccurate. Continued development of a gravel budget is needed to inform gravel augmentation activities, but the use of gravel storage as a primary management objective is discouraged. The core Program objective to create spatially complex channel morphology is better assessed by direct evaluation of bed topography.

Introduction

The Trinity River Restoration Program (TRRP) began an intensive sediment transport monitoring program designed to quantify annual bedload and suspended load sediment fluxes through the Trinity River (CA) in water year 2004. As of 2015, transport data were collected and annual sediment loads were computed for 11 of those 12 years, with the only exception being the critically dry water year of 2014 when flows were too low to generate significant sediment transport. The relatively long time span covered by this monitoring dataset provides an excellent opportunity to identify temporal and spatial patterns in how sediment fluxes have responded to flow and sediment management, evaluate potential causes of changes in the sediment transport regime, and to assess which components of the sediment monitoring program are most valuable for guiding management decisions. Most sediment monitoring results, however, have thus far been presented only in year-specific reports, and the data is distributed among hundreds of separate spreadsheets. A major objective of this report is to synthesize these data into a coherent summary of what is known about sediment transport in the Trinity River has how it has changed in response to management.

TRRP's sediment monitoring program was originally intended to support sediment budgets that quantify changes in the quantity of coarse sediment and fine bed material stored in the river reaches downstream from Lewiston Dam (USFWS and HVT 1999; GMA 2001; Wilcock 2004; GMA 2015). Completion of Trinity and Lewiston Dams in the early 1960s altered sediment balances in the Trinity River to two ways. First, the dams and trans-basin flow diversions to the Sacramento River basin greatly reduced stream flows in the Trinity River, allowing sandy sediments that are continuously delivered from tributary watersheds to accumulate to levels that adversely affect stream ecology (Wilcock et al. 1996; USFWS and HVT 1999). Second, the dams completely block the delivery of coarse sediment from the upper Trinity River basin, eventually leading to a depletion of coarse bed material in the reaches downstream from the dams, as infrequent floods flushed those materials downstream (Wilcock et al. 1996; USFWS and HVT 1999; GMA 2001; Wilcock 2004). As a result, the TRRP restoration strategy includes coarse and fine sediment management activities (coarse sediment augmentation to replenish the supply of gravel and small cobble downstream from the dams and watershed rehabilitation to reduce fine sediment delivery from tributaries) intended to reduce the quantity of fine bed material stored in the river and to maintain or increase the storage of coarse sediment. By definition, tracking progress toward both of these goals requires a sediment budget approach.

Sediment monitoring is also critical for evaluating potential restoration objectives and guiding important management actions. TRRP was founded on the hypothesis that the Program's fishery restoration goals are achieved by encouraging the fluvial processes that create and maintain complex physical habitat in the river. The fluvial processes referred to include vertical scour and fill, bank erosion, lateral accretion, planform change, and reach-scale incision or aggradation. The rates at which these processes operate ultimately depend on the mobilization and transport of the coarse sediments that compose the bed and lower banks of the channel (McLean and Church 1999). Thus, the objective of encouraging fluvial dynamics in the Trinity River is directly quantified by measuring the rate at which gravel and cobble are transported through the system. Consequently, increasing coarse sediment transport rates was adopted as a major sub-objective in the Program's Integrated Assessment Plan (TRRP and ESSA 2009) and that document lists bedload transport measurements and computed coarse sediment loads as key performance measures.

Annual coarse sediment transport monitoring has become increasingly important for informing coarse sediment augmentation activities in recent years. The Program's augmentation strategy has evolved to focus on maintaining coarse sediment transport rates near the dams at levels similar to those observed in downstream reaches where tributary-derived sediment supplies are considered adequate (Gaeuman 2014b). Sediment monitoring is indispensable for assessing how coarse sediment transport rates in different parts of the river are changing in response to augmentations and flow management, and for ensuring that augmentation quantities match or exceed downstream transport rates.

Sediment monitoring also provides empirical data needed to refine the process models that guide flow and sediment management. For example, sediment monitoring data collected over the past decade suggests that transport rates tend to decline with time if flows are held constant for more than a few days. This observation has led Program managers to shorten peak flow durations in recent years, thereby using less water to accomplish a similar amount of geomorphic work. However, considerable uncertainty remains regarding what flow durations, flow magnitudes, and flow fluctuations are most effective for achieving specific geomorphic results. Such questions provided the impetus for implementing an experimental hydrograph consisting of two brief but high-magnitude peaks during the 2016 spring flow release.

In summary, sediment monitoring provides data that directly addresses a range of management questions, including:

Are coarse sediment or fine bed material transport rates changing with time?
Where are coarse sediment or fine bed material transport rates changing?
Why are coarse sediment or fine bed material transport rates changing?
How far downstream are the effects of coarse sediment augmentations propagating?
What augmentation quantities are needed to replenish downstream transport?
What hydrograph shapes transport coarse sediment most efficiently?
What hydrograph shapes transport fine bed material most efficiently?
Do the effects of hydrograph shape on sediment transport vary spatially?
Is coarse sediment storage in the upper river increasing?
Is fine bed material storage in the upper river decreasing?

Some of the above questions were generated by considering past sediment monitoring results. That is, information gained through past monitoring was instrumental for developing new working hypotheses. This report presents analyses that answer a few of these questions and make progress toward a solution to a few others. Many, however, will remain unresolved and await clarification through future monitoring.

Continuing to collect sediment transport data into the future is important precisely because TRRP management is explicitly intended to change the rate and character of sediment transport processes in the river. This necessity is aptly described by Wilcock (2004):

> "Once sediment flux relations have been determined from field measurements, it can be tempting to reduce the monitoring effort. This would be unwise in a case such as the Trinity River, where changes to sediment budget components are part of the management plan: sediment flux relations are likely to change with time in response to management actions. . . . A static SRC [sediment rating curve] cannot be assumed if management actions are intended to alter the sediment transport. Given the data scatter and uncertainty typical of sediment transport measurements, detection of shifts in the sediment rating curves requires a prolonged and consistent measurement program."

Sediment Monitoring Methods

Sediment transport monitoring, in various forms, has sporadically been performed at various sites in the Trinity River watershed since the mid-1950s (Knott 1974). Sediment monitoring efforts increased in the 1990s as part of studies that ultimately led to establishment of the TRRP (USFWS and HVT 1999). Systematic sediment monitoring implemented by TRRP began in 2004, following what could be regarded as a pilot monitoring campaign in 2002. This more recent monitoring program (2004 to present) focuses on collecting physical sediment samples in the mainstem Trinity River during annual spring high-flow releases from Lewiston Dam. A small number of samples were also collected in the mainstem and in a few principal tributaries during winter storms in January of 2006. This report considers only the data collected in the mainstem river under the modern TRRP monitoring program (2004 to present). All of these data were collected in one of four sediment monitoring reaches by the same contractor (Graham Matthews and Associates, now GMA Hydrology) using consistent sampling protocols. The sediment transport data presented herein, as well as the contractor's reports, are available on TRRP's on-line data portal: http://odp.trrp.net/.

Sediment Sampling Locations

The Trinity River Restoration Program (TRRP) currently operates four sediment sampling stations on the mainstream Trinity River (Figure 1). In order of increasing distance from Lewiston Dam, the sampling locations are Trinity River at Lewiston (TRAL), Trinity River at Grass Valley Creek (TRGVC), Trinity River at Limekiln Gulch (TRLG), and Trinity River at Douglas City (TRDC). TRAL is about 1.5 miles downstream from Lewiston Dam and is downstream from just one relatively small tributary. TRDC is about 19 miles downstream from the dam and is downstream from at least four tributaries that deliver significant quantities of sediment to the river. Thus, the four sampling locations are positioned to span spatial differences in the magnitudes of natural sediment supplies and the effects of restoration actions such as mechanical channel reconstruction and coarse sediment augmentation.

The TRGVC sampling transect was established in water year 2006, and was moved about 300 ft farther downstream in 2011 to accommodate changes in channel alignment that resulted from a 2010 rehabilitation project in the area. The TRDC sampling transect was located near the center of the BLMs campground near Douglas City in 2004 and 2005, but was moved more than 1000 ft upstream in 2011, also to accommodate changes in channel alignment resulting from a 2010 rehabilitation project. The 2011 TRDC sampling transect proved to be in a difficult location, so it was moved back downstream about 200 ft in 2012. The TRAL and TRLG transects were both established prior to 2004 and remain in their original locations.

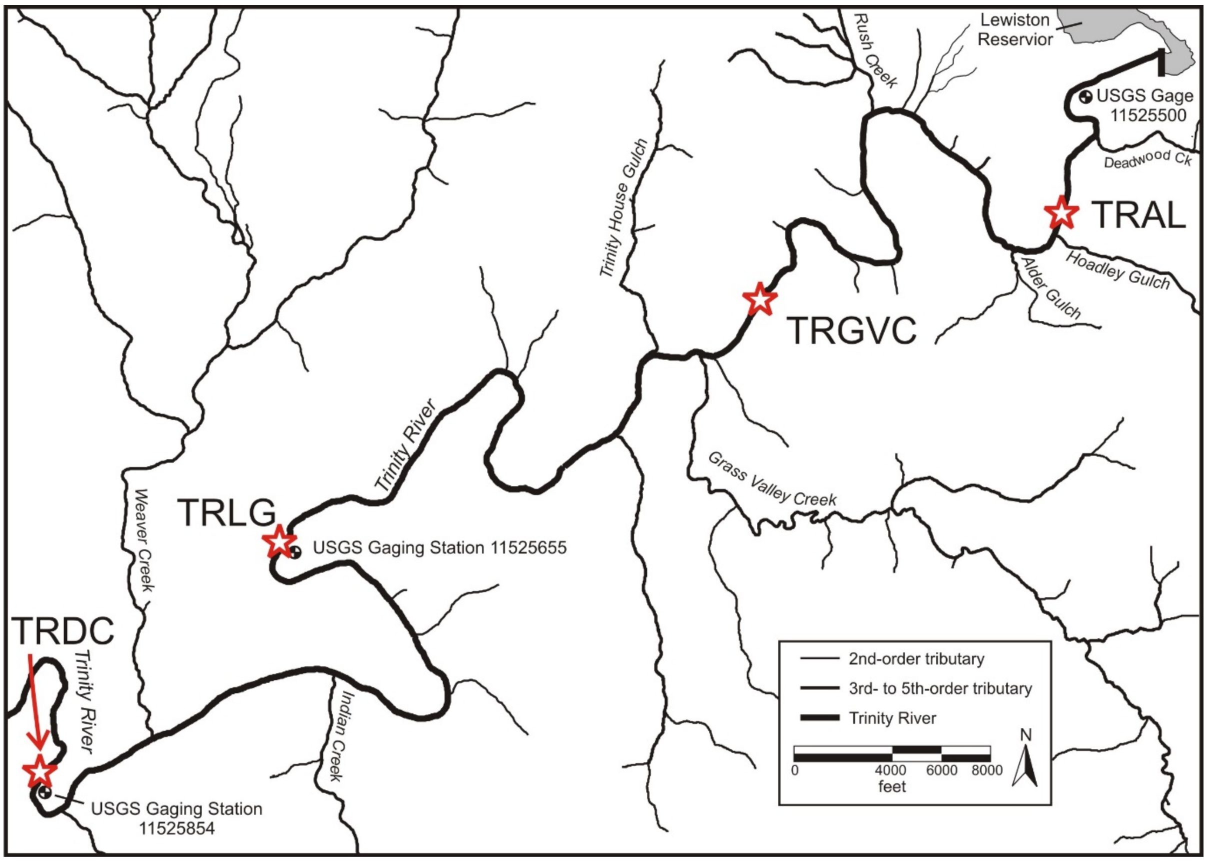


Figure 1: Map of the Trinity River basin downstream from Lewiston Dam showing the locations of sediment monitoring stations.

Sediment Sampling Protocol

Two types of physical sediment samples are collected: bedload and suspended load samples. Streams typically transport sediment by carrying the finer particles in suspension within the water column and moving larger particles along the stream bed via rolling, sliding, or skipping. The particles suspended within the water column, which in the Trinity River are typically 2 mm in diameter or finer, are referred to as suspended sediment. The larger particles moving along the stream bed can range in size from medium sand to large cobbles, and are collectively referred to as bedload. Different equipment and somewhat different methods are used to sample these two modes of sediment transport.

TRRP is focused primarily on aspects of physical habitat in the stream channel, so the sediments of greatest interest to the Program are those composing the bed and lower banks of the channel. The literature associated with Trinity River restoration activities usually classifies these bed material sediment according to two size fractions: coarse sediment, defined as particles larger than 8 mm in diameter, and fine bed material, defined as particles between 0.5 and 8 mm in diameter (USFWS and HVT 1999). Sediment fractions smaller than 0.5 mm are mostly absent from the channel bed and so are of less concern to TRRP managers, although high concentrations of these finer sediments produce elevated levels of turbidity and can therefore be important for determining water quality.

Bedload Sampling

As coarse sediment consists of gravel and cobble sizes, it is hereafter referred to as "gravel." This portion of the sediment load moves exclusively as bedload, and so is monitored using bedload sampling methods.

All bedload samples considered in this report were collected by GMA Hydrology (GMA) using a cable-suspended Toutle River 2 (TR-2) bedload samplers deployed from a cataraft attached via rollers to temporary cableways secured to trees on either side of the channel. The TR-2 sampler has an intake nozzle measuring 0.5 by 1 ft and a 0.5-mm mesh bag. Sampling is conducted by lowering the sampler to the bed at 10 to 14 verticals, depending on sampling location and discharge, spaced 10 ft apart across the width of the active channel following standard USGS equal-width increment procedures (Edwards and Glysson 1999). The sampler is placed on the river bed at each vertical for durations ranging from 30 seconds to three minutes, depending on the transport rate at the time.

As reported herein, "bedload sample" refers to the composite of all material collected by lowering the sampler to the bed once at each vertical on the sampling cross section. An average of about 30 samples are collected per sampling location during the spring high-flow release in a typical year, with more samples being collected in years with larger peak flows and longer release durations and fewer samples being collected in years with smaller, shorter releases. All sediment captured for each sample is subsequently dried and sieved into ½-phi size classes. The resulting sample data for each year is then used to compute separate load estimates for the gravel (> 8 mm) and the fine bed material (0.5-8 mm) sediment size fractions. More details on GMA's sampling and laboratory methods can be found in any one of the contractor's annual reports to TRRP (e.g., GMA 2007).

Suspended Sediment Sampling

In contrast to the gravel-sized sediments, fine bed material can be transported as either suspended load or as bedload. This has led TRRP to collect suspended sediment samples in addition to bedload samples to fully account for transport of the finer bed material fractions. An average of about 15 suspended sediment samples are collected per sampling location during each spring flow release using a D-74 depth-integrated suspended sediment sampler following standard USGS equal-width increment procedures (Edwards and Glysson 1999).

The suspended sediment sampler is deployed at the same verticals and from the same cataraft sampling platform used for bedload sampling. Standard laboratory procedures are used to determine the sediment concentrations of the 0.5-2 mm and < 0.5 mm fractions of the samples, and total loads for both fractions are computed. See one of several contractor's reports to TRRP for details (e.g., GMA 2007).

Ancillary Data

TRRP began collecting some additional data needed to provide a context for the sediment transport rates measured at the different sampling locations in water year 2007. These data consist of channel cross section surveys and bed surface pebble counts (minimum of 100 measurements) at the sampling transects and water surface slopes through the sampling transects. The cross section survey and pebble counts have been performed prior to and after the spring high flow release in most years since 2007. Water surface slope are typically collected over distances spanning several channel widths and at multiple discharge levels during the flow release. Pebble counts for TRLG and TRGVC in 2012 and TRAL in 2015 could not be located at the time this report was being prepared, and water surface slope information for a couple of the site-year combinations was found to be unusable.

Analysis Methods

As noted in the introduction section, one of the primary purposes of sediment monitoring is to quantify how much sediment the river transports at particular flow rates and how those transport rates change over time and space. This type of information is generally summarized in terms of sediment rating curves, i.e., empirical equations that predict average transport rates as a function of water discharge (Glysson 1987). Rating curves are developed by statistically fitting the parameters of a transport model to a set of paired water discharge and sediment transport measurements. Perhaps the most common transport model used for this purpose is a simple power function:

$$Q_s = aQ^b \qquad (1)$$

where Q_s is the sediment transport rate, Q is the water discharge, and a and b are parameters.

Although equation (1) can often be fit to yield a curve that approximates the shape of the transport relationship, the power function model can fail to accurately represent the physical process involved, particularly when applied to the transport of coarse bed material that remains immobile until the flow rate exceeds a threshold for sediment entrainment. Such a threshold can be accommodated by fitting bedload transport data with a shifted power function in which a discharge threshold required for the initiation of sediment transport (Q_c) is subtracted from Q:

$$\begin{aligned} Q_s &= a(Q - Q_c)^b \qquad && \textit{for } Q_c > Q \qquad (2) \\ Q_s &= 0 && \textit{otherwise} \end{aligned}$$

This 3-parameter transport model is analogous to numerous sediment transport equations (e.g. Meyer-Peter and Müller 1948) that express the sediment transport rate as a function of the excess dimensionless shear stress exceeding a critical value defined by the Shields number. Inclusion of Q_c in the rating relation accounts for the behavior of coarse bedload fractions that remain motionless at small discharge levels, such that the fitted parameters can be interpreted as metrics that quantify the magnitude of the entrainment threshold and the rate at which transport increases with increasing flow. It has been shown that use of equation (1) when a non-zero entrainment threshold does exist results in distorted parameters values that no longer provide insight into physical process (Gaeuman 2015a). Where the data show that no such threshold exists, Q_c can take a value of zero, thereby reducing (2) to a standard two-parameter power function.

The statistical method used to fit rating curves is also worthy of consideration. One reason that equation (1) is used by many practitioners is that it is easy to fit by applying ordinary least squares to log-transformed data (OLS). Although this practice is expedient, it imposes some potentially problematic conditions on the data. First, regression with log-transformed data can be subject to transformation bias, which can cause under-prediction of the dependent variable. Various corrections have been proposed to address that difficulty (e.g. Duan 1983; Ferguson 1986; Ferguson 1987). A second disadvantage of OLS stems from the fact that the log of zero is undefined. Consequently, data sets that contain zero-valued sediment samples cannot be accommodated in a straight-forward way. OLS also implicitly assumes that the log transformed data are homoscedastic in log space. That is, the log of the uncertainty in the measurements is treated as a constant. This can cause measurements taken at certain flow levels to be weighted too heavily (or too lightly) when optimizing the statistical fit (Gaeuman 2015b). It has also been suggested that ordinary regression is inappropriate for situations in which the underlying relationship between the independent and dependent variables is sought, but the value of the independent variable is itself subject to uncertainty. In such cases, a related technique known as functional analysis is recommended (Mark and Church 1977).

The first two of the issues can be avoided by fitting raw, rather than log-transformed, data. This, however, is more computationally expensive than ordinary least squares, and the need to assume a variance structure remains. This latter issue can potentially be addressed by using regression methods that weight the regression residuals differently. For example, a variance model can be incorporated into the regression, or an alternative sum other than the sum of the squared residuals can be minimized. All of the problems noted above can be avoided by using the maximum likelihood (ML) method described by Gaeuman (2015b) instead of regression.

This report makes use of three methods for optimizing rating curve parameters, depending on what the curves are to be used for and the quality of the particular data set. For data sets that lack sufficient samples to support a physical interpretation of the rating curve parameters or when physical interpretations of the parameters are not needed the optimization is performed using either OLS or by minimizing the absolute value of the residuals, which we refer to as least absolute residuals (LAR). Where physical interpretations of the parameters are needed and the data is of sufficient quality to support it, the ML method is used. We develop separate rating relations for gravel transport, fine bed material transported as bedload, and suspended bed material, as well as for different time periods. Explanations as to when and why each optimization method is applied to produce these rating curves are provided in the relevant sections below.

Another primary purpose of sediment monitoring is to estimate annual sediment loads transported by the river. This type of analysis is accomplished by applying the sediment rating curve developed from the sample data to the water discharge record to compute the total sediment flux transported over a period of time. For example, the total sediment load over a flow hydrograph (L_r) could be computed from a power function rating curve and a daily flow record lasting *n* days according to:

$$L_r = \Sigma_{i=1 \text{ to } n} (aQ_i^b) \qquad (3)$$

where *i* is the summation index. The type of computation illustrated by (3) can be performed at different temporal resolutions. Where one rating relation is defined for an entire flow event, a single set of parameter values (i.e., *a* and *b*) is used for all *n* terms in the sum. Alternatively, different relations can be defined for different portions of the flow event (e.g., rising and falling limbs), such that different values of *a* and *b* are used for different days. Sediment loads are computed separately for the gravel and fine bed material size fractions. Gravel loads are computed from the coarse bedload (> 8 mm) rating curves only, whereas fine bed material loads are computed as the sum of the fine bedload and the suspended bed material loads.

Sediment loads computed by the authors of this report and presented herein use rating curves developed from samples collected over time spans ranging from individual spring flow releases to the sediment monitoring record (2004 through 2015). The choice of time scale depends on the purpose of the particular load estimate, as will be explained later. Annual sediment loads computed by GMA and reported later differ in that they are based on samples that have been separated into much shorter time spans, using a method referred to as continuous partial-load computation (GMA 2016). The method consists of graphing the sample data from a site as a function of time in order to identify clusters of samples that represent unique transport characteristics during relatively short time periods lasting hours to a few days. Each of these sample groups is fit with a separate 3-parameter rating curve that captures short-term variability in transport rates over the course of the flow event. This approach is believed to produce more accurate load estimates than is possible with a single rating curve that represents the entire flow event. However, it obviously can only be applied to the particular flow event over which the sampling occurred.

Aside from their value for quantifying the sediment fluxes moving through the Trinity River system and the spatial and temporal variations in those fluxes, annual sediment load estimates are the building blocks needed to construct the gravel and fine bed material budgets called for in TRRP's foundational documents (USFWS and HVT 1999). Methods for constructing sediment budgets are described in the section on that topic.

Variability in Sediment Transport Rates

Sediment transport in rivers is known to be spatially and temporally variable over a wide range of scales (Gomez 1991; Gray 1991; Kleinhans and Ten Brinke 2001; Singh et al. 2009). Sources of variability include the stochastic variations in hydraulic forcing associated with turbulent flow, bedform dynamics, and changes in the quantity or grain size distribution of sediment supplied to a stream reach. At one end of the scale are momentary fluctuations driven by chaotic fluid turbulence and grain-to-grain interactions, whereas basin-scale changes in land use can produce persistent shifts in sediment yield spanning decades or centuries (Trimble 1999). Intermediate-scale variability includes daily, seasonal, and annual hysteresis in which sediment transport rates on the rising limb of a hydrograph differ from rates observed on the falling limb (Moog and Whiting 1998; Mao 2012; Mao et al. 2014; Waters and Curran 2015). Such variability in sediment transport rates has previously been reported at the annual (Gaeuman 2010b) and decadal scale in the Trinity River basin (Gaeuman 2008).

TRRP management actions are explicitly intended to alter sediment transport characteristics in the Trinity River. Specifically, gravel augmentations are performed to increase the entrainment and transport of coarse bed material, whereas watershed restoration projects are implemented to reduce the quantity of fine bed material supplied to the river. Consideration of how fine and coarse bed material transport rates have changed over time is therefore of primary importance for assessing and adaptively managing TRRP activities. The domain over which TRRP seeks to manage sediment availability and transport spans approximately 17 river miles from Lewiston Dam, where natural supplies of both coarse and fine bed material are almost non-existent, to Indian Creek, below which sediment supplies are believed to be abundant. Thus, past and present sediment transport characteristics vary with distance from the dam, as do expected future changes to those characteristics. Consideration of how fine and coarse bed material transport rates differ in different parts of the river is therefore also of great importance for assessing and adaptively managing TRRP activities

Spatial Variability

Fine Bed Material Transport

Estimated annual fine bed material loads at the four sediment monitoring locations in the mainstem Trinity River from 2004 through 2015 are plotted in Figure 2. All loads are as reported by GMA, except for the 2006 fine bed material load corrected per Gaeuman and Krause (2011). It can be seen that inter-annual fluctuations in the loads at individual sites frequently span an order of magnitude or more, and that the patterns traced by years with larger and smaller loads are similar across all four sites. Annual load are smallest at TRAL and largest at TRDC, where the annual loads exceed the TRAL figures by an order of magnitude or more. Fine bed material loads at TRGVC and TRLG are intermediate in magnitude, with the loads at TRLG usually exceeding those at TRGVC by about 50%. Loads at those two sites typically exceed the loads at TRAL by a factor of about 3.5 and 5.5, respectively, and are about three to five times smaller than the loads at TRDC. Gaeuman (2013) conservatively estimated the uncertainty margins for annual loads estimated by GMA to be ±50%. As the uncertainty margins are small compared to the temporal and spatial variability being described, they are omitted on the figure.

The total cumulative loads of fine bed material at these sites increases with distance from Lewiston Dam. Fine bed material fluxes are small at TRAL because that sampling location is downstream from just one tributary stream that can deliver significant quantities of sediment to the river. TRGVC, however, is located downstream from the confluence with Rush Creek, which is among the larger tributaries and sediment sources in the 40 miles of the Trinity River managed by TRRP (Gaeuman 2008). Several more named tributaries supply additional fine sediment to the TRLG sampling location, including Grass Valley Creek and Trinity House Gulch. Sediment fluxes at TRDC are substantially increased by sediment deliveries from Indian Creek and Weaver Creek, which are two more of the most significant sediment sources in the study area.

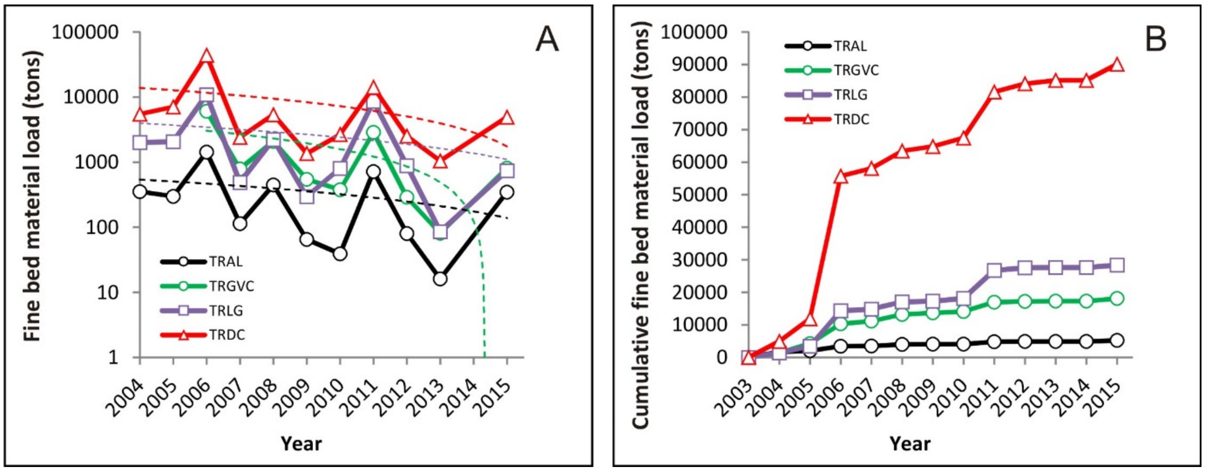


Figure 2: A) Estimated annual fine bed material loads at sampling locations in the mainstem Trinity River with linear trend lines shown, and B) cumulative fine bed material loads from 2004 through 2015. Cumulative load at TRGVC begins with 4245 tons as of 2005, based on 2004/2005 sampling at a discontinued monitoring transect located 2.4 miles upstream from TRGVC.

Gravel Transport

Estimated annual gravel loads at the four sediment monitoring locations in the mainstem Trinity River from 2004 through 2015 are plotted in Figure 3. All loads are as reported by GMA. Inter-annual variability in gravel transport within sites is even greater for gravel transport than it is for fine bed material, with fluctuation from one year to another exceeding two orders of magnitude in some instances. As with the fine bed material transport, the largest loads are found at TRDC and the pattern of inter-annual fluctuations follows a similar path across all four sites.

Contrary to the case for the fine bed material, however, gravel fluxes at TRAL exceed the fluxes at both TRGVC and TRLG by about 35%. The cumulative gravel flux at TRAL is also much closer to the flux observed at TRDC, which exceeds the TRAL flux by a factor of just

2.3, as compared to a factor of more than 17 for fine bed material transport. The elevated gravel loads at TRAL above those at TRGVC and TRLG are undoubtedly related to the fact that TRRP has been implementing gravel augmentation projects upstream from that sampling location on a nearly annual basis over the past decade. Gravel augmentations in the area include the placement of about 6000 yd^3 (9000 tons) of gravel at the Lewiston fish hatchery (1.5 miles upstream) in 2006 and 2007, high-flow injections totaling about 8500 yd^3 (12750 tons) of gravel at the Diversion Pool (1 mile upstream) between 2008 and 2015, and placement of about 5400 yd^3 (8100 tons) of gravel immediately upstream from the sampling transect as part of the 2008 Cableway and Deadwood Creek channel rehabilitation projects (Gaeuman 2011).

Gravel loads at TRGVC are sustained mainly by gravel deliveries from Rush Creek, but the fact that the fluxes at that sampling location remain smaller than those at TRAL suggests that the bulk of the gravel added to the river near Lewiston Dam has yet to reach TRGVC. TRRP has addressed this apparent delay in gravel arrival at more downstream locations with repeated gravel augmentations at the upstream end of the Lowden Ranch channel rehabilitation site (Gaeuman 2014a). Approximately 2050 yd^3 (3075 tons) was pushed into the river during the 2011 spring flow release at a point approximately 500 ft upstream from the TRGVC sampling location, but the TRGVC gravel load that year remained smaller than the loads at all three of the other sampling locations. It has been hypothesized that gravel transport rates during that flow release remained relatively small due to the 2010 construction of an artificial meander bend immediately upstream from the gravel injection location. According to Gaeuman (2014a), meander construction created a new hydraulic control that caused gravel entering the reach to deposit in the backwater upstream from the meander. Gravel fluxes at TRGVC increased relative to the other sites in subsequent years, and by the summer of 2015, after a second gravel augmentation consisting of 700 yd^3 had been performed during the 2015 flow release, the cumulative gravel flux from 2012 through 2015 was 4.6 and 1.8 times larger than the cumulative fluxes at TRLG and TRAL, respectively.

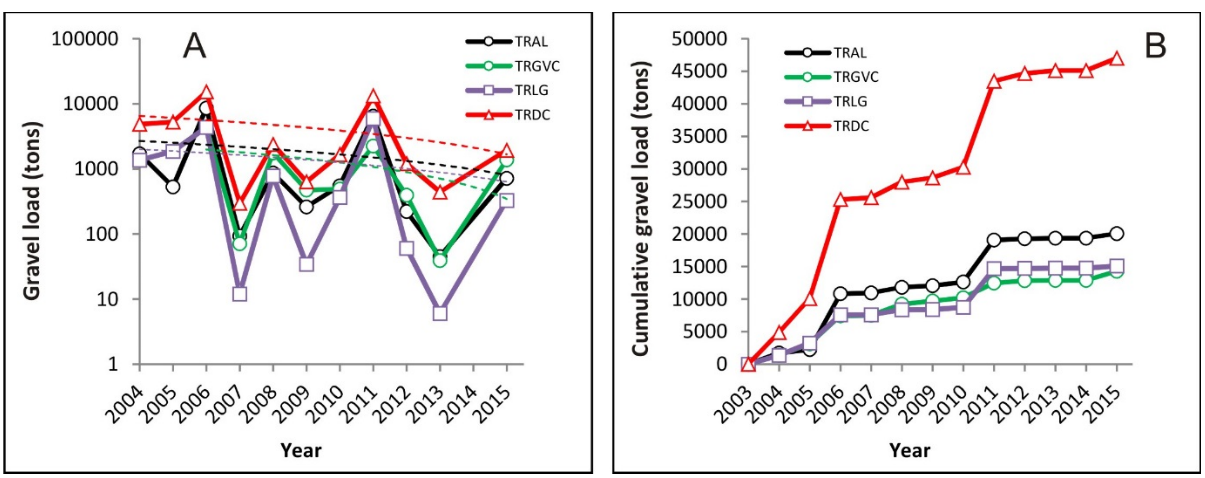


Figure 3: A) Estimated annual gravel loads at sampling locations in the mainstem Trinity River with linear trend lines shown, and B) cumulative gravel loads from 2004 through 2015. Cumulative load at TRGVC begins with 3125 tons as of 2005, based on 2004/2005 sampling at a discontinued monitoring transect located 2.4 miles upstream from TRGVC.

Although the cumulative gravel load at TRGVC and TRLG were approximately equal as of 2015, TRLG has become the monitoring site with the smallest loads in recent years. Although loads at TRLG were slightly larger than at TRGVC in all years prior to 2007, loads at TRGVC have surpassed the loads at TRLG in all but one year since. It appears that gravel augmented near Lewiston Dam and more recently at Lowden Ranch has yet to reach the TRLG sampling location, 13 miles downstream from Lewiston Dam and 5.5 miles downstream from TRGVC with no significant gravel-producing tributaries in between. TRDC, however, is located downstream from Indian and Weaver Creeks in a section of river that is believed to contain an abundant supply of coarse bed material (Gaeuman 2014b). Gravel loads at TRDC are consequently much larger than at the more upstream sampling locations.

Inter-annual Variability and Trends

Fine Bed Material Transport

The patterns traced by the fine bed material loads in Figure 2a are qualitatively similar to the time series of larger and smaller flood events over the same time period (Figure 4), except that linear regression lines fit to the time series of annual loads at all four sites show a downward trend whereas a regression line fit to the flow peaks is almost perfectly flat. Coefficients of determination for the trends shown for the fine bed material loads are all rather low (0.06 to 0.31), so the statistical relationships are weak. This is at least partially due to the essentially random signal imposed on the loads by the temporal fluctuations in peak discharges. The slopes of the regression lines, however, are large and negative. Given that essential no trend in discharge peaks is evident, this suggests that fine bed material transport rates for given flow magnitudes are decreasing with time. From upstream to downstream, the slopes of the best fit trend lines are –37 at TRAL, –365 at TRGVC, –260 at TRLG, and –1100 at TRDC. From 2004 to 2015, these slopes correspond to decreases in the loads indicated by the respective trend lines of 115%, 210%, 110%, and 145% of the average for each corresponding sampling location.

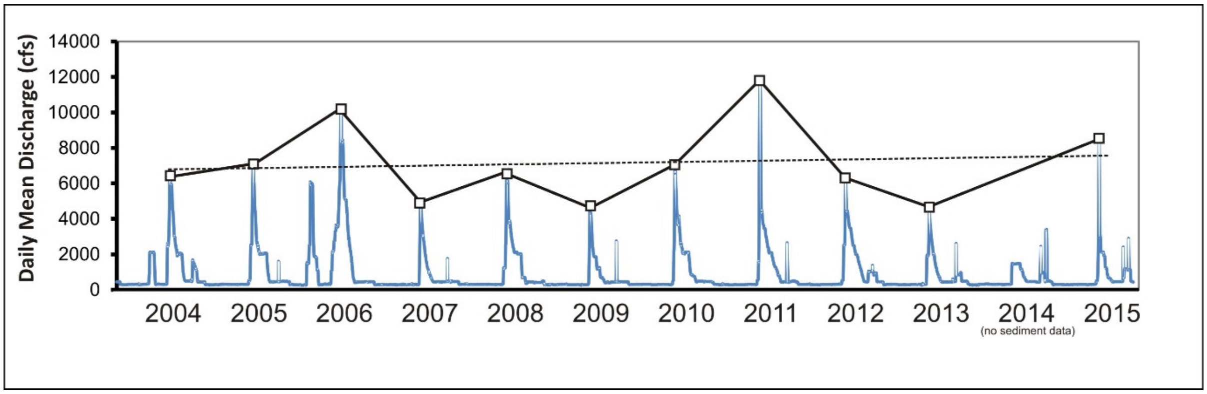


Figure 4: Daily mean flows released from Lewiston Dam with annual daily peaks and linear trend line of peaks shown in black.

Relationships between stream flow and bed material transport obviously depends on the durations of flood and other aspects of the annual hydrographs beyond peak discharge, and the above observations are intended to serve only an introduction to the topic. To better account for the influence of different stream flows in different years, temporal changes in fine bed material transport rates are also investigated using sediment rating curves. This analysis requires the use of rating curves representing discrete time periods, some of which span more than one water year. Pooling sample data into multi-year time periods is sometimes necessary because sample data for single years often lack samples that span a sufficient range of flow rates to support rating curve development. For example, sampling over the spring flow hydrograph is sometimes concentrated on steady peak flow bench lasting multiple days and perhaps one lower discharge level. For curve fitting purposes, this is essentially equivalent to having just two sample points. These kinds of data issues were mitigated by defining seven time periods spanning the 12 years of monitoring since 2004. Samples from 2004 were combined with the 2005 data, as were the 2007, 2008, and 2009 samples. Rating curves were not developed for 2013 or 2014 because only four samples were collected at most sites in 2013 and no sampling was performed in 2014.

Two rating curves were developed for each time interval at each site. A fine bedload rating curve was developed from the bedload sample data, and a second rating curve relating the concentration of suspended sand in the water column to water discharge was developed from the suspended sediment sample data. Each set of data was fit with a 2-parameter power function using LAR regression, and the two partial loads were summed to yield the total fine bed material load. LAR regression was used to fit these data because the suspended sediment samples can occasionally include very high sand concentrations, and LAR is less sensitive to outliers than OLS. In all, 54 period-specific rating curves were fit for this analysis – seven curves for fine bedload and seven curves for suspended bed material at each of three of the sampling locations, plus six curves for each type of sediment at the fourth location. Those rating curves and the corresponding data are displayed in Appendix A.

The trend toward decreasing fine bed material transport rates over time suggested by the loads computed at each site is less apparent when transport characteristics are evaluated in terms of the rating curves. Transport rates predicted for a moderate flow event of 6000 ft^3/s [an approximately 1.7-year event (USFWS and HVT 1999)] at each sampling location in each of the seven time periods are shown in Figure 5. Slopes of the trend lines are negative at three of the four sites, with the exception being TRDC. At TRAL the trend line decreases by about 5.3 tons/day from 2004-05, which represents about 35% of the average transport rate for the seven time periods. The decreases at TRGVC and TRLG are 67 and 55 tons/day, respectively, which is equivalent to about 106% and 55% of the average transport rates. The trend at TRDC shows an increase of 36 tons/day, or about 88% of the average for the site.

The fluctuations in the estimated transport rates, however, do not correspond well to the linear model represented by the trend lines and the explanatory power of the fits are poor (r^2 ranges from 0.04 to 0.21). Instead, large deviations from the linear trends appear at consistent times across all four sites. TRAL, TRGVC, and TRLG all show maximum or near maximum transport rates for the 2007-08-09 time period, and all sites have minimum or near minimum transport rates in 2010.

The reasons for these fluctuations cannot be determined from the available data, but it is theoretically attractive to suppose that fine bed material transport rates are primarily controlled by the quantity of fine sediments supplied to the channel from tributary and other sources. The clear increase in transport rates after 2010 shown for TRDC could perhaps be an indication that tributary sediment deliveries upstream from that location increased in recent years. This hypothesis is mildly strengthened by estimates of tributary inputs to the river given by Gaeuman (2013), which indicate that fine bed material deliveries from Indian, Weaver, and Reading Creek (all located a short distance upstream from the TRDC sampling location and downstream from all other sampling locations) were relatively large in 2011, 2012, and 2015. Overall, however, the balance of the evidence does not support this hypothesis – for example, estimates of tributary inputs to the river given by Gaeuman (2013) suggest that tributary sediment deliveries upstream from TRAL, TRGVC and TRLG were rather small during 2007-09 when mainstem transport rates were comparatively high, and tributary sediment deliveries were several times larger in 2010 when mainstem transport rates were very low.

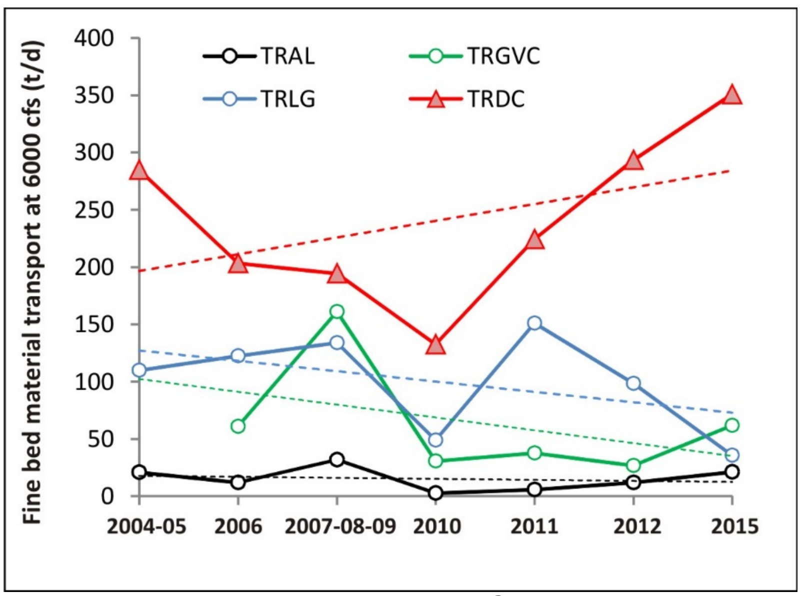


Figure 5: Fine bed material transport rates at 6000 ft^3/s predicted with sediment rating curves developed from sample data binned into seven time periods spanning 2004 through 2015. Linear trend lines shown.

The observed temporal pattern in rating curve estimates of transport rates could perhaps be explained better in terms of sediment concentration. Rating curves predict hypothetical transport rates, not actual loads. It is conceivable that even the smaller flow releases from Lewiston Dam to the Trinity River are capable of mobilizing nearly all of the fine bed material that is delivered to the river over the course of the year. In that case, fine bed material fluxes would depend on the quantity available for transport, not on the flow magnitude. If similar quantities of sediment were available in two different years, then the year with the smaller flow releases would produce a steeper rating curves because a similar quantity of sediment would have been transported with less water. This point can be illustrated by observing that the fine bed material loads transported in each of the four years spanning 2007 through 2010 were similar (Figure 2), and supposing that those loads represent all the available fine sediment that was supplied to the river in each of those years. The three flood peaks in 2007-09 averaged 5280 ft^3/s, whereas the 2010 peak reached 7480 ft^3/s. This would require that the concentration of fine bed material in the flow at a given water discharge was greater in 2007-09 than in 2010. That, in turn, corresponds to a rating curve that predicts higher sediment concentrations and transport rates for the same flow levels. Any extrapolation beyond the range of flows the rating curves are based on will amplify that effect (in this case, 5280 ft^3/s is extrapolated to 6000 ft^3/s). This explanation for some of the temporal variability in these estimated transport rates, however, should be regarded as conjecture. The only conclusion about temporal changes in fine bed material transport rates that can be draw from this analysis is that the rating relations are highly variable through time at all sites. That variability can be summarized by the ratios of the maximum and minimum transport rates predicted for a flow of 6000 ft^3/s in the different time periods, which range from a low of 2.6 at TRDC to a high of 12.3 at TRAL.

The magnitude of these year-to-year changes in fine bed material transport rates are such that future loads cannot accurately be predicted from past measurements. Figure 6 compares the annual fine bed material loads computed for each site by GMA with the loads estimated with long-term composite rating curves developed from all sediment samples collected at each site in water years 2004 through 2015. Separate long-term composite curves were developed for the bedload and suspended portions of the fine bed material load at each site using LAR regression without log transformation. This curve-fitting method was chosen because the sample data contain high outliers that would influence the results to an inordinate degree if the residuals were squared, and because the presence of numerous suspended sediment samples containing no sediment in the > 0.5 mm class preclude log transformation. Partial loads corresponding to bedload and suspended load were computed for each water year and summed to yield the total fine bed material load for the year. These eight long-term composite rating curves are plotted in Appendix A. Deviations of the fine bed material loads calculated from the rating curves (L_r) from the loads reported by GMA (L_{GMA}) are quantified in terms of error ratios (E), defined by:

$$E = L_r/L_{GMA} \qquad \text{for } L_r \geq L_{GMA} \qquad (4)$$
$$E = (L_{GMA}/L_r)^{-1} \qquad \text{for } L_r < L_{GMA}$$

As previously noted, fine bed material transport rates and loads appear to be decreasing over time. This trajectory is illustrated in the Figure 6, which indicates that the multi-year rating curves tend to under-predict loads prior to 2009 and to over-predict loads in most years after 2009. The largest under-predictions occur in 2006 through 2008, with maximum errors at TRGVC (5.77^{-1}) and TRLG (3.25^{-1}). Over-predictions are observed at all sites in 2010, when transport at TRAL and TRGVC were over-predicted by factors of 3.53 and 1.89, respectively. Over-predictions were also common in 2012 and 2013, with the maximum for TRLG of 3.26 occurring in 2013. Under-predictions returned at three of the four sites in 2015, giving the time series plots a convex upward form over the 2006-2015 time interval.

The largest under-prediction at TRAL (3.59^{-1}) occurred in 2015. Over all measures, the average *E* is about 1.5^{-1} and the standard deviation of *E* is 2.31 (± 131% error). Overall, the 95% confidence range of predicted loads across sites is about 24% to 308% of the actual load for a given year.

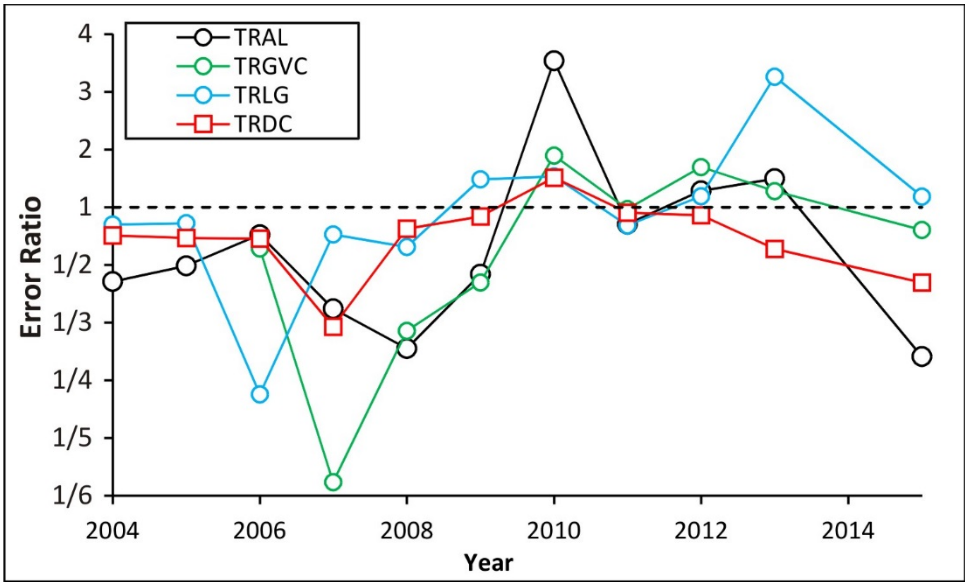


Figure 6: Error ratios (*E*) in estimated annual fine bed material loads determined from rating curves developed from all sediment samples collected in 2004 through 2015.

Gravel Transport

As is the case for the fine bed material loads, the patterns traced by the gravel loads in Figure 3a tend to follow the ups and downs of the flow peaks over the same time period (Figure 4), but trend lines fit to the gravel loads decrease slightly with time. Again, those trends are statistically weak (r^2 = 0.04 to 0.15), but have large negative slopes. From upstream to downstream, the slopes of the best fit trend lines are –171 at TRAL, –182 at TRGVC, –124 at TRLG, and –440 at TRDC. From 2004 to 2015, these slopes correspond to decreases in the loads at all four sites by about 100% to 130% of their long-term averages.

As was done for fine bed material transport, we investigated temporal changes in gravel transport rates using sediment rating curves developed for the same seven time periods used to evaluate changes in the transport of fine material. For gravel transport, however, just one rating curve is needed per time period and sampling location. The gravel rating curves also differ from those used for the finer sediment fraction in that the 3-parameter transport model given by equation (2) is used, and the model was fit using the ML method of Gaeuman (2015b). The ML method was chosen for use with the gravel sediment fraction specifically to support optimization of the 3-parameter model. The resulting 27 period-specific gravel rating curves and corresponding data are plotted in Appendix A.

The overall temporal trend in gravel transport rates is qualitatively similar to the overall trend for fine bed material transport in that decreasing transport rates are observed at TRAL, TRGVC, and TRLG, while a mild increase over time is apparent at TRDC. Gravel transport rates predicted for a 6000 ft^3/s event at each sampling location in each of the seven time periods are shown in Figure 7. At TRAL the trend line decreases from the 2004-05 level by about 7.5 tons/day for each time interval, which is equivalent to a decrease of about 77% of the average transport rate over all seven time periods. The rates of decrease at TRGVC and TRLG are 8 and 16 tons/day per time period, respectively, which are equivalent to about 55% and 160% of the average transport rates over the entire time series. TRDC shows a rate of increase of 4.3 tons/day per time period, or about 20% of the average for the site over all seven periods. Once again, the explanatory power of the statistical fits are poor, although with r^2 ranging from 0.09 to 0.40 it is substantially stronger for gravel than for fine bed material.

Gravel transport rates at TRAL, TRGVC, and TRLG mirror the fine bed material transport rates by showing anomalously large transport rates in the 2007-2009 time period, followed by a sudden drop in transport in 2010. Meanwhile, the time series of gravel transport rates at TRDC is similar to that site's fine bed material time series in that each reaches its maximum value in 2015.

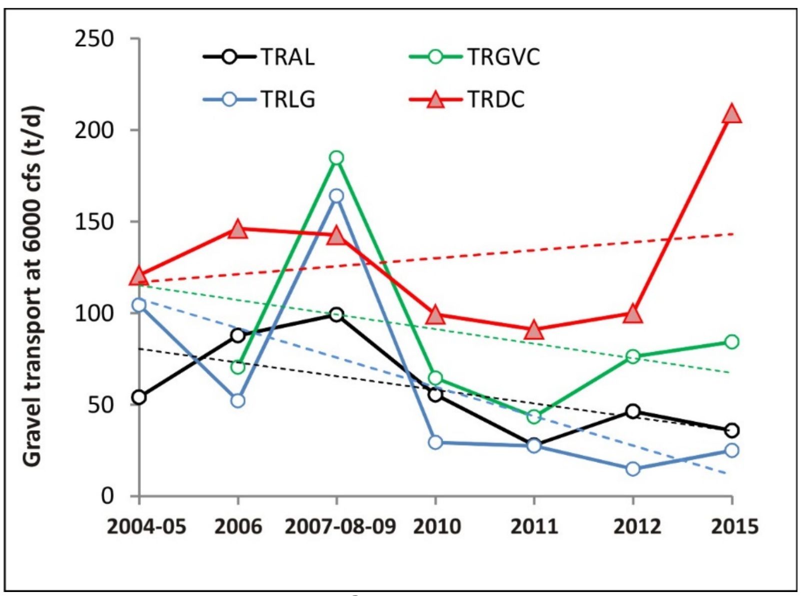


Figure 7: Gravel transport rates at 6000 ft^3/s predicted with sediment rating curves developed from sample data binned into seven time periods spanning 2004 through 2015. Linear trend lines shown.

The above results show that gravel transport and flux rates have tended to decline upstream from TRDC over the past decade, and that the temporal trends in gravel transport closely mimic a similar trend in fine bed material transport. The strength of this correspondence is demonstrated with a pairwise comparison between fine bed material loads and gravel loads.

Linear regression yield strong correlations between the two sediment fractions with r^2 values ranging from 0.76 to 0.88 (Figure 8a). It has already been hypothesized that the decreases in the transport and flux rates of fine bed material is related to a decrease in the supply of these finer sediment available for transport in the river. However, this hypothesis is not as applicable to the apparent decrease in gravel transport rates because the channel itself is composed primarily of gravel-sized sediments. A reduction in gravel supplies delivered to the river would become evident only through a progressive increase in the size distribution of the gravel and cobble that make up the stream bed over an extended period of time.

A more plausible explanation for the relatively rapid fluctuations in the gravel transport rates described herein is that the changes in gravel transport are driven primarily by changes in the abundance of fine sediment in the river. It is well known that gravel mobilization thresholds are significantly reduced when sand is added to the sediment mixture (Wilcock et al. 2001; Wilcock and Crowe 2003; Curran and Wilcock 2005). The dependence of gravel transport on fine sediment abundance is quantified in bedload transport equations that cast the entrainment thresholds of large sediment particles as a function of the abundance of fine particles on the bed. According to the Wilcock-Crowe equations, for example, the dimensionless reference shear stress needed for significance gravel entrainment varies from 0.036 to 0.021 as the percentage of fine sediment of the bed varies from 0 to about 30% (Wilcock and Crowe 2003).

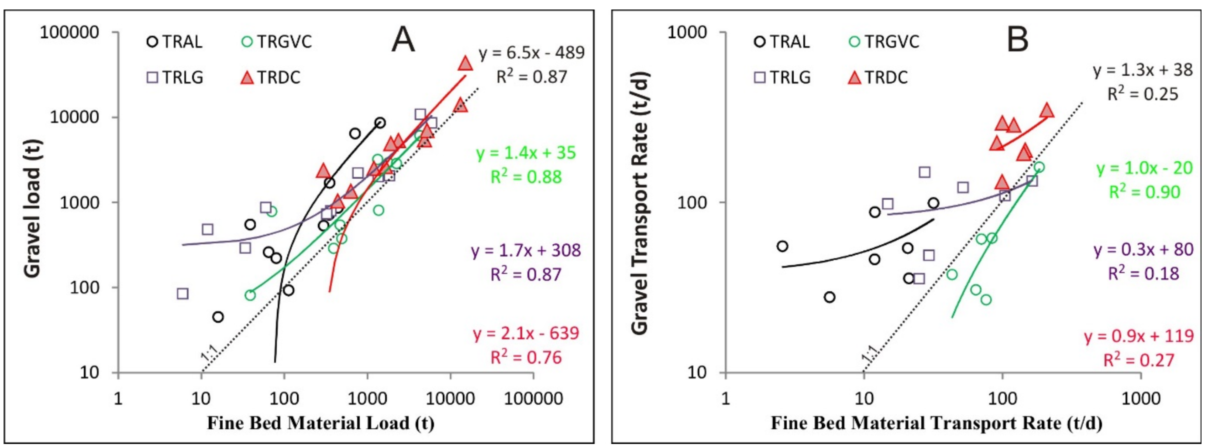


Figure 8: A) Yearly gravel loads versus fine bed material loads, and B) gravel transport rates calculated with period-specific rating curves for a discharge of 6000 ft^3/s during the seven time periods shown in Figure 7 versus fine bed material transport rates also computed with period-specific rating curves. Loads are as reported by GMA. Linear trend lines shown and regression.

This strong correspondence between the annual coarse and fine bed material loads is expected, since both sediment size fractions respond to the same time series of annual flow hydrographs. The direct dependence of the loads on flow magnitudes can be removed by considering the transport rates predicted for a discharge of 6000 ft^3/s with the rating curves developed for the seven time periods described above. Although correlations between the estimated transport rates for fine and coarse bed material are substantially weaker than for the loads, a positive correspondence remains (Figure 8b).

Another way to evaluate the hypothesis that changes in gravel entrainment thresholds are responsible for the observed trends in gravel transport characteristics is to examine the water discharges required to initiate gravel transport. The gravel rating curves developed for different time periods provide a means to investigate this potential. Values of Q_c fit to TRAL data show a clear upward trend, with the onset of gravel transport occurred at larger discharges in 2010 and later (Figure 9). The smaller values of Q_c observed prior to 2010s could be partially due to gravel augmentation projects. About 2000 yd^3 (3000 tons) of gravel were spread on the channel bed 1000 ft upstream from the sampling transect in the summer of 2003 and another 5400 yd^3 (8100 tons) of gravel were placed in constructed bars immediately upstream from the sampling transect in 2008 in conjunction with the Cableway and Deadwood Creek channel rehabilitation projects (Gaeuman 2011). Freshly placed gravel is relatively loose and easily entrained compared to gravel that has been water-worked (Gaeuman et al. 2009; Gaeuman 2014a), so these gravel augmentations may very well have reduced entrainment thresholds in the first year or two after their placement. Subsequent gravel augmentations upstream from TRAL were implemented a mile or more upstream, and so may not have had as much effect on entrainment thresholds at the sampling location.

A slight upward trend in values of Q_c is also apparent in the TRGVC data, but the strength of the relationship is considerably weaker (Figure 9). The weaker signal at TRGVC could be partly due to the fact that the no samples were collected at that location prior to 2006. The relationship is also weakened by a rather low value of Q_c in 2011. The spring flow release for that year, however, followed the construction of the Lowden Ranch channel rehabilitation project in which the channel immediately upstream from the sampling location was moved into a constructed meander bend with a substrate that had never before been subjected to flows capable of entraining gravel (Gaeuman 2014a). Only an anomalously small value of Q_c in 2006 hints at any upward trend to the data at TRLG, whereas the TRDC data lack any trend whatsoever.

We evaluated the potential utility of using past bedload transport measurements to predict gravel fluxes in future years by developing long-term composite long-term composite rating curves for gravel similar to those described above for fine bed material. We fit the gravel curves, however, with a standard 2-parameter power function optimized via the OLS regression. This simple approach was selected because it is the method that practitioners are most likely to use. The use of a transformation bias correction was explored but not implemented, for reasons discussed later. The long-term composite curves were used to compute annual gravel loads at each of the four sampling locations, which were then compared with the past loads reported by GMA Hydrology (Figure 10). The four long-term composite rating curves developed for gravel transport are plotted in Appendix A.

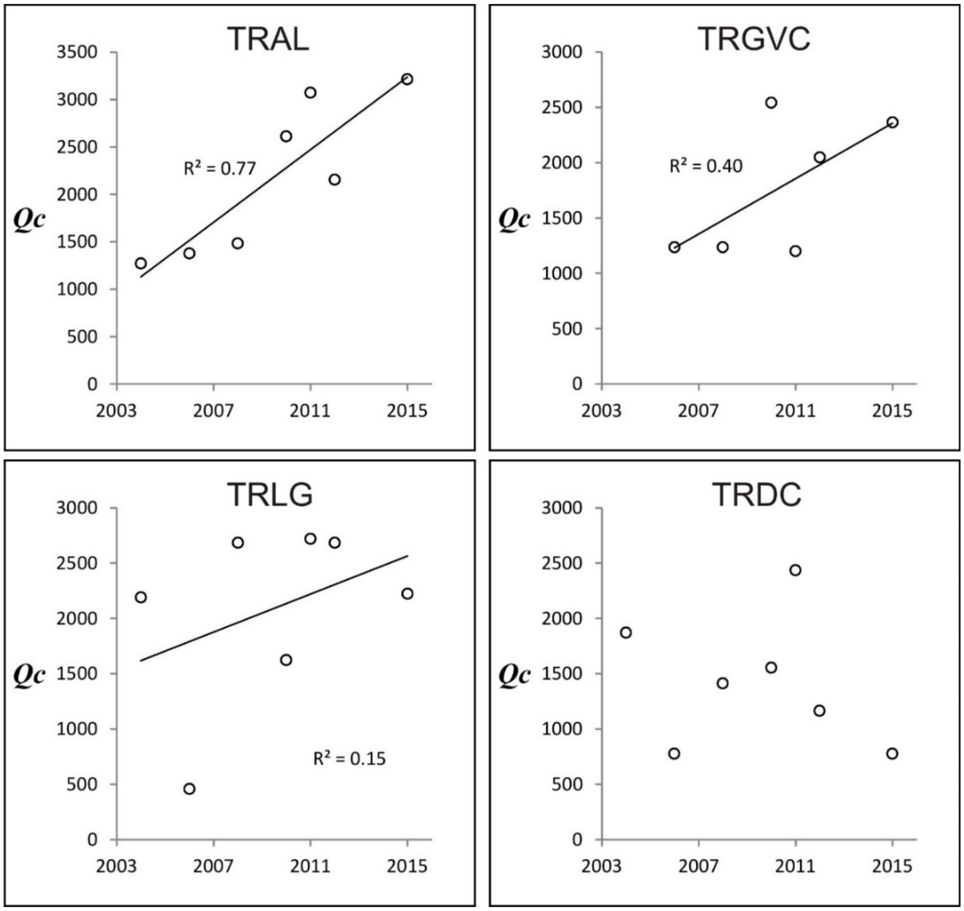


Figure 9: Fitted values of Q_c in gravel rating curves for developed from sample data binned into seven time periods spanning 2004 through 2015.

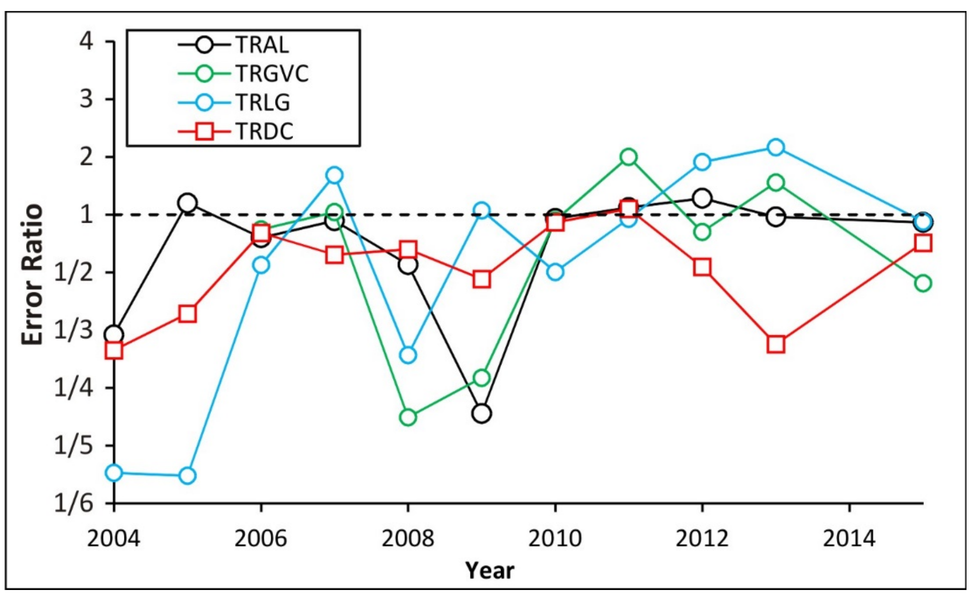


Figure 10: Error ratios (E) in estimated annual gravel loads determined from rating curves developed from all sediment samples collected in 2004 through 2015.

The aforementioned trends toward decreasing gravel loads over time are evident, in that values of *E* tend to be less than unity (long-term rating curves under-predict the load) prior to about 2010 and they tend to be near or slightly larger than unity (over-prediction) in recent years at two of the four sampling locations. The largest under-prediction errors occur early in the time series (e.g., 5.52^{-1} at TRLG in 2005 and 4.51^{-1} at TRGVC in 2008), and the largest over-prediction errors occur relatively late (e.g., 2.16 at TRLG in 2013 and 2.0 at TRGVC in 2011). The values of *E* computed for 2015, however, show slight under-predictions at both sites. The other two sites, TRAL and TRDC show virtually no temporal trend in *E*.

The lack of a temporal trend toward larger positive *E* at TRAL may seem odd, since the trend toward larger values of Q_c over time, as determined with the seven period-specific rating curves, is most convincing at that location (Figure 9). This result can be explained by noting that gravel transport rates are not dependent on the entrainment threshold alone. Other characteristics of the relationship between water flow and gravel transport can adjust to produce larger or smaller fluxes for different flow levels. In the case of TRAL, the value of the rating curve exponent (*b*) also increases with time (Figure 11). This indicates that, although larger flows are required to initiate transport in later years, once transport has begun it increases more rapidly with flow in the later years. Exponents for TRGVC show a similar, but weaker, relationship, which also mirrors the Q_c relationship for that site in that the generally upward trend in the values of *b* is disrupted by rather small estimate for that parameter in 2011 (Figure 11). Also similar to the results for Q_c, values of *b* at TRLG and TRDC show essentially no temporal trend.

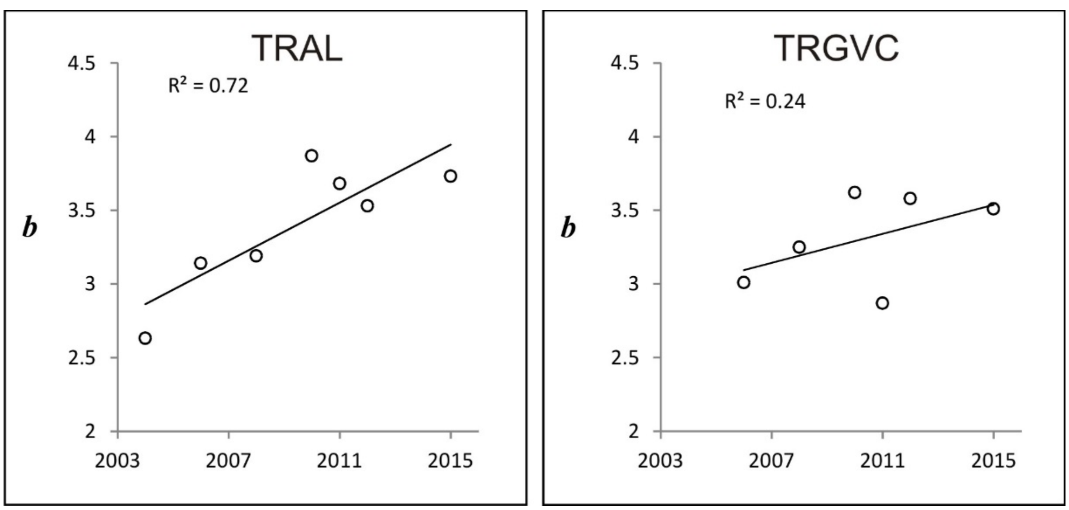


Figure 11: Fitted values of *b* in gravel rating curves for developed from sample data binned into seven time periods spanning 2004 through 2015. No temporal trends can be inferred from plots for TRLG and TRDC (not shown).

The tendency for changes in Q_c and *b* to compensate for one another can be more clearly seen by plotting those parameters against one another. Figure 12 shows that the values of Q_c and b are positively correlated at every location. There are at least three possible explanations for this result. An obvious and rather unappealing possibility is that mutual adjustments among the rating curve parameters are nothing more than artifacts of the statistical fitting procedure. That is, scatter in the data leads to erroneously large or small estimates in one parameter, which requires a compensating erroneous error in another parameter to ensure minimization of the regression residuals. If correct, this explanation would imply that no physical meaning can be drawn from the rating curve parameter values.

A second possible explanation for the compensatory relationship illustrated in Figure 12 is that a large value of Q_c could mean that the most of the bedload samples were collected at discharges close to the threshold of entrainment. Bedload transport theory holds that the rate at which the transport rate increases with shear stress is large near the threshold of entrainment and decreases with increasing shear stress. For example the Parker (1990) bedload equations indicate that the transport rate increases as the 14.2 power of the excess shear stress at the reference transport rate level (a small but measureable rate), but asymptotically approaches a rate of increase given by the excess shear stress raised to the 1.5 power. Because an increase in Q_c means that any given discharge is closer to the threshold for entrainment, it potentially could cause bedload samples to fall on a steeper part of the discharge-transport curve so that the resulting rating curve fails to accurately represent the flatter portion of the relationship (Gaeuman 2015a). Casting b as a function of transport stage (T) provides evidence that this may be the case for the Trinity data discussed here. For this comparison, T is computed as $(Q_{avg} - Q_c)/Q_c$, where Q_{avg} is the mean discharge at which the bedload samples were collected weighted by sample mass. Regression between b and T at the four sampling locations produced inverse relationships with coefficients of determination ranging from 0.54 to 0.98. If correct, this explanation would imply that Q_c represents actual changes in the threshold of gravel entrainment, but that apparent changes in b cannot be assumed to reflect real changes in bedload dynamics.

Finally, it is possible that there is an actual physical linkage between the observed increases in Q_c and increases in b, although the nature of the linkage is open to speculation. One possible hypothesis is that Q_c responds to changes in sediment mobility near the sampling locations, whereas b reflects changes in the distances to upstream sediment sources. We illustrate the point using TRAL as an example. In order for a change in substrate conditions to affect the value of Q_c measured at TRAL, it is necessary for particles that are mobilized at Q_c to reach TRAL quickly, before the water discharge at that location increases with the rising flood. This could have happened in the cases of the 2003 and 2008 augmentations noted above. But other gravel augmentations were implemented well upstream from TRAL – about 6000 yd^3 (9000 tons) of gravel was placed at the Lewiston fish hatchery (1.5 miles upstream) in 2006 and 2007 and about 8500 yd^3 (12750 tons) of gravel was injected into the channel during flow releases at the Diversion Pool (1 mile upstream) between 2008 and 2015 (Gaeuman 2011; Gaeuman 2014b; unpublished data). These upstream gravel additions presumably prevented the decline in gravel transport observed elsewhere in the study area, but if they lowered the threshold for gravel entrainment it occurred far enough upstream that many hours or days were required for the mobilized material to reach TRAL. By that time, the water discharge at TRAL would have increased with the rising flood. This means that the measured value of Q_c would necessarily be larger than the discharge that caused the initial entrainment. Moreover, the arrival of the sediment from the upstream reaches would increase the transport rate measured at TRAL beyond the rate that would have resulted from local entrainment alone. Such a delayed addition of sediment fluxes from upstream sources would produce a rapid increase in the sediment transport rate and a sediment rating curve with a large exponent.

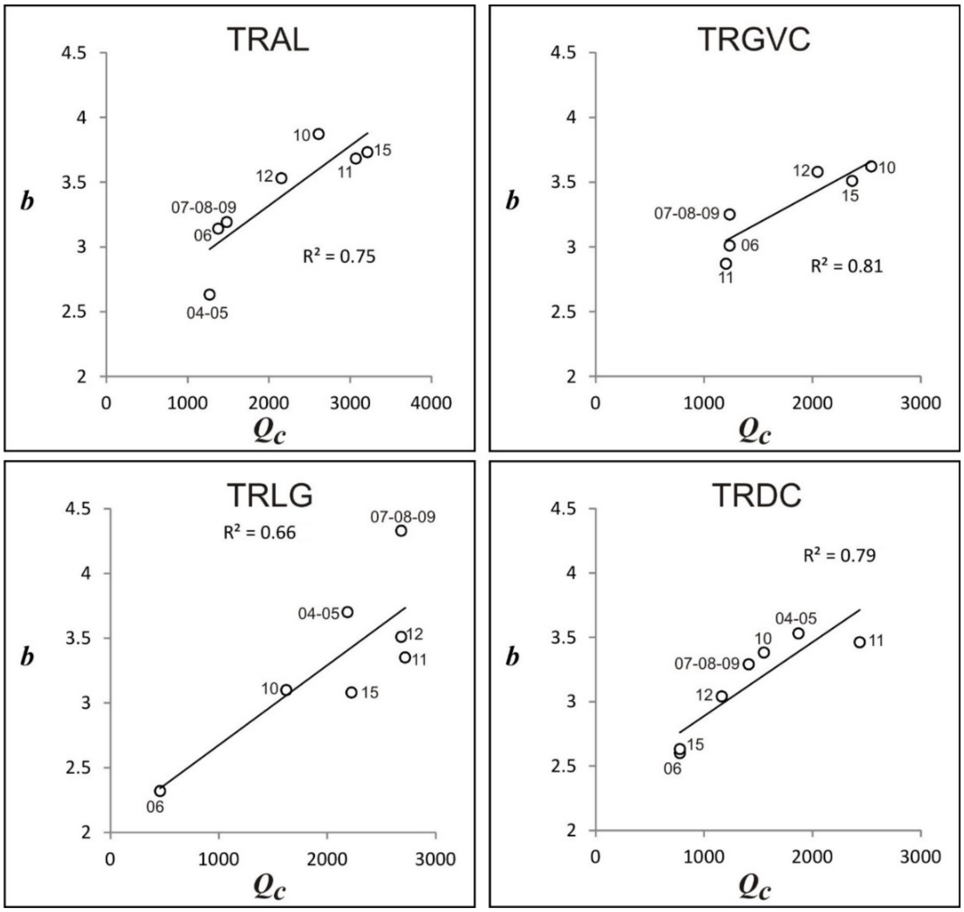


Figure 12: Values of *b* from plotted as a function of Q_c. Parameters are from gravel rating curves for seven time periods spanning 2004 through 2015. Time intervals associated with individual points are indicated.

The scenario described in the preceding paragraph is hypothetical, and should not be interpreted as an analytical result. Rather, we suspect that the observed patterns in sediment fluxes, rating curves, and rating curve parameters are the result of a combination of factors that include measurement errors, statistical artifacts, and a variety of physical processes, some of which can be tentatively identified. It is important to recognize that the processes involved are complex and interpreting the physical meaning of these data must be approached with caution. Other potential causes of the observed changes in sediment fluxes and transport rates will be discussed in more detail in a later section describing changes in channel geometry and substrate conditions.

Regardless of the reasons for why gravel flux rates and rating curves have changed over the past decade, it is clear that the rating relations can be highly variable. The average *E* across all sampling locations and all years is about 1.82^{-1} and the standard deviation is 2.40, which is equivalent to an error of ± 140%. The overall 95% confidence interval for loads predicted with the long-term rating curves is between 22% and 298% of the loads reported by GMA. The ratios of the maximum and minimum gravel transport rates predicted for flows of 6000 ft^3/s range from a low of 2.3 at TRDC to a high of 11.0 at TRAL. The magnitude of these year-to-year fluctuations in transport rates are such that future transport rates cannot accurately be predicted from past measurements.

As a final note to this section of the report, we wish to point out an additional difficulty associated with the use of long-term composite rating curves. Because these log-term datasets combine data from different years in which transport characteristics can vary substantially, they contain a high degree of scatter. This scatter means that the transport data is internally inconsistent, such that no single curve can accurately represent its structure. An obvious deficiency in the rating curves is signaled by the fact that the values of *E* plotted in Figure 10 tend to be less than unity, particularly for TRDC. This means that the loads estimated from the period-specific rating curves tend to be somewhat smaller than the loads reported by GMA. One possible reason that the gravel rating curves underestimate the annual loads could be that the curves were fit to log-transformed data, but we did not apply a transformation bias correction to the resulting curves. We did, however, evaluate the use of bias correction and found that it did not improve the correspondence between the two sets of load estimates. According to Ferguson (1986), an appropriate correction ($\hat{C}$) is given by $\exp(2.65\sigma^2)$, where σ is the standard error with two degrees of freedom of the base-10 logarithm of the rating curve residuals. We found the computed values of $\hat{C}$ for the four datasets to range from 2.01 to 3.17. Application of these corrections to the rating curves would increase the predicted loads by a factor of between 2 and 3 and increase values of *E* by between 4 and 6. For example, a point on Figure 10 indicating that a load estimate exceeds the GMA load by a factor of 2 could shift upward to indicate that it exceeds it by a factor of as much as 6. The ‘corrected’ rating curve estimates would differ from the loads reported by GMA by considerably wider margins than the estimates obtained without bias correction.

Although transformation bias and other methodological factors may contribute, the difficulty in removing bias from the rating curves primarily arises from the inherent inadequacy of attempting to fit rating curves to highly-scattered composite transport data. The difficulty is illustrated using the long-term composite gravel transport data collected at TRDC as an example. Figure 13 shows data collected at TRDC in different years using different symbols and a separate power function for each year. The exponents (slopes) and intercepts of the various curves can be seen to differ substantially. The ends of the curves near the low end of the discharge range span more than an order of magnitude of transport rates, and extrapolating some curves (e.g., 2007) to high discharges suggest differences in transport rates exceeding two orders of magnitude. The character of any single rating curve fit to this collection of distinct transport relations will depend as much on factors such as how many samples were obtained in the different years or how the samples were distributed over discharge as much as on the sediment transport characteristics of the site.

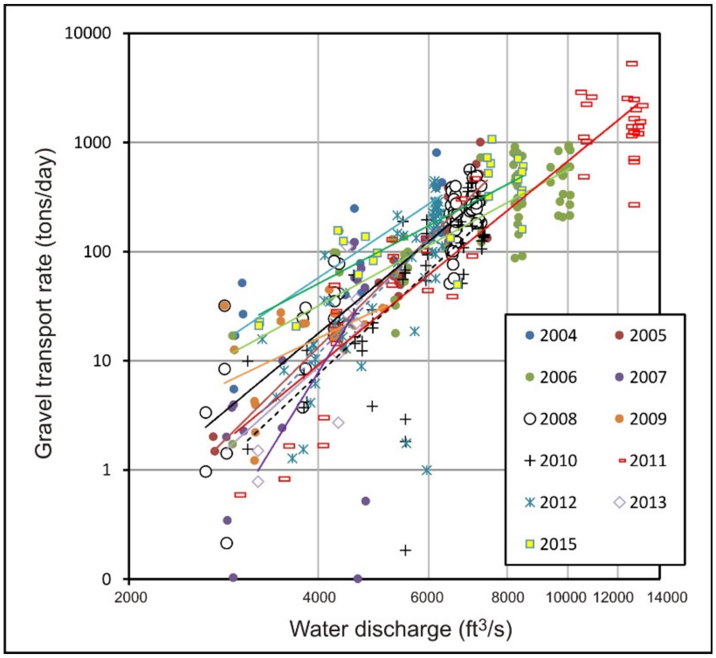


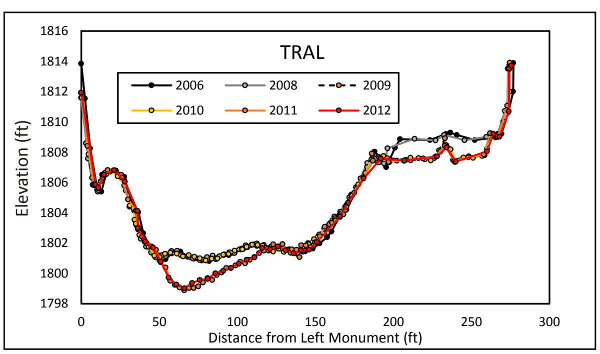
Figure 13: Gravel bedload samples collected at TRDC in water years 2004 through 2015.

Channel Morphology

Sediment monitoring activities were in 2006 to include collection of water surface slopes, channel cross section surveys, and surface grain size information at the sampling transects. These types of data are crucial for assessing factors that could be influencing changes in the measured transport rates. Theoretical models for quantifying sediment transport rates typically incorporate sediment grain size information and a measure of fluid force, which is most commonly expressed as shear stress at the stream bed (τ_0). The magnitude of the fluid forces for a given water discharge is a function of channel geometry – i.e., channel width, depth, and slope – and the effectiveness of a given τ_0 level for mobilizing sediment depends on the size of the sediment particles on the stream bed. Changes in any of these factors can alter sediment transport rates.

The simplest expression available to quantify shear stress in a wide, steady, uniform, open-channel flow is $\tau_0 = \rho ghS$, where ρ is the density of water, g is gravitational acceleration, h is the flow depth, and S is the water surface slope. It is obvious that increasing h or S, with all other factors remaining the same, will cause τ_0 to increase. Recalling that the total water discharge, Q, is equal to the product of h, the channel width (w), and the average flow velocity (U), it is also clear that, everything else remaining the same, increasing w will tend to decrease h and therefore cause a decreases in τ_0 and the sediment transport rate per unit channel width. However, these three factors are inter-related, so it cannot be assumed that a change in one factor is not compensated by a change in another factor. For example, it is possible that an increase (decrease) in w that decreases (increases) τ_0 could nonetheless increase (decrease) the total sediment transport rate because active transport could be occurring over a wider (narrower) portion of the streambed. Or, to give another example, an increase in *S* at a cross section will tend to increase τ_0 unless the cross section adjusts its shape or roughness enough to produce a compensating decrease in *h*. *S* itself is semi-independent of the local geometry. Its value depends on the geometry of hydraulic controls located upstream and downstream of the sampling transect and the measurement locations chosen. Water surface elevations at most points in a river are determined by hydraulic controls located some distance downstream, so the values of *h* measured at a given cross section can also be semi-independent of the local geometry. Despite these complications, the ancillary data collected at the four sampling locations provides some insight to what factors might be responsible for the observed changes in sediment transport characteristics.

Change in channel geometry can be evaluated with topographic surveys of the channel cross section at the sampling locations. The earliest of these surveys were conducted after the 2006 flow release, as high water in the early spring prevented data collection prior to the release. Figure 14 displays multiple repeated cross section surveys collected at the TRAL and TRLG sampling transects. Two changes are evident in the TRAL surveys: a decrease in the elevation of the right overbank area after 2008 and deepening of the channel thalweg after 2010. The first of these changes is entirely due to mechanical excavation associated with the Cableway channel rehabilitation project, which was implemented in the summer of 2008. This artificial floodplain lowering had no effect on *w*, *h*, or *S* within the active channel (the portion of the channel bed that conveys bedload) and so likely had a negligible effect on sediment transport rates. The second change indicates that the 2011 flow release, which peaked near 12000 ft^3/s, produced up to 2 ft of scour along the left side of the active channel. Although this change likely increased the maximum flow depth in the cross section, its impact on sediment transport rates, is uncertain. Channel geometry at this cross section may have changed during the relatively large 2015 flow release as well, but 2015 survey data could not be located for inclusion in this report. Repeat cross section surveys at TRLG indicate that virtually no changes in channel geometry have occurred at that sampling location since 2006.



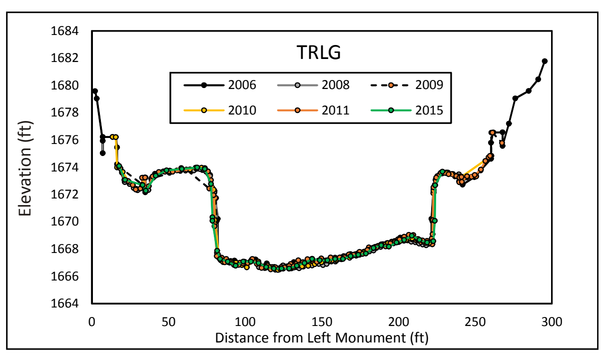


Figure 14: Repeated channel cross sections at TRAL and TRLG.

Due to a channel rehabilitation project implemented in 2010, the sampling transect at TRGVC was moved about 300 ft downstream from its original location prior to the 2011 flow release. Changes at those two sampling transects are therefore presented separately. The only change to occur at the original transect location prior to the 2011 flow release was excavation of the left overbank area that was implemented as part of the 2010 rehabilitation project (Figure 15a). Project designers intended this excavation to decrease τ_0 and promote gravel deposition in the area during peak flow events, and subsequent monitoring indicates that those objectives were at least qualitatively met (Gaeuman 2014a). Some of that deposition is apparent in Figure 15b, which shows changes that occurred at the new transect location over a period spanning the 2011 and 2014 flow releases. Peak stream flows during the drought years of 2013 and 2014 were too small to generate large changes in channel geometry, so virtually all of the change depicted in the graph occurred in 2011 or 2012. Peak flows in 2012 were moderate at this site and so may have generated some change, but 2012 cross section data could not be located for inclusion in this report.

Interpretation of changes in cross section geometry at the TRDC sampling transect are complicated by the fact that the sampling location was moved twice. The first move occurred prior to the 2011 flow release to accommodate changes in channel alignment resulting from a 2010 rehabilitation project. The 2011 sampling location proved to have undesirable hydraulic characteristics, so the transect was moved again prior to the 2012 release. The time series of surveys shows no change in channel geometry through 2010 (Figure 16a). The 2011 release, however, produced up to 3 ft of scour near the left edge of the channel bed (Figure 16b). Cross section data from 2012 could not be located for this report, but surveys in 2015 indicate that the relatively large 2015 flow release produced only minor adjustment in channel geometry (not shown).

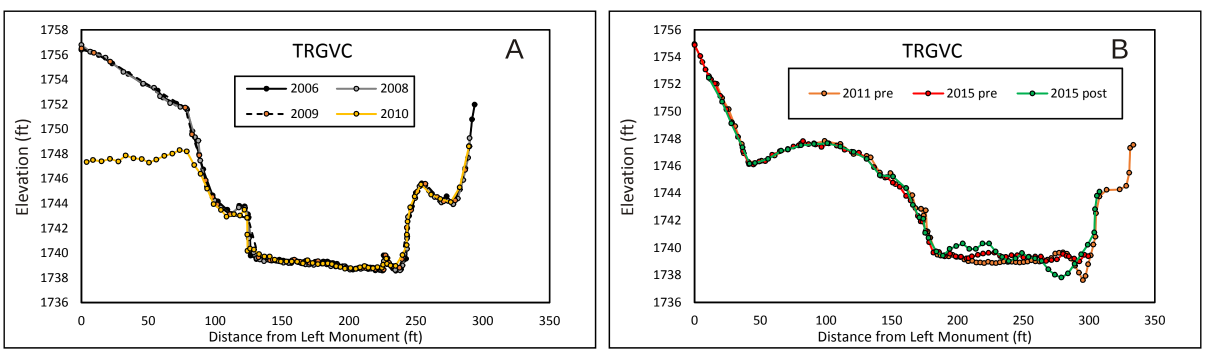


Figure 15: Repeated channel cross sections at TRGVC.

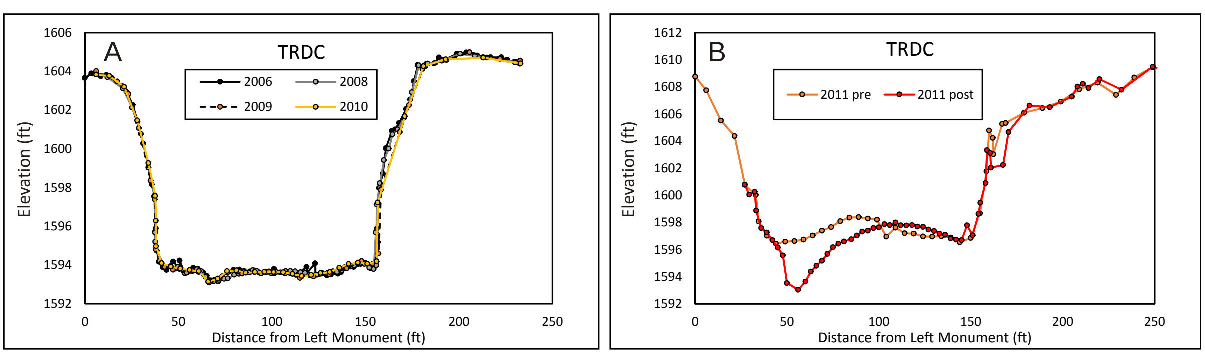


Figure 16: Repeated channel cross sections at TRDC.

Figure 17 displays water surface slopes through the sampling transects measured at multiple discharge levels in selected years. The data for TRAL, which is based on water surface elevations measured at the upstream and downstream ends of a reach spanning 830 ft, seems to indicate that *S* increases abruptly as discharge exceeds about 6500 ft^3/s (indicated by the vertical dashed line in Figure 17). This increase is presumably due to washing out of a hydraulic control that creates backwater conditions through the sampling location at lower flow levels. There is no evidence, however, of a temporal shift in *S* at TRAL. Likewise, the data for TRLG give no indication of temporal changes in *S* at that location. Some anomalous 2011 *S* measurements at discharges between 8000 and 10000 ft^3/s (indicated by the “?” in Figure 17) hint at the possibility of transient bed dynamics, but the long-term stability shown by the TRLG cross section and the presence of abundant bedrock in the downstream hydraulic control suggest that the anomalous data are more likely due to measurement error. The deviation of those measurements from the trend of the remaining data is about 0.0005. These slopes were measured over a relatively short channel distance of 370 ft, so that magnitude of error in the slope requires an error in the water surface elevation measurements of less than 0.2 ft.

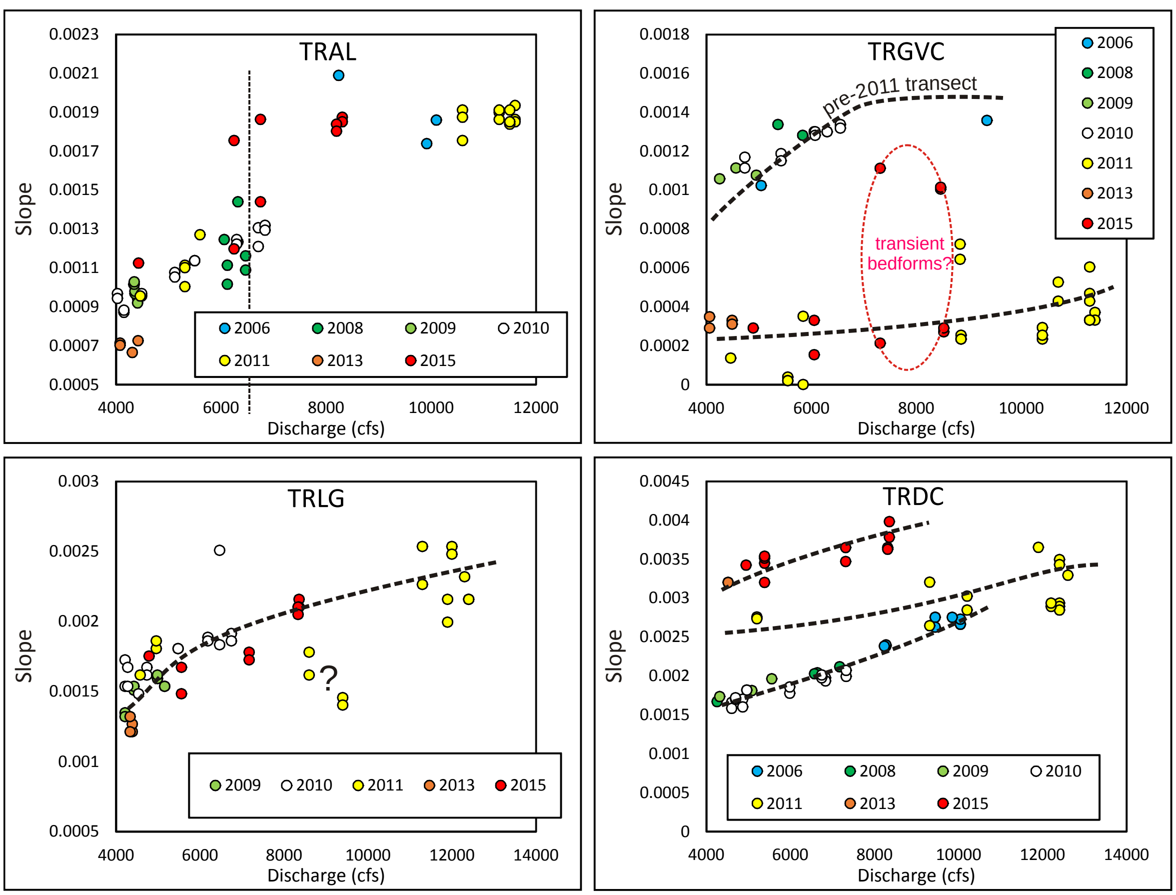


Figure 17: Water surface slopes through the sampling transects measured at multiple flows in different years.

Water surface slopes measured at TRGVC show a clear difference between the original pre-2011 transect location and the new transect location established for the 2011 and later flow releases. Measurements at the original and later locations spanned channel lengths of 540 and 515 ft, respectively. *S* for the new location is on the order of four times smaller than *S* for the original location, a finding that could partially account for lower-than-expected sediment transport rates after 2010, such as in 2011 when gravel transport rates at this site reached their minimum level (Figure 7). Low transport rates were observed during the 2011 flow release even though 2050 yd^3 (3075 tons) of gravel were injected into the flow immediately upstream from the sampling transect during the peak of the release. As previously noted, this was likely due to the 2010 construction of an artificial meander bend that created backwater conditions upstream from the meander. Large fluctuations in *S* for discharges of about 7000 to 9000 ft^3/s measured in 2015 (red dashed ellipse in Figure 17) and to a lesser extent in 2011 may be due to the migration of transient bedforms through the reach. Gaeuman (2014a) reported that the topographic relief of the bed increased by 36% over the course of the 2011 flow release, and bathymetric data collected during the 2015 release clearly show the development and migration of gravel dunes approximately 1.5 ft high in the vicinity of the sampling transect (unpublished data).

Water surface slopes measured at TRDC appear to differ between the original pre-2011 transect location, the 2011 transect, and the post-2011 transect. Measurements at the three locations spanned channel lengths of 785, 510, and 450 ft, respectively. The smallest range of *S* values (0.0015 to 0.0025) are observed at the original transect location, whereas slopes measured in 2015 at the current transect were nearly twice as large. This relative increase in *S* could be partially responsible for the recent upturn in fine bed material and gravel transport rates at TRDC, particularly in 2015 when both reached their historical maxima (Figure 5 and Figure 7).

The size distribution of sediment particles on the channel bed affects sediment transport rates in several different ways. Bed material sediments in gravel-bed rivers are composed of particles spanning a wide range of sizes, from fine sand to cobbles or even boulders. It is intuitively obvious that larger fluid forces are necessary to mobilize larger particles, and the mobility of sediments composed of various sized particles is often estimated by representing the sediment mixture with a single particle size. The median particle size of the mixture, which is denoted D_{50}, is the most common percentile selected for this purpose. Addition of sand to a gravel stream bed increases the mobility of the sediment mixture in two ways. First, the addition of sand increases the fraction of the bed composed of smaller particles and so can decrease the D_{50}. But, perhaps more importantly, the sand smooths the bed, which increases near-bed flow velocities so the larger particles on the bed become more mobile even if the absolute size of the D_{50} remains constant. The larger particles on the bed, such as the 90th percentile size (D_{90}) – also play a key role in determining the mobility of the sediment mixture. These larger particle tend to shelter smaller particles in their wakes, reducing the mobility of the smaller sediments. In summary, increasing the concentration of smaller particles increases the mobility of the entire stream bed, including the largest particles, whereas increasing the concentration or size of the larger particles decreases the mobility of the smallest particles. This generalization is true even when the median particle size remains constant. It should be recognized, however, particle organization also influences bed mobility. Although changes in the degree of bed surface imbrication or other stabilizing structures may have contributed to the observed changes in transport, no data for evaluating those factors are available.

Temporal changes in the D_{50} and D_{90} particle sizes on the stream bed measured at the four sediment monitoring locations are shown in Figure 18. The particle size metrics presented in these graphs refer to the size distribution of the gravel (> 8 mm) fraction of the bed surface only. That is, sand and other fine bed material was excluded from the computation. Two of the sites, TRLG and TRDC, show an apparent decrease in the D_{90} particle size over time. TRGVC also shows a weak trend toward smaller D_{90} over time, but the apparent correlation is heavily dependent on a single large D_{90} observed in late 2006. Temporal trends are mostly absent in the D_{50} values, except for at TRLG where a slight decrease is apparent. Grain sizes at TRAL show little variability over time, except for a sharp decrease in both size percentiles observed in 2009. That change in the bed surface particle size can be attributed to the 2008 Cableway channel rehabilitation project that included placement of 5400 yd^3 (8100 tons) of mobile gravel immediately upstream from the sampling transect.

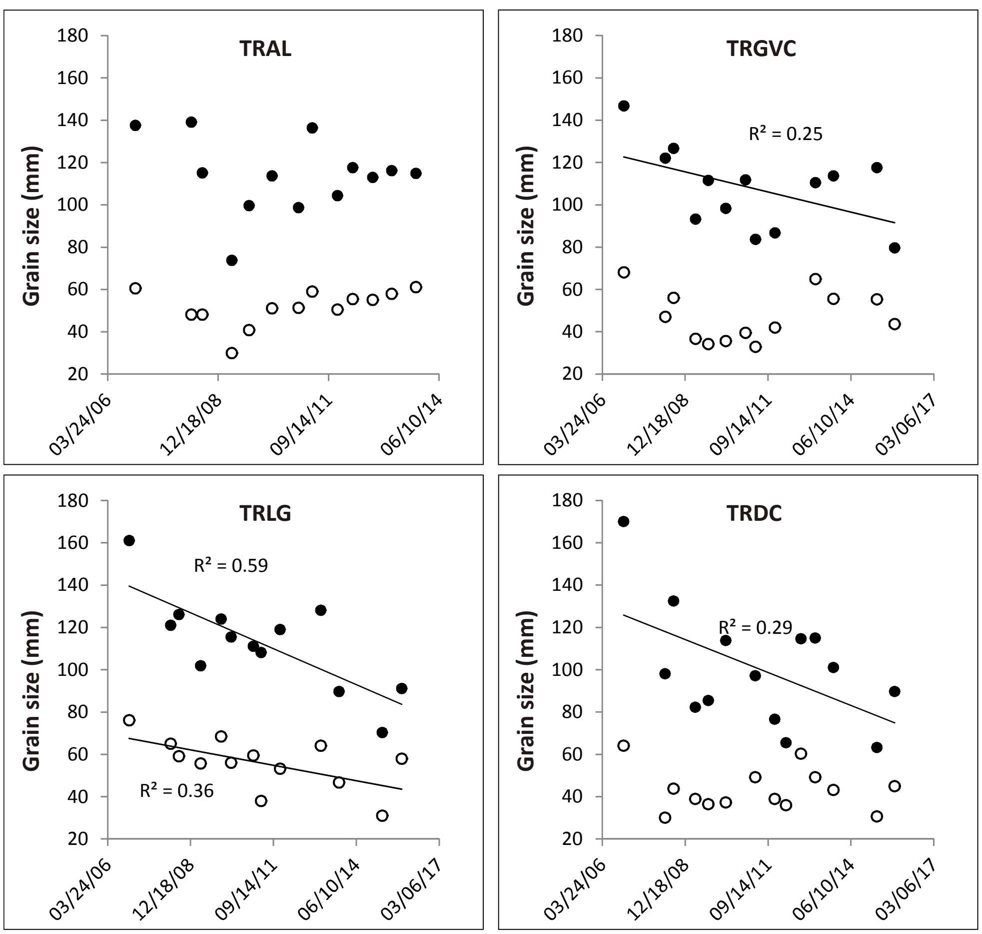


Figure 18: D_{50} (open circles) and D_{90} (filled circles) bed surface particles sizes measured by pebble count. Regression lines are shown where apparent trends exist.

Temporal changes in the percentage of fine bed material on the stream bed at the four sediment monitoring locations are shown in Figure 19. The proportion of finer sediment fractions on the stream bed appears to be decreasing with time at three of the four sampling locations, but the correlations are poor. TRDC shows perhaps the most geomorphically significant change – the trend line at that site indicates a decrease in the proportion of surface fines at that site from a characteristic value of about 7% in the first years of the time series to between about 1.5% in recent years. According to the equation presented by Wilcock and Crowe (2003), this change corresponds to an increase in the dimensionless reference shear stress needed to mobilize the mean surface grain size (τ^*_m) of more than 50%. In other words, the fluid forces required to mobilize the bed surface increased by a factor of 1.5 over time. The characteristic proportion of fines observed at TRAL was about 2.5% early and decreased to 0% later, suggesting a potential increase in τ^*_m by about 20%. The plot of surface fine content at TRGVC includes more scatter, but still shows a weak trend for surface fines content decreasing from about 7% to about 2.5%, which would theoretically correspond to a 22% increase τ^*_m. No trend in the proportion of surface fines is apparent at TRLG.

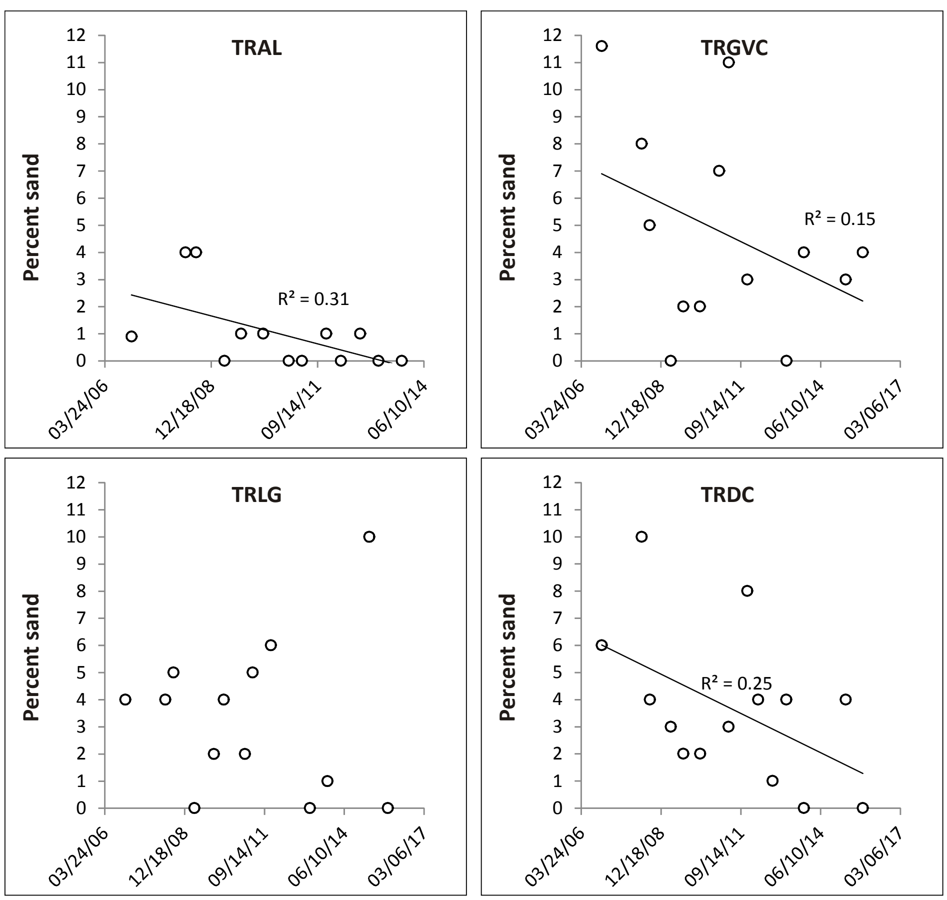


Figure 19: The percentage of the bed surface composed of fine bed material, as determined by pebble count. Regression lines are shown where apparent trends exist.

The morphologic data presented above provides some insight into the causes of the long-term trends in gravel transport described in the previous section, but considerable uncertainty remains. In summary, gravel transport rates at most sites tended to be larger prior to about 2010 than after that year, except for in 2015 when gravel transport rates recovered to a relatively high level. The exception is at TRAL, where gravel transport characteristics have been relatively stable from year to year. We hypothesize that these long-term trends reflect a general decrease in the quantity of fine bed material and other fine sediment fractions delivered to the river channel. A loose correspondence between the long-term fine bed material transport characteristics and gravel transport characteristics and trends toward decreasing percentages of fine sediment on the bed surface over time at some sampling locations provides some evidence to support this hypothesis. This explanation is also consistent with the relative stability of transport characteristics at TRAL, since the percentage of fine sediment on the bed at that site has always been small and so has changed relatively little. It does not explain changes in transport rates observed at TRLG, however, because no decrease in the percentage of fine sediment on the bed was detected at that site. These relationships and their interpretations are complicated by the fact that the exact locations of the sediment monitoring transect changed at two (TRGVC and TRDC) of the four monitoring sites during the study period.

It is possible that changes in the supply of fine sediment at the three more downstream sites were much larger and more consistent than is indicated by observations of the percentage of fine sediment on the bed surface. Regardless of the year, those percentages are small compared to the proportions of the total sediment loads that consist of fine bed material. Except at TRAL, where fine bed material transport rates are much smaller, the finer bed material fractions typically comprise 50% to 90% of the bed material load (Figure 20). This strongly suggests that the amount of fines on the bed at sampling transects is a poor indicator of the quantity of fine sediments available for transport in the river. We suspect that most of the fine material that is activated during high flow periods is stored in pools, eddies, along the channel margins, and in voids within the gravel substrate, rather than on the bed surface at sampling transects, which are intentionally located in reaches with simple prismatic geometry and minimal bed relief.

The observed long-term gravel transport trends at TRGVC and TRDC are also related to the relocation of those sampling transects, both of which were moved after 2010. The relocated transects differ from the original transects in cross sectional geometry and, more significantly, in slope. The slope through the post-2011 TRDC sampling transect is about twice as steep as the original transect. This increase could easily account for the upturn in gravel transport rates in 2015, regardless of any changes in the fine sediment supply or other factors. Likewise, the 4-fold decrease in the slope through the post-2010 transect at TRGVC compared to the original transect, as well as floodplain excavation performed as part of the 2010 Lowden rehabilitation project, undoubted reduced sediment transport capacity at the sampling transect. Given these alterations, plus the apparent decrease in the fine sediment supply over time, a large decline in gravel transport rates after 2010 should be expected. Although gravel fluxes were smaller after 2010 than in some other years, it is perhaps surprising that they remained as large as they did. As noted above, post-2010 gravel transport rates at TRGVC were undoubtedly boosted by gravel augmentations implemented 500 ft upstream from the sampling transect in 2011 and again in 2015 (see the gravel budget section of this report). Cross section slope and geometry have no relevance for temporal changes in gravel transport rates at the other two sampling locations (TRAL and TRLG), as those transects have not changed appreciably over the study period.

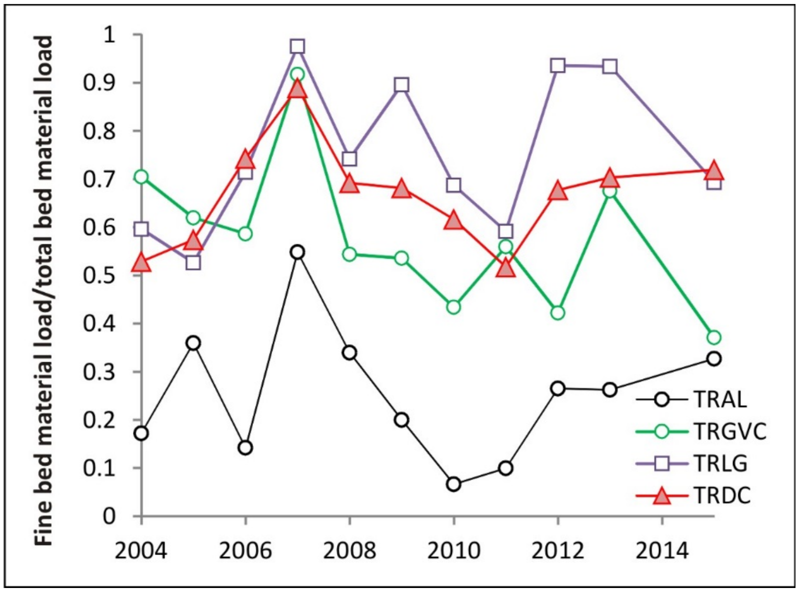


Figure 20: The fraction of the total annual sediment loads comprised of fine bed material.

Changes in bed surface gravel size distributions appear to be of secondary importance for driving temporal trends in gravel transport. A trend toward decreasing D_{90} values at TRGVC might be expected to increase transport rates, but the effect is difficult to discern given the competing effects of slope changes, mechanical alterations, and gravel augmentations. A similar trend at TRDC may have contributed to the increased transport rate in 2015, but cannot be separated from the change in the transect slope. The gravel sizes on the bed at TRAL have remained relatively constant, as have gravel transport rates.

Of the four sediment monitoring locations, TRLG stands out as presenting the greatest challenge for reconciling the trend in gravel transport with the observed morphologic changes. That location shows a relatively clear trend toward decreasing gravel transport with time, but no morphologic change that could account for that trend is apparent. Cross section geometry and slope and the percentage of fine bed material on the bed surface at that site have remained constant, and clear trends toward decreases in both the D_{90} and the D_{50} surface gravel sizes should cause transport rates to increase, rather than to decline. The only evidence hinting at a cause for the long-term trend in gravel transport at the site is a roughly parallel pattern of decreasing fine bed material transport, which suggests that both trends are driven by a decrease in the overall supply of fine sediment size fractions.

Geomorphic Significance of Temporal Variability

It is demonstrated above that sediment transport characteristics in the Trinity River are subject to significant inter-annual fluctuations superimposed on multi-year trends produced by a variety of known and unknown factors. As a result, sediment monitoring data collected in past years are of limited value for estimating sediment fluxes in future years – sediment loads based on pre-existing data can easily deviate from loads based on data collected during a particular flow event by a factor of three or more. We now evaluate the significance of errors of this magnitude when applying sediment monitoring results to adaptive management of the river. Such an evaluation requires consideration of the management actions these data are intended to inform.

TRRP gravel augmentation activities are intended to increase bed mobility and gravel transport rates in the reaches of the river upstream from Indian Creek (USFWS and HVT 1999; TRRP and ESSA 2009). A quantitative target for this objective has been identified by scaling transport rates at TRDC to the hydrology in the more upstream reaches (Gaeuman 2014b). The total gravel flux at TRDC from 2004 through 2015 exceeds the fluxes at the more upstream monitoring locations by factors of about 2.3 to 4.2, so a commensurate increase in transport is a clear management objective. Although it is obvious that future changes cannot be detected in the absence of future data collection, the level of sampling effort required to usefully estimate future sediment transport rates is not. It is easy to see, however, that the magnitude of inter-annual fluctuations in gravel transport characteristics is similar to the magnitude of the changes the monitoring is intended to detect. Multiple years of sampling are therefore necessary to demonstrate that management has successfully altered the sediment regime at a particular sampling location.

The need to accommodate inter-annual fluctuations in sediment transport rates speaks to the frequency of sampling required. This aspect of the monitoring is influenced by the magnitude of the flow events in the particular year in two ways. First, small flows transport less sediment than large flows, so that it is most important to sample in years with larger flow releases. Secondly, sediment transport rates are more erratic when rates are small and more consistent when transport rates are relatively large. This increased variability at low transport rates is partially due to the fact that very small changes in τ_0 produce disproportionally large changes in the transport rate when conditions are near the threshold for sediment entrainment. In addition, sampling variability increases at low transport rates when fewer particles are in motion because the number of particles captured is small and therefore has a large variance relative to its mean. Thus, both the quality of the measurements themselves and their relative importance are greater in years with larger flows.

The effect of flow magnitude on measurement quality is evident in the values of E calculated with long-term composite rating curves compared to GMA loads as presented earlier. Values of E for gravel loads are considerably larger for years with peak flows of less than about 7000 ft^3/s than for years with larger peaks (Figure 21a). This can be explained by noting that gravel transport rates during the smaller flow events are very low so the sample sizes are dominated by stochastic variability in the numbers of particles captured. The tendency for E to be smaller for larger flows, however, is only partly due to improved sample quality at higher transport rates. Rather, it also reflects the fact that the high-discharge end of the long-term composite rating curves are fit to data from just one flow event that attained that magnitude. That single event has a disproportionate influence on the shape of the fitted curves so that the long-term composite relations for each sampling location are virtually guaranteed to approximate the transport rates that would be predicted by curves fit to only the data from that year. The relatively small values of *E* associated with the largest flow event should not be construed as an indication that future flow events with a similar peak magnitudes will produce transport rates similar to those observed in the past.

Sediment loads increase with water discharge, so the actual errors in the load estimates follow a somewhat different pattern than do the values of *E* themselves. Errors in the dimensional gravel loads estimated with a single long-term composite rating curve tend to be large for the larger flows (Figure 21b). This arises because, although *E* for the smallest flows are large, the actual magnitude of the transport over the smaller releases is very small, whereas the dimensional errors associated with larger flows are large even for relatively small *E* because the loads themselves are large.

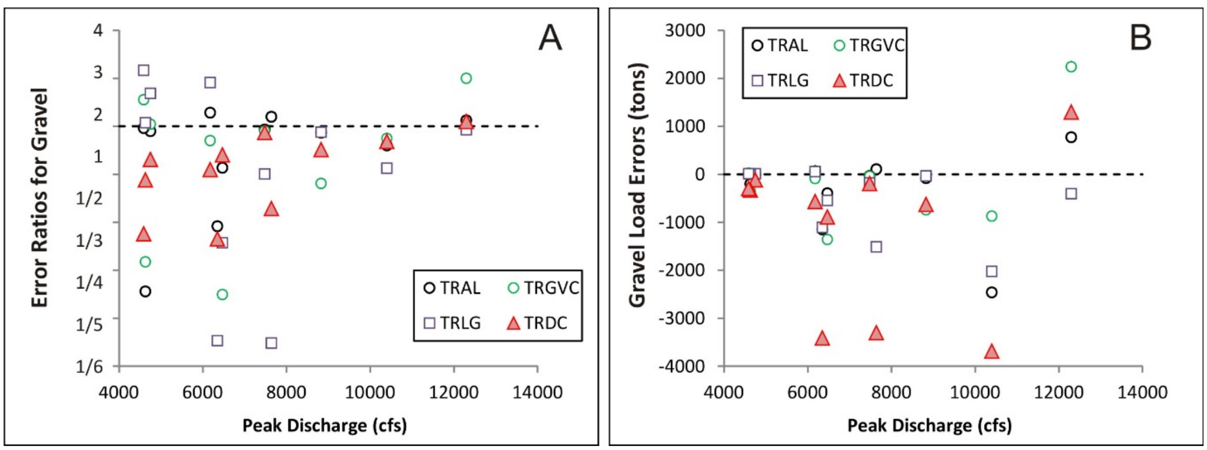


Figure 21: A) Gravel error ratios (equation 4) and B) dimensional errors in gravel loads estimated by long-term composite rating curves relative to load reported by GMA plotted as a function of the peak flow released from Lewiston Dam.

Apart from the need to detect trends toward increased (or decreased) sediment transport at the sampling locations, TRRP's foundational documents stress the importance of sediment monitoring for the purpose of tracking sediment budgets for the gravel and fine bed material size classes (USFWS and HVT 1999). The potential impact on budget computations of errors arising from the use of long-term composite rating curves to estimate loads can be assessed by summing the potential errors over the duration of sediment monitoring at each of the four sampling locations. Although both positive and negative errors exist, the record is dominated by negative errors, as already discussed in a previous section of this report. That is, loads transported by the larger flow events tend to be underestimated, whereas loads transported by smaller event are often overestimated. Cumulative errors are therefore negative at all sites. Despite the fact that the negative errors are partially cancelled out by the positive error, the absolute magnitude of the errors are large enough to be geomorphically significant. The cumulative errors due to the use of the long-term composite rating curves to estimated gravel loads are -17%, -10%, -38%, and -26% of the cumulative gravel fluxes based on GMA load estimates at TRAL, TRGVC, TRLG, and TRDC, respectively. The corresponding cumulative errors for fine bed material are -39%, -34%, -39%, and -29%. A similar situation would remain regardless of whether the data plotted in Figure 10 were shifted upward with a transformation bias corrections – the difference would be that the cumulative errors would be positive instead of negative, and larger than if left uncorrected. The significance of the cumulative errors in the gravel loads for interpreting gravel budget results is considered in greater depth in the gravel budget section of this report.

Bedload Hysteresis

Hysteresis occurs when flow-transport relationships differ in different parts of the flow hydrograph. Clockwise hysteresis is defined by higher sediment transport rates for a given flow early in a flow event, such that a plot of transport rates versus flow discharge traces a clockwise loop with respect to time. Anticlockwise hysteresis refers to instances when transport rates for a given flow are higher late in the flow event. In some cases, different portions of a hydrograph can show clockwise and anticlockwise behavior, resulting in a figure-8 trace with respect to time on a plot of transport rate versus discharge. Hysteresis has been attributed to a variety of factors, including changes in the organization of surface sediments (Gaeuman 2010b, Mao 2012), exhaustion of readily mobile sediments (Moog and Whiting 1998), activation of different sediment sources (Mao et al. 2014), and increased turbulence intensity on the rising limb of a flood (Tabarestani and Zarrati 2015).

Traditionally, the terms “early” versus “late” in a flow event are taken to mean before and after the peak of the hydrograph. This way of dividing flow events is most applicable to natural hydrology in which rising and falling limbs of the hydrograph are separated by a clear peak. High-flow events on the Trinity River, however, often include a steady peak flow bench lasting multiple days, so a clear separation between rising and falling limbs may be absent. Thus, we broaden the definition of hysteresis to include systematic variations in the sediment transport rate across a period of steady flow.

The potential for hysteresis in Trinity River bedload transport rates is relevant to the development of high-flow release hydrographs with peak magnitudes and durations that will achieve certain sediment management objectives. One such objective is to support gravel augmentation efforts by mobilizing the added gravel and distributing it downstream to areas where gravel supplies may be limited. Success in meeting this objective could theoretically be measured in terms of total gravel loads, where larger loads imply that more of the augmented gravel has been redistributed downstream. In that case, the presence of clockwise hysteresis means that a given flow magnitude becomes relatively less effective for achieving the management objective as the duration of the flow increases, such that managers may choose to implement shorter peak flow durations to conserve the available water volume for other uses. Another potential objective of high flow releases is to flush excess fine bed material downstream. In the context of that objective, clockwise hysteresis would indicate that excess fine bed material is rapidly flushed downstream, whereas anticlockwise hysteresis would indicate that a prolonged peak flow is required.

The type and degree of hysteresis in Trinity River bedload transport samples is herein evaluated for the high-flow portions of most of the spring flow releases implemented in water years 2004 through 2015. Hysteresis is evaluated separately for the fine (0.5-8 mm) and coarse (>8 mm) components of bedload by plotting transport rates for each of those size fractions with the corresponding release hydrograph and visually identifying instances where the transport rates increase or decrease for given flow levels over the time periods when flows are large enough to generate significant bedload transport (i.e., 3000 to 4000 ft^3/s). Water years 2013 and 2014, which spanned the worst part of an historic multi-year drought, are excluded from the analysis because a total of just four samples were collected in 2013 and no samples were collected in 2014.

Two limitations of this analysis must be acknowledged. First, because bedload samples collected at relatively low discharges were ignored, it is possible that the analysis failed to identify instances of hysteresis that occur at relatively low flows on the leading and trailing tails of the hydrographs. This deficiency, however, is of little importance for assessing management actions because sediment transport at those lower flows represent a negligible contribution to the river's overall sediment budget. A perhaps more important limitation of the analysis is that no attempt has been made to evaluate the statistical significance of the results. This is because, in most cases, the data are inadequate to support a rigorous statistical treatment. Bedload transport data are notoriously variable for a variety of reasons that include the possibility for large sampling errors and the highly stochastic nature of the transport process itself. At the same time, the number of samples that can be collected in a given flow release is limited by the difficulty of the sampling procedure. Thus, indications of hysteretic behavior often rest on just a handful of samples that cannot support a high level of statistical confidence. Results reported below should therefore be regarded as indications of the likelihood that hysteresis may have occurred during a given flow event, rather than as assertions that it did or did not occur.

Bedload Hysteresis by Site and Size Fraction

Coarse bedload samples at TRAL show some evidence of clockwise hysteresis in six of the 10 sample years evaluated. Decreases in transport rates across the peak bench portion of the hydrograph are apparent in 2004, 2007, 2008, 2010, and 2012, with the decreases typically occurring on the second or third day of the bench (Table 1, Figure 22). Clockwise hysteresis is also indicated by low transport rates at lower flows on the falling limb of the 2009 release, even though maximum transport rates were attained on the fifth day of the peak bench. The highest gravel transport rates during the 2015 flow release were attained at the end of the peak flow period, suggesting anticlockwise hysteresis in that year. Little evidence of any type of hysteresis can be discerned from the data for the remaining three years.

Fine bedload samples at TRAL display evidence of clockwise hysteresis in six of the 10 years, those being 2006, 2007, 2008, 2010, 2012, and 2015 (Table 1, Figure 22). Data from the remaining years lack convincing evidence that hysteresis occurred. The largest transport sample in 2004 was recorded on the final day of a 10-day peak bench, but too few samples are available to conclude that anticlockwise hysteresis was present at TRAL that year.

Table 1: Frequency of apparent hysteresis in Trinity River bedload samples.

	Gravel Transport			
	Clockwise	Anticlockwise	Figure-8	None
TRAL	6 of 10	1 of 10	0 of 10	3 of 10
TRGVC	5 of 8	0 of 8	0 of 8	3 of 8
TRLG	4 of 10	0 of 10	0 of 10	6 of 10
TRDC	3 of 10	3 of 10	0 of 10	4 of 10
Total Gravel	18 of 38 (47%)	4 of 38 (11%)	0 of 38 (0%)	16 of 38 (42%)
	Fine Bedload Transport			
TRAL	6 of 10	0 of 10	0 of 10	4 of 10
TRGVC	8 of 8	0 of 8	0 of 8	0 of 8
TRLG	4 of 10	0 of 10	0 of 10	6 of 10
TRDC	3 of 10	1 of 10	2 of 10	4 of 10
Total Fine	21 of 38 (55%)	1 of 38 (3%)	2 of 38 (5%)	14 of 38 (37%)
Total Both	39 of 76 (51%)	5 of 76 (7%)	2 of 76 (3%)	30 of 76 (39%)

Gravel transport rates at TRGVC suggest the occurrence of clockwise hysteresis in five of the eight years considered at that site (Table 1, Figure 23). We note that the preponderance of clockwise hysteresis at TRGVC during this time frame may be partly due to the fact that high-flow gravel injections were implemented immediately upstream from the sediment monitoring transect in 2011 and 2015 (Gaeuman 2014a). Both injections were performed within one day of the time when the maximum flow was attained, and so may have contributed to the larger gravel transport rates observed early in the peak period. No evidence for gravel hysteresis is apparent in the data for the remaining three years (2007, 2010, and 2012). Clockwise hysteresis was even more dominant for fine bedload at TRGVC, with data from all eight years providing some support for that interpretation.

Hysteresis was less frequent at TRLG than at the more upstream stations, with indications of hysteresis appearing in just four of 10 years for both components of the bedload (Table 1, Figure 24). Hysteresis was clockwise in all cases, appearing in 2004, 2008, 2011, and 2015 for gravel transport and in 2008, 2010, 2011, and 2015 for fine bedload. No convincing evidence for any type of hysteresis was found in data from the remaining years, although a few sample sets (fine bedload in 2007 and both bedload components in 2009) include a few samples hinting at possible anticlockwise hysteresis (Figure 24).

Patterns of hysteresis become increasingly diverse at TRDC, where indications of clockwise hysteresis in gravel transport is observed in just three of 10 years (2009, 2010, and 2011), but evidence of anticlockwise hysteresis is observed in the three years of 2006, 2012, and 2015 (Table 1, Figure 24). No hysteresis in gravel transport is evident for the four remaining years. Fine bed material transport characteristics at TRDC are even more variable. Clockwise hysteresis is apparent in three of the 10 years (2009, 2010, and 2012), anticlockwise hysteresis appears to have occurred in 2011, and evidence of a figure-8 pattern of hysteresis appears in 2 years (2006 and 2008). No hysteresis in fine bedload transport is evident for the four remaining years.

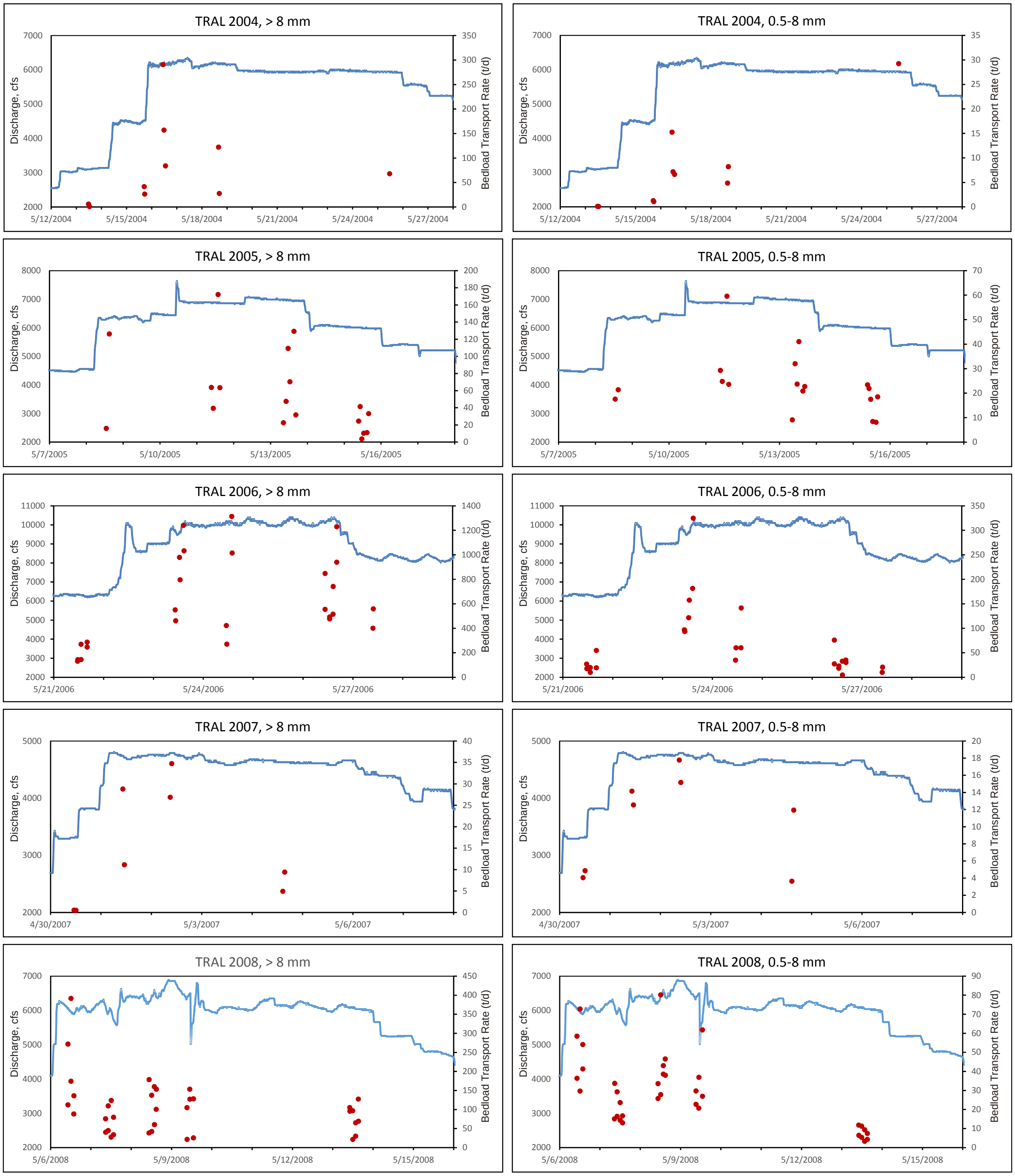
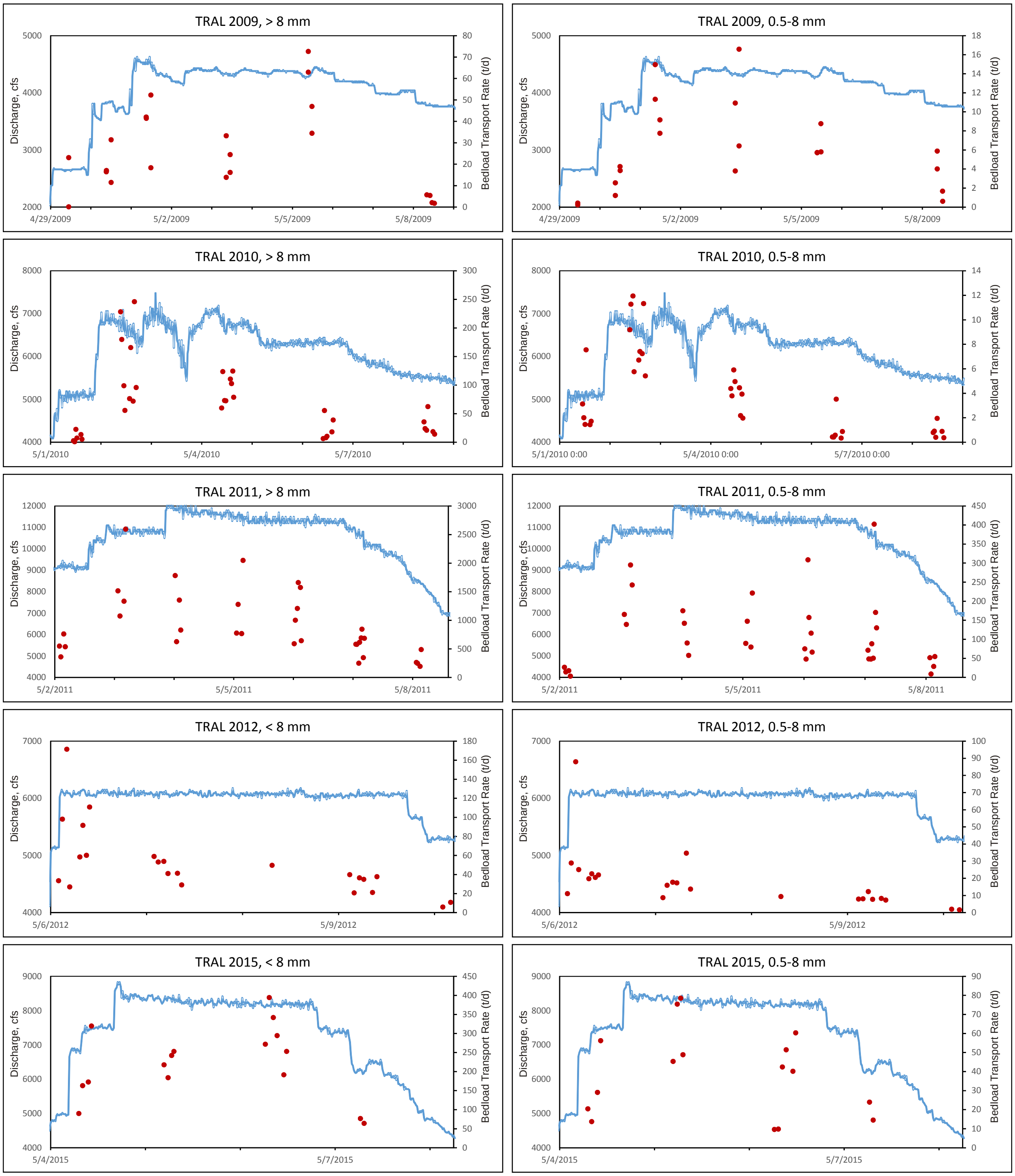


Figure 22: Bedload transport samples and flow hydrograph during high-flow period at TRAL.



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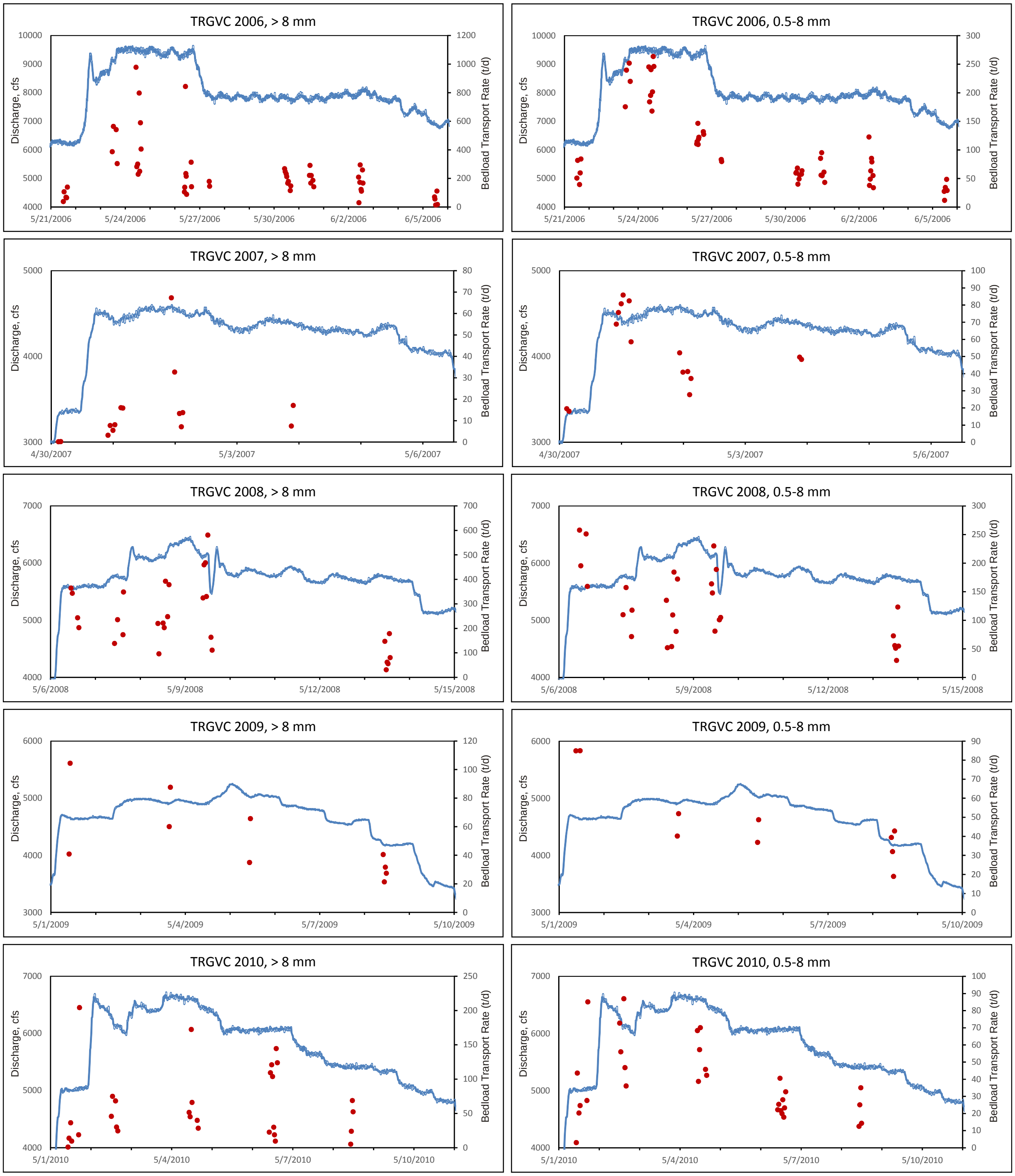

Figure 23: Bedload transport samples and flow hydrograph during high-flow period at TRGVC.

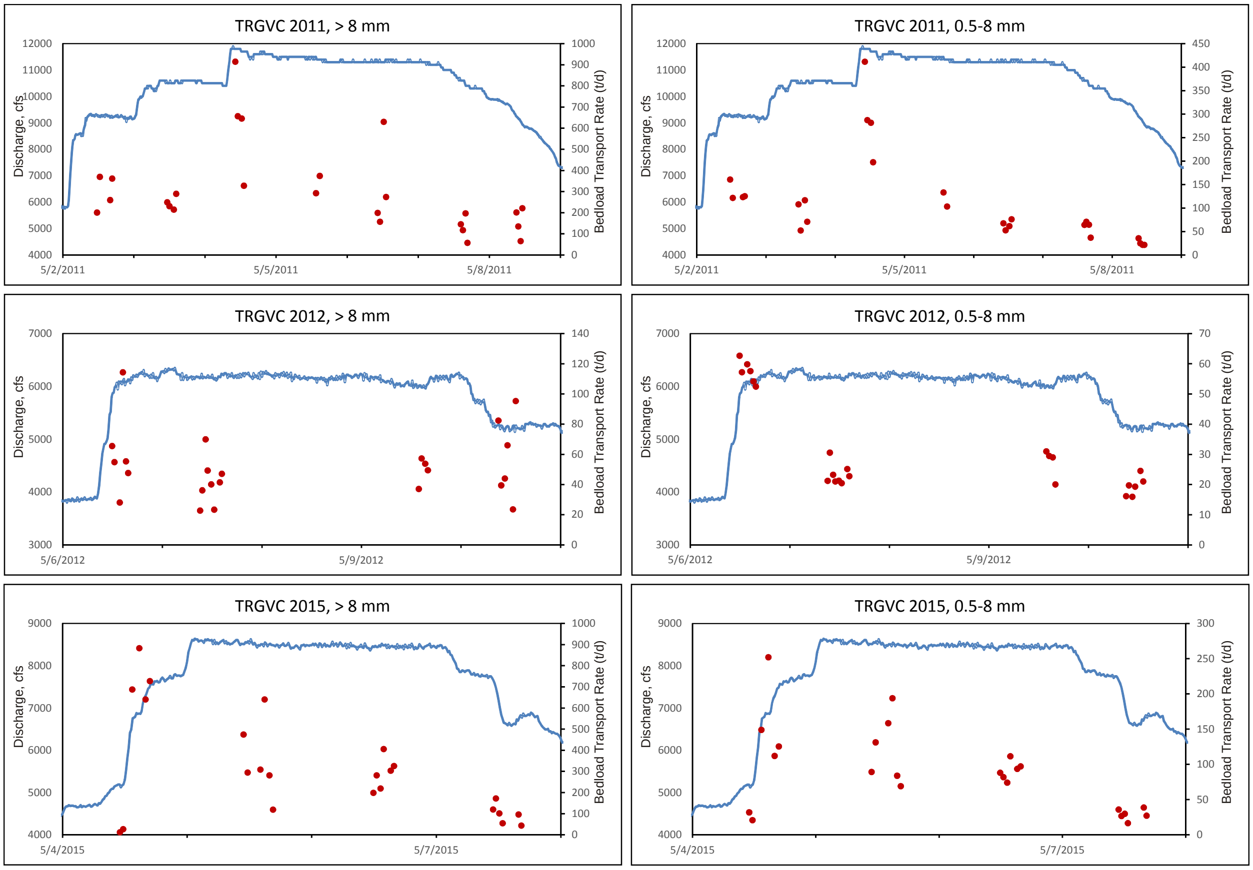

Figure 23, continued

Overall, 51% of the datasets show indications of clockwise hysteresis, whereas anticlockwise and figure-8 hysteresis is suggested in just 10% of the datasets (Table 1). If just the 56 datasets associated with the most upstream three locations are considered, 59% show clockwise hysteresis and just 1 (2015 gravel transport at TRAL) shows evidence of a different type of hysteresis. The preponderance of clockwise hysteresis at the more upstream three locations is likely due to depletion of the available sediment supply over the course of the flow release. At the beginning of the spring flow release from Lewiston Dam, sediment delivered to the Trinity River from tributaries during the winter is available for transport. However, sustained high flows in the main river can deplete those supplies over time, causing sediment transport rates to decrease. This is particularly true for the finer fractions of the sediment load, which can be transported downstream much farther and more rapidly than the gravel factions. Because gravel transport rates are increased by the presence of fine bed material, depleting the supply of the finer sediment fractions is likely to contribute to clockwise hysteresis in gravel transport as well.

At TRDC, however, clockwise hysteresis is no longer the dominant behavior. Instead, evidence for anticlockwise or figure-8 hysteresis appears in 30% of the 20 datasets associated with that location, which is the same as the proportion of datasets that show evidence of clockwise hysteresis there. For example, transport rates for both gravel and fine bedload attained relatively high levels at TRDC on May 23 and May 24, 2006, on the first two days of a 10000 ft^3/s flow bench (Figure 25). Transport rates for both bedload components then decreased slightly on May 25 and 26, suggesting a clockwise pattern of hysteresis across the flow bench. Flows then dropped to about 8500 ft^3/s on May 28. The immediate response was for transport rates to decrease for both bedload components. But fine bedload transport rates increased to their highest levels observed during the entire release three days later, even though flow rate had decreased. Gravel transport rates likewise increased during the middle of the 8500 ft^3/s bench, possibly as a result of the arrival of a higher concentration of the finer bedload component. At any rate, these increases in the transport rates of both bedload components define a phase of anticlockwise hysteresis that, coupled with the decline in transport across the peak bench, suggests a figure-8 hysteresis loop for the full flow release.

We hypothesize that the greater complexity of transport characteristics at TRDC can be attributed to the fact that TRDC is farther downstream from Lewiston Dam than the other three sampling locations and therefore is downstream from a larger number of potential sediment sources. Sediment reaching TRDC is derived from a multitude of sources, some of which are nearby and some of which are located far upstream. For example, nearby sediment sources include Weaver Creek and Indian Creek, both of which are located within a mile of the TRDC sampling location, but it is also conceivable that fine sediments derived from Rush Creek 16 miles upstream could reach TRDC during a prolonged high flow. Because the time required for sediment to arrive at TRDC increases with distance from the source, fine sediments derived from distant sources have the potential to boost fine bedload transport rates late in the flow release. In addition, the delayed arrival of fine sediment from far upstream has the potential to stimulate an increase in the coarse bedload transport rate, thereby producing anticlockwise hysteresis in the transport of both components.

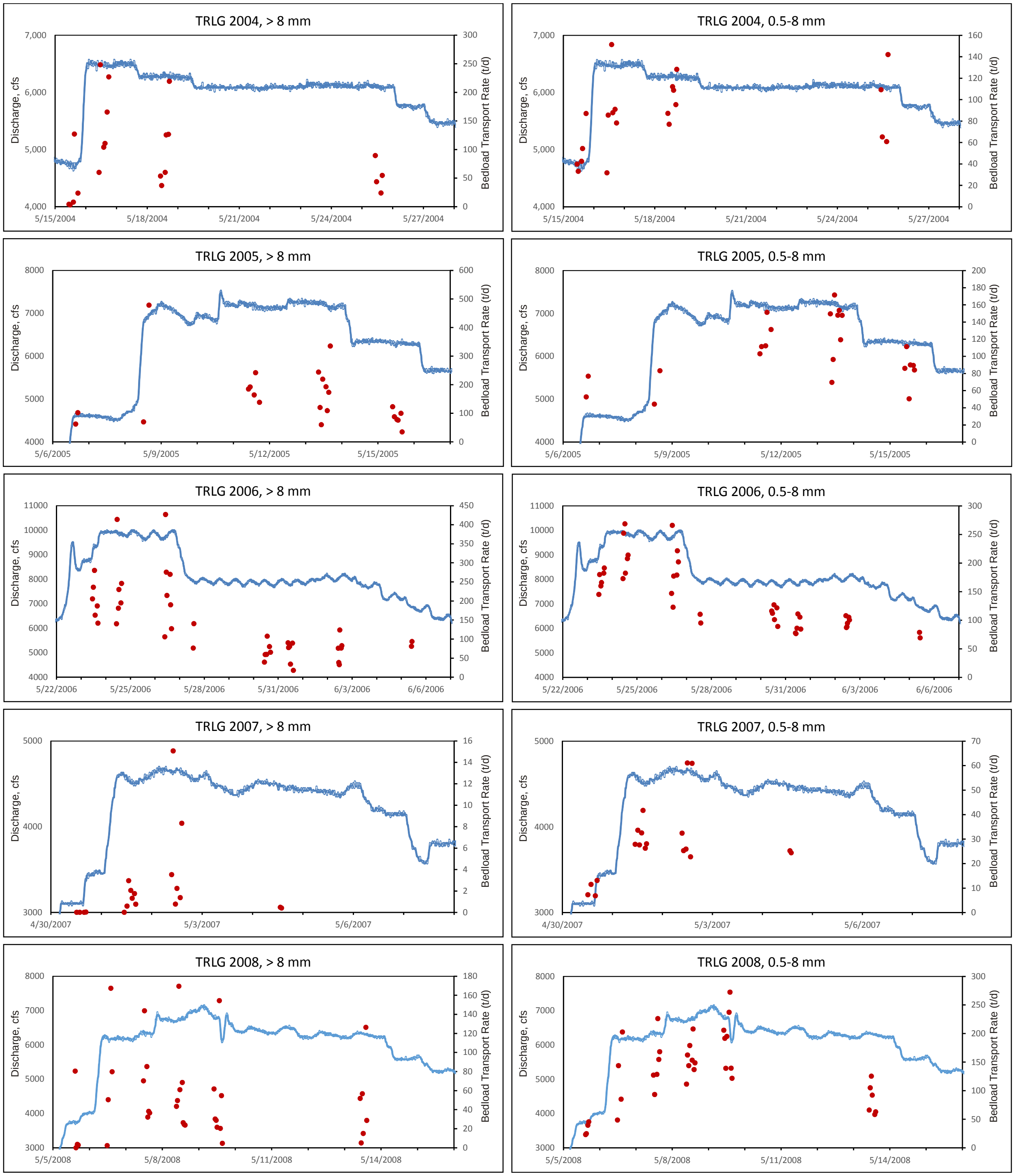

Figure 24: Bedload transport samples and flow hydrograph during high-flow period at TRLG.

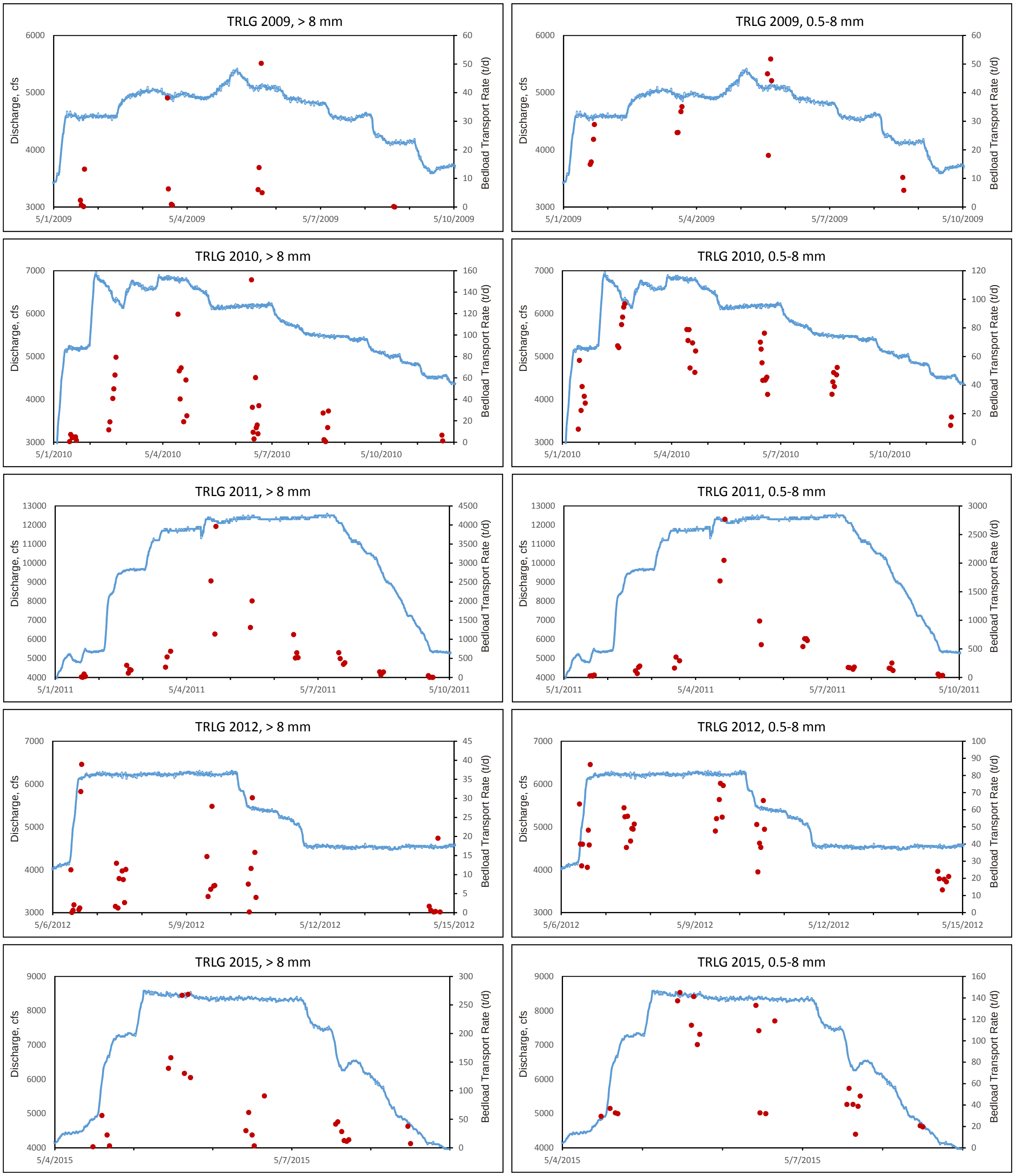

Figure 24, continued

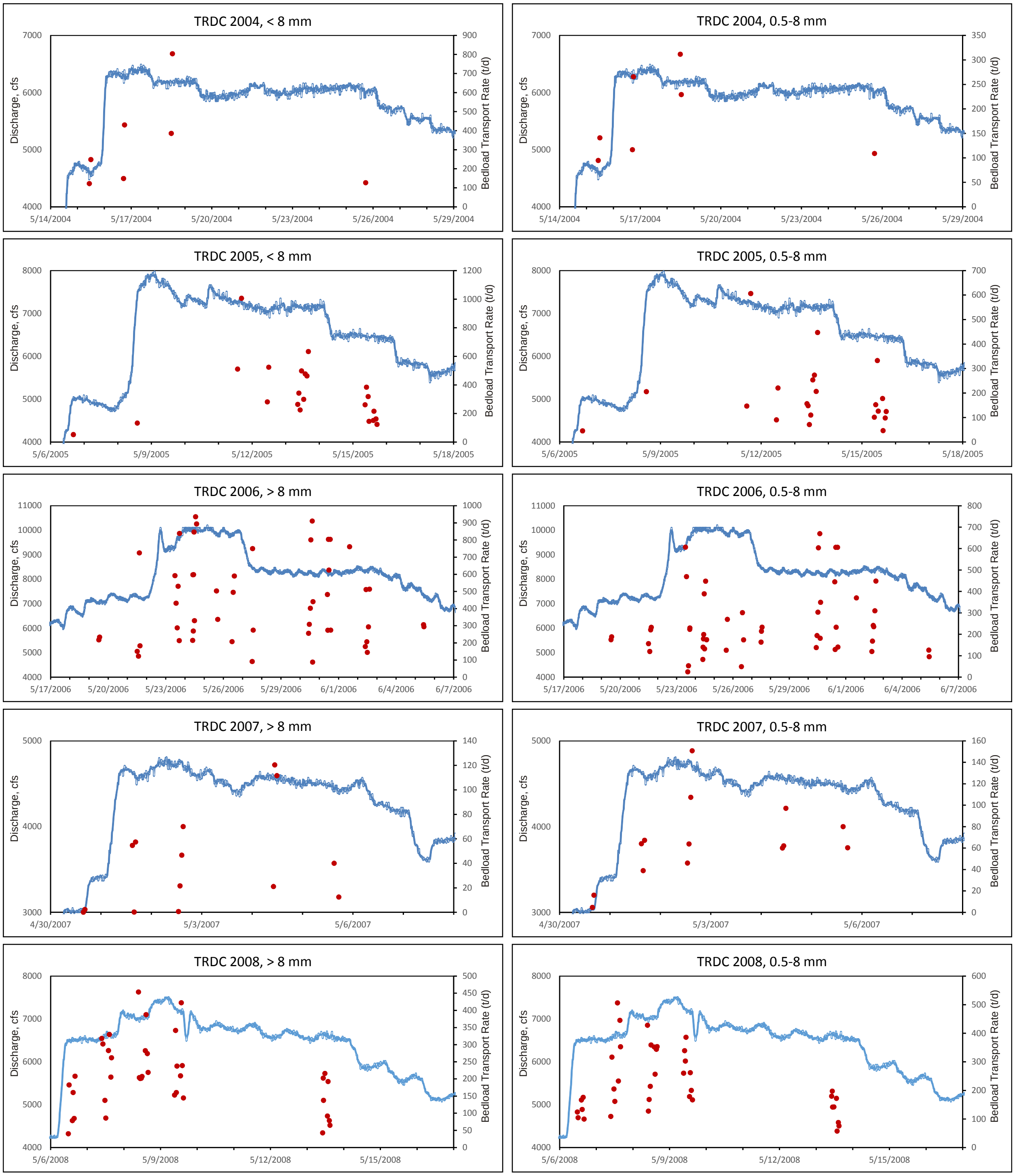

Figure 25: Bedload transport samples and flow hydrograph during high-flow period at TRDC.

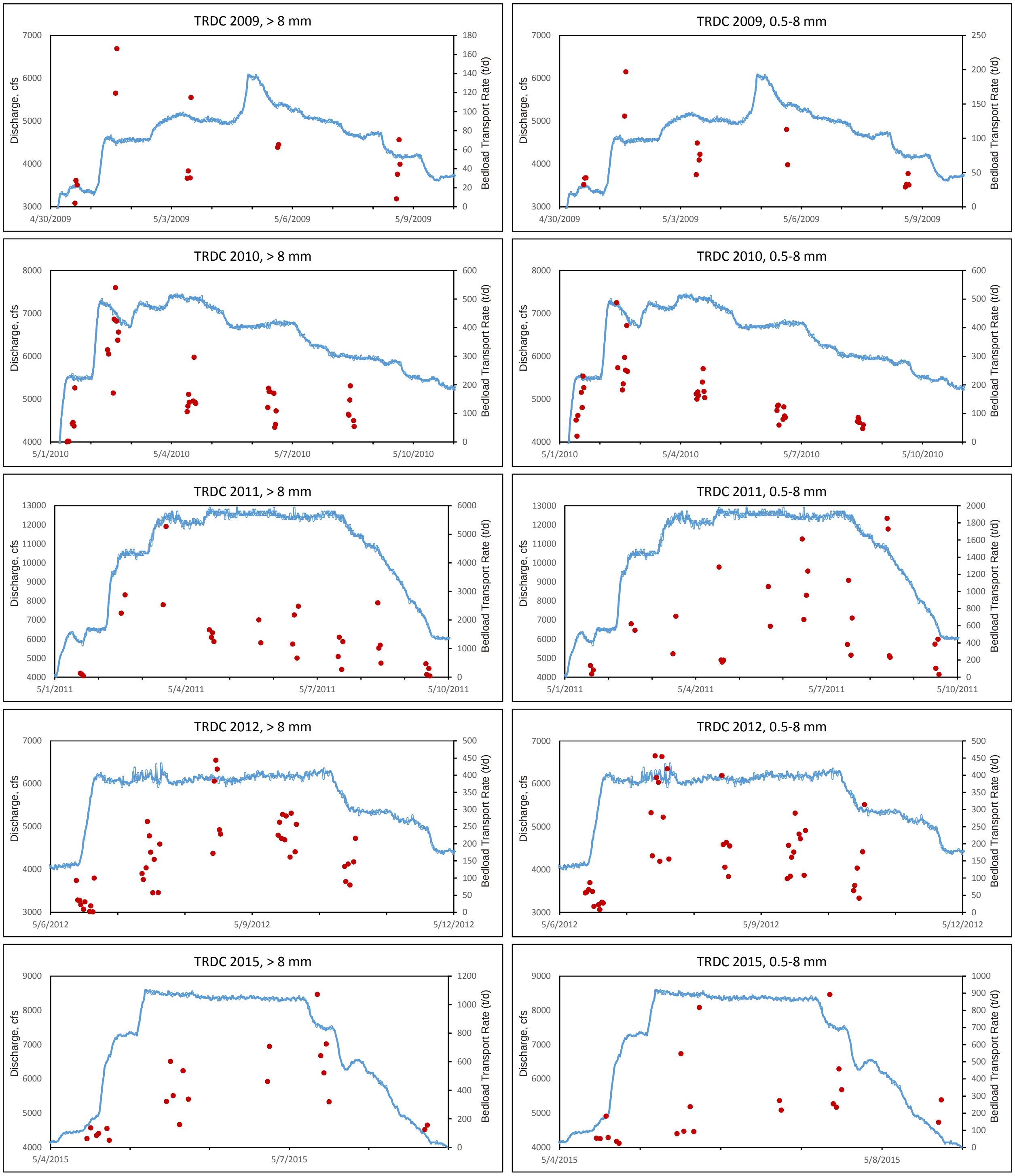

Figure 25, continued

Relationship between Gravel and Fine Bedload Hysteresis

Gravel and fine bedload transport for a given year and sampling location appear to behave in a similar fashion most of the time. Of the 38 datasets, 24 (63%) show evidence of the same type of hysteresis for both components of the bedload or no evidence of hysteresis for either component (Table 2), whereas evidence of opposite types of hysteresis is observed in just three (8%) of the datasets. Some form of hysteresis in one component of the bedload is coupled with a lack of evidence for hysteresis in the other component in at least 30% of the dataset from the two most upstream sampling locations, whereas that combination of behaviors appears in just 20% of the datasets from the two more downstream locations. Two of the three cases of opposite types of hysteresis and six of the seven instances of anticlockwise or figure-8 hysteresis occurred at TRDC. Although the number of instances involved in these associations are too few to support a high level of statistical confidence, these results suggest that gravel and fine bedload transport characteristics are more tightly coupled at TRLG than at TRAL or TRGVC, and that the transport characteristics of the finer and coarse bedload components at TRDC are relatively independent of one another.

Table 2: Comparison of coarse and fine bedload hysteresis types for each year at each site. C = clockwise hysteresis, A = anticlockwise, N = no hysteresis indicated, F8 = figure-8 hysteresis with both clockwise and anticlockwise at different times during the same release.

Year	TRAL Gravel/Fine	TRGVC Gravel/Fine	TRLG Gravel/Fine	TRDC Gravel/Fine
2004	C/N		C/N	N/N
2005	N/N		N/N	N/N
2006	N/C	C/C	N/N	A/F8
2007	C/C	N/C	N/N	N/N
2008	C/C	C/C	C/C	N/F8
2009	C/N	C/C	N/N	C/C
2010	C/C	N/C	N/C	C/C
2011	N/N	C/C	C/C	C/A
2012	C/C	N/C	N/N	A/C
2015	A/C	C/C	C/C	A/N
Percent Same	60%	63%	80%	50%
Percent N with hysteresis	30%	37%	20%	20%
Percent Opposite	10%	0%	0%	20%

It is possible that the transport behaviors displayed by the fine and coarse bedload components are similar more often at TRLG than at TRAL or TRGVC because the supply of fine bed material is relatively limited at the two more upstream locations. Both of those locations are upstream from Grass Valley Creek, which has historically been regarded as being among the largest sources of fine sediment supplied to the river (Trso 2004; Gaeuman 2010a). A relative lack of fine sediment supply upstream from that point is reflected in the cumulative fine bed material load at TRGVC since 2003, which is approximately two-thirds of the load at TRLG and about a fifth of the load at TRDC (Figure 2). The cumulative load at TRAL is even smaller, comprising less than a seventh of the TRLG load and about one twenty-third of the TRDC load. At TRAL in particular, where the cumulative fine bed material flux since 2003 is less than a fifth of the cumulative gravel flux, it is questionable whether the abundance of fine bed material is sufficient to significantly alter gravel transport rates. Thus, a tight correspondence between the types of hysteresis observed for the gravel and fine components of the bedload should not be expected. At TRLG, on the other hand, the cumulative fine bed material flux since 2003 is 93% larger than the cumulative gravel flux, so it seems reasonable to suspect that the supply of fine bed material could be sufficient to materially alter gravel transport rates. Consequently, gravel transport rates behave in a similar fashion as the fine bedload transport rates 80% of the time and in no cases do they show an opposing type of hysteresis.

The proportion of the fluxes of fine and coarse sediments at TRDC since 2003 is almost identical to that at TRLG, with the cumulative fine bed material flux exceeding the cumulative gravel flux by 93%. Consequently, fluctuations in the supply of fine bed material are likely to contribute to corresponding fluctuations in the gravel transport rate at TRDC, thereby leading to instances of clockwise or anticlockwise hysteresis in both components. But the frequency of differing types of hysteresis at this location suggests that independent fluctuations in the gravel supply are also responsible for changes in gravel transport rates. Such fluctuation in the gravel supply can also be due to the existence of discrete upstream source areas, although the distances to those sources are relatively limited. Observations of gravel transport in the Trinity River indicate that it is unlikely that the gravel component of the bedload travels more than a mile or two over the course of a flow release (Gaeuman 2011; Gaeuman and Krause 2013), but the proximity of TRDC to several significant gravel-producing tributaries (Reading Creek and McIntyre Gulch, per Gaeuman 2014b, in addition to Indian and Weaver Creeks) creates the potential for gravel derived from those different sources to reach TRDC at different times during a given flow event. Thus anticlockwise hysteresis in the gravel transport rate can occur with or without anticlockwise hysteresis in the fine bedload transport rate.

Gravel Budget

Sediment budgets address questions regarding how sediment storage volumes are changing. The TRRP sediment monitoring program was initially founded to track budgets for fine sediments as well as a coarse sediment budget. This report considers the coarse sediment, i.e. gravel, budget only.

The gravel budget presented herein continues previous sediment budgets for the Trinity River downstream from Lewiston Dam. Previous sediment budgets drawn on for this report cover the periods 2004-2009 (Wilcock 2010), 2004-2010 (Gaeuman and Krause 2011), and 2004-2012 (Gaeuman 2013). This report develops a sediment budgets for gravel (particles > 8 mm in diameter) only. This budget is intended to inform gravel augmentation activities by assessing whether gravel additions are balancing gravel fluxes in the river near Douglas City, CA, and whether gravel storage is increasing in specific sections of the Trinity River downstream from Lewiston Dam.

At its core, gravel augmentation in the Trinity River has one physical purpose. That is, to ensure that the quantity of mobile coarse bed material available for transport in the river is sufficient to support bar formation and a continual reshaping of channel topography. This end is embodied in two sub-objectives: a short-term sub-objective to increase storage of gravel and small cobble bed material in the upper river to eliminate any local dam-induced deficit in those materials, and a long-term sub-objective to maintain that storage level by continuously replenishing the gravel that is transported downstream by environmental flow releases (USFWS and HVT 1999).

Methods and Data Sources

A sediment budget tracks changes in sediment storage (ΔS_{ij}) in a particular area, *i*, over a particular time period, *j*, according to:

$$\Delta S_{ij} = I_{ij} + E_{ij} \tag{5}$$

where I_{ij} is the total amount of sediment that enters area *i* in time period *j*, and E_{ij} is the total amount of sediment exported from the same area in the same time period. Sediment budgets for the Trinity River make use of four budget areas, hereafter referred to as budget cells, whose boundaries are defined by four sediment monitoring locations and Lewiston Dam, which serves as the upstream boundary for the entire study area. From upstream to downstream, the four monitoring locations are referred to as Trinity River at Lewiston (TRAL), Trinity River above Grass Valley Creek (TRGVC), Trinity River at Limekiln Gulch (TRLG), and Trinity River at Douglas City (TRDC). Budget cells defined by these boundaries are Lewiston Dam to TRAL (budget cell 1), TRAL to TRGVC (budget cell 2), TRGVC to TRLG (budget cell 3), and TRLG to TRDC (budget cell 4). Locations of sediment monitoring stations, budget cells, and major tributaries are illustrated in Figure 26.

The sediment budgets include just one export term (E_{ij}) for each cell, these being equal to the annual quantities of sediment transported across the downstream boundary of the cell. In-channel excavation associated with rehabilitation activities is not considered. The input terms (I_{ij}) to the sediment budgets, however, are composed of numerous sediment sources, including the sediment exported from the budget cell immediately upstream and sediments delivered from tributary watersheds. In some cases, the sources also include coarse sediments added to the active channel as part of gravel augmentation activities, and/or sediment eroded from the stream banks. It may be worth noting that inclusion of sediments introduced into the channel via bank erosion raises some ambiguity regarding how one defines the relevant sediment budget storage reservoirs; see Gaeuman (2013) for a discussion of this issue.

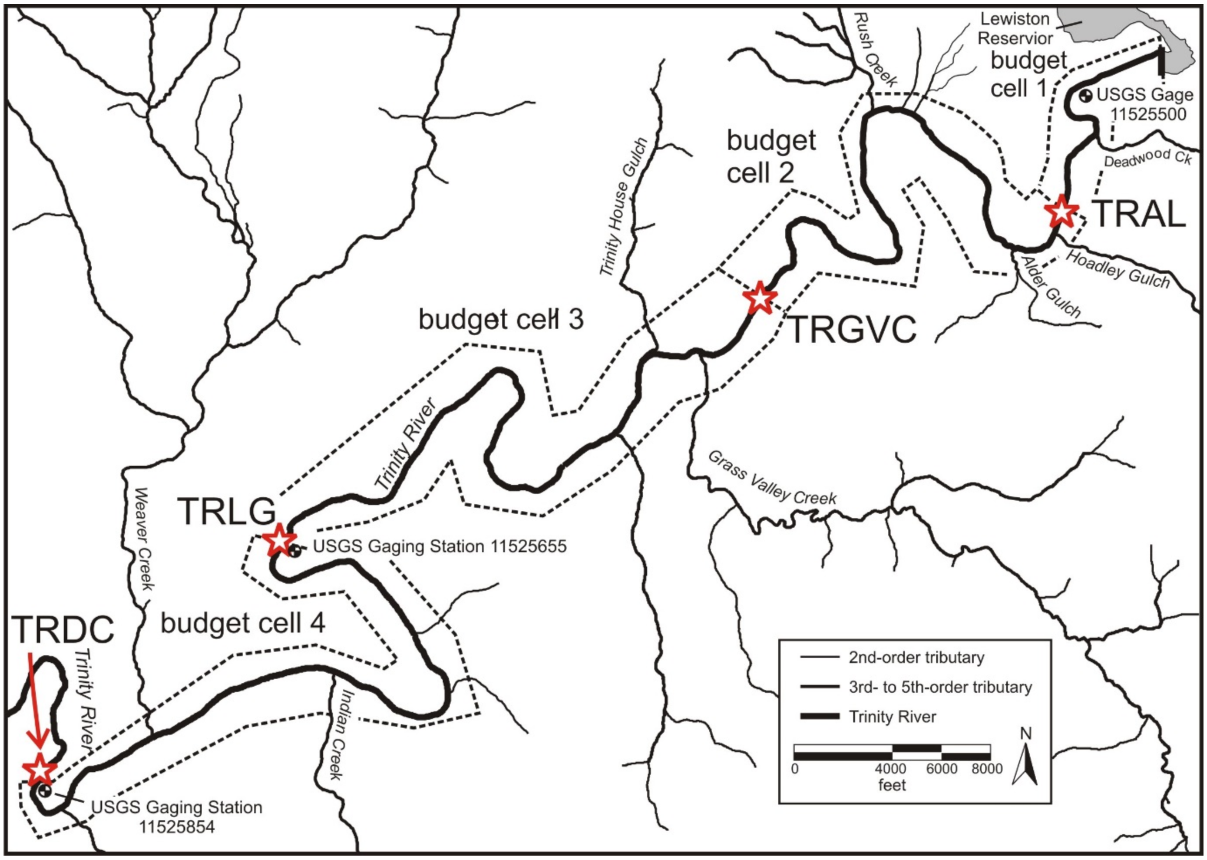

Figure 26: Map of the Trinity River basin downstream from Lewiston Dam showing the locations of the four sediment budget cells discussed in the text.

Although TRRP's foundational documents identify two sediment size fractions of concern (coarse sediment and fine bed material), this report presents a sediment budget for the gravel fraction only. Prior sediment budgets for the Trinity River have included assessments of finer sediment fractions, but this is has been discontinued for reasons given by Gaeuman (2013).

Mainstem Bedload Sampling and Gravel Load Estimates

Budget output terms consist of the annual gravel loads transported past the mainstem sediment monitoring transects. Table 3 lists estimated annual gravel loads at the four sampling transects for 2004 through 2015. All figures are given in tons. Most of the loads given are those reported by Graham Matthews and Associates, Inc. (GMA), who computed loads from bedload transport samples collected during high flow periods of each year. The sampling and load computation methods used are described in a series of reports to TRRP (most recently, GMA 2016). The exceptions are the loads given for 2004 and 2005 at TRGVC. No sediment samples were collected at TRGVC in those years, and the loads given are those estimated by Wilcock (2010). Uncertainty margins for the annual loads estimated from the GMA sample data are taken to be ±50% (Gaeuman 2013), and that same margin has been applied to the Wilcock (2010) estimates.

Table 3: Estimated gravel (> 8 mm) loads in tons passing the Trinity River sediment monitoring transects in 2004-2015 with ± uncertainty margins.

	TRAL	TRGVC	TRLG	TRDC
2004	1700 ±850	1336 ±668	1359 ±680	4869 ±2435
2005	531 ±265	1789 ±895	1853 ±926	5229 ±2615
2006	8610 ±4305	4290 ±2145	4350 ±2175	15200 ±7600
2007	93 ±46	71 ±35	12 ±6	297 ±149
2008	863 ±431	1750 ±875	775 ±387	2380 ±1190
2009	260 ±130	470 ±235	34 ±17	634 ±317
2010	550 ±275	492 ±246	364 ±182	1650 ±825
2011	6460 ±3230	2250 ±1125	5930 ±2965	13200 ±6600
2012	222 ±111	394 ±197	60 ±30	1200 ±600
2013	45 ±23	39 ±20	6 ±3	440 ±220
2014	0 ±0	0 ±0	0 ±0	0 ±0
2015	715 ±358	1370 ±685	326 ±163	1920 ±960

Gravel Inputs by Source

The gravel budget incorporates sediment inputs from tributaries, sediment delivered from upstream mainstem budget cells, and the gravel placed or injected into the channel as part of the TRRP gravel augmentation program. Previous sediment budgets also included sediments transferred to the active channel from bank erosion as a sediment input. Although bank inputs remain as components of the annual budgets computed for years prior to 2013, they are excluded from the computations for the more recent years for reasons described by Gaeuman (2013).

Gravel Augmentations:

Gravel augmentation quantities since 2004 are tabulated in units of tons in Table 4. Krause (2012) contains details on the locations and augmentation methods associated with augmentations through 2010, and Table 5 lists the specific locations and quantities of gravel augmentations implemented in 2012 through 2015. These gravel additions consist of both high-flow injections and low-flow bar placements. Such introductions are usually recorded in units of yd^3, which for gravel budget calculations are converted to tons using a conversion factor of 1 yd^3 = 1.45 tons. This conversion is based on recent measurements with stockpiled augmentation gravel. Uncertainty in the conversion, as well as in the precise volumes of the augmented material, is accounted for by assigning uncertainty margins of ±10% to the reported quantities. Gaeuman (2013) provides details on the locations, quantities, and computation methods for 2011 gravel additions, which include material eroded from constructed bars that were originally intended to remain in place and so are associated with different uncertainty margins.

Augmentation data are presented in terms of “geomorphic years” (GY), the beginning of which are here defined to coincide with the falling limb of the annual spring flow release in early May.

The concept of a geomorphic year is analogous to the water year concept used in hydrological studies, in that the beginning of the year is shifted to better correspond to natural breaks in sediment transport. The spring flow release is the dominant geomorphic event responsible for transporting coarse bedload in the Trinity River between Lewiston Dam and TRDC. Gravel added to the channel before or during a flow release peak is likely to be redistributed during the spring release, but gravel added after the release remains inactive for the rest of the geomorphic year. Thus, any gravel injected during a flow release is assigned to the geomorphic year corresponding to the calendar and water years, whereas sediment added during the summer or fall construction season is assigned to the following geomorphic year.

Table 4: Gravel augmentation quantities in tons since GY2004. Figures include both high-flow injections and low-flow placements.

	Dam to TRAL (Cell 1)	TRAL to TRGVC (Cell 2)	TRGVC to TRLG (Cell 3)	TRLG to TRDC (Cell 4)
2004	3000 ±300	0	0	0
2005	0	0	0	0
2006	0	0	0	0
2007	2430 ±243	0	0	0
2008	9000 ±900	1000 ±100	0	0
2009	8800 ±880	9200 ±920	0	0
2010	2290 ±229	8340 ±834	2220 ±222	0
2011	4740 ±474	6280 ±544	8630 ±1233	0
2012	0	0	0	0
2013	290 ±29	0	0	0
2014	0	2175 ±218	0	0
2015	1450 ±145	985 ±100	0	0

Table 5: Gravel augmentations in tons during GY2013-2015.

	tons
2012	
No gravel augmentations	
2013	
Dam to TRAL (Cell 1)	
Diversion Pool High-flow Injection	290 ±29
2014	
TRAL to TRGVC (Cell 2)	
Sawmill IC-7 Low-flow Placement	2175 ±218
2015	
Dam to TRAL (Cell 1)	
Diversion Pool High-flow Injection	1450 ±146
TRAL to TRGVC (Cell 2)	
Lowden Upstream High-flow Injection	985 ±100

Gravel Inputs from Tributaries:

Gravel is potentially delivered to the Trinity River from six perennial tributaries between Lewiston Dam and the TRDC sediment monitoring site (Table 6). Perennial tributaries in the study area include Grass Valley Creek, but that creek does not appear in the table because its gravel deliveries are negligible due to the fact that virtually all bedload and suspended sand produced in the watershed is captured in a pair of dredged sediment detention ponds near the creek's mouth (Trso 2004; Gaeuman 2010a). A visit to these ponds in the summer of 2015 verified that sediment accumulations were largely confined to the more upstream of the two ponds even though the ponds have not been dredged since 2007.

Table 6: Water years in which stream flow and bedload sediment sampling data are available for principal tributaries of the Trinity River between Lewiston Dam and the TRDC sediment monitoring site.

Tributary	Stream flow	Bedload Samples
Deadwood Creek	1997-2004	1998-2001, 2004
Rush Creek	2002-present	1997-2001, 2004-2006
Indian Creek	2004-present	1997-1998, 2000, 2004, 2006
Weaver Creek	1959-1969	2000
Reading Creek	--	2000

Tributary gravel loads and uncertainty margins reported for 2004 through 2012 are taken from Gaeuman (2013), and loads and uncertainty margins for 2013, 2014, and 2015 were estimated using the methods described in Gaeuman (2013). Those methods involve application of a sediment rating curve to measured hydrology in Rush and Indian Creeks, whereas estimates for in Deadwood, Weaver, and Reading Creeks are based on scaling the delivery of nearby tributaries by basin area. Either way, these estimates are highly uncertain due to a lack of recent sediment transport data and, in the cases of Deadwood, Weaver, and Reading Creeks, a lack of stream flow data. For those streams, the uncertainty margins can exceed 100%, which, if applied symmetrically to the delivery estimate, imply the potential for actual tributary deliveries less than zero. As negative sediment deliveries do not make physical sense, these large uncertainty margins are applied to the load estimates in terms of an uncertainty factor, $F = \delta/100 + 1$, where δ is the uncertainty expressed as a percentage of the estimate. For example, an uncertainty of 120% yields $F = 2.2$. The dimensional upper and lower uncertainty margins ($\delta_{U,E}$ and $\delta_{L,E}$) for a given tributary load estimate, L_t, are computed as:

$$\delta_{U,E} = L_t(F - 1) \quad (6a)$$

$$\delta_{L,E} = L_t(1 - 1/F) \quad (6b)$$

Total coarse bed material loads delivered by Rush and Indian Creeks in water years 2012 through 2015 were also evaluated using an alternative method based on repeated topographic surveys of the tributary deltas. The topography of these tributary deltas as of the summer of 2011 is depicted on a digital terrain model (DTM) that spans the 40 miles of river between Lewiston Dam and the North Fork Trinity River. That terrain model consists of bathymetric data collected with an array of three to seven sonar transducers mounted on a boat (GMA 2012) coupled with airborne LiDAR covering sub-aerial portions of the study area (Woolpert Inc. and Watershed Sciences 2012) as well as conventional ground surveys.

The topography of the deltas after the 2015 winter storm season was captured in surveys of the Rush and Indian Creek confluences conducted in April 2015, just prior that year's spring flow release from Lewiston Dam. Data were collected in submerged portions of the deltas using a boat-mounted sonar system similar to the system employed in 2011 (GMA 2015), whereas sub-aerial portions of the delta were surveyed using a Terrestrial Laser Scanner (TLS) supplemented with conventional ground surveys. The raw TLS point cloud contains elevation points that correspond to vegetation and other objects above the ground surface. These unwanted data points were removed using Trimble Real Works software, and the remaining data were converted to a triangulated irregular network (TIN).

All terrain surfaces were resampled to produce summer 2011 and spring 2015 elevation grids with cell sizes of 0.5-ft for Rush Creek and 1-ft for Indian Creek, and the 2011 grids were subtracted from the corresponding 2015 grids to create difference surfaces. Differences due to random errors caused by sub-grid roughness, instrument noise, and other sources was typically less than 0.2 ft. As these types of random and independent errors cancel out over large samples, they have negligible impact on the average elevations of the delta areas (Gaeuman 2014a). Biases between successive surveys, however, become increasingly important as the size of the surveyed areas increases. In an analysis of topographic change based on the 2011 bathymetry and LiDAR surveys plus an earlier survey, Gaeuman (2014a) estimated the mean bias between successive surveys to be on the order of 0.05 ft. As this delta analysis is based on essentially the same 2011 survey and a more recent survey collected with even more advanced technology, we assume that any bias between the two surveys is of a similar or smaller magnitude.

Although more than three years elapsed between the collection of the initial topographic data and the survey just prior to the 2015 release, flows large enough to generate large gravel transport rates were nearly absent in that time interval (Figure 27). More than a decade of sediment transport monitoring at four locations along the Trinity River provides abundant evidence that mainstem gravel transport rates remain small until flow exceeds about 5500 ft^3/s. Thus, it is believed that little if any coarse bed material was transported out of the reaches containing the deltas in water years 2012 through 2014 prior to the 2015 release, and that any increases in gravel storage detected by differencing the 2011 and 2015 surfaces represent the total gravel accumulations in those reaches over that full time period.

It is also assumed that the relatively low mainstem flows between the two survey periods were incapable of transporting coarse sediment onto the deltas from upstream reaches of the Trinity River. Large backwater pools located immediately upstream from both deltas likely capture coarse sediment from upstream at all but the largest flows (USFWS and HVT 1999). Consequently, it is also assumed all the gravel that accumulated around the tributary confluences during the study period were either delivered by the tributaries or were derived from sources within the reaches containing the deltas.

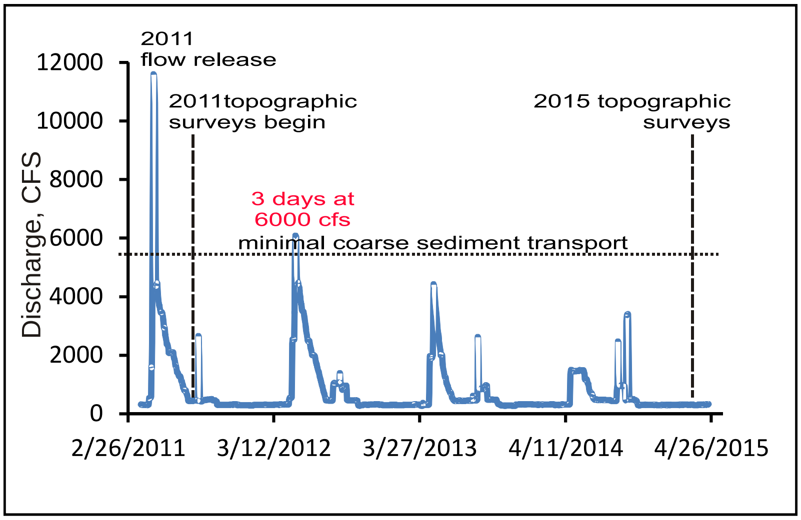

Figure 27: Daily flows releases to the Trinity River from Lewiston Dam between the March of 2011 and May of 2015. Flows were below the threshold for significant gravel entrainment for most of the time period between the summer 2011 topographic surveys and the 2015 spring flow release. The 2011 spring flow release hydrograph is included for comparison.

Most of the elevation change detected in the Rush Creek delta area between 2011 and 2015 is positive, indicating net deposition. Field observation confirmed that most of the deposited material consisted of clast supported gravel and cobble with finer material filling the interstitial spaces. However, some areas in which significant volumes of sand were deposited were observed. The extents of these sand patches were mapped using a combination of GPS and manual sketching on aerial photographs, and their thicknesses were estimated by driving rebar into the sand until a firm surface was reached. These data were used to create a grid of sand deposit thicknesses and an estimate for the volume of the sand deposits of 344 ± 76 yd^3. The stated uncertainty bounds incorporate uncertainties of ± 0.2 ft in the depths measured with the rebar, mapping errors, and errors attributed to interpolating between the relatively sparse array of depth measurements. The sand thickness grid was subtracted from the elevation difference grid to produce a corrected grid corresponding to the difference in the elevation of the gravel deposits (Figure 28).

Gravel delivered from Rush Creek appears to comprise a depositional lobe whose thickness exceeds 3 ft near the mouth of Rush Creek and gradually diminishes downstream before reaching a patch of bed erosion a little more than halfway through the reach (Figure 28). It is assumed that none of that material was transported into the reach through the mainstem backwater pool upstream from the Rush Creek delta. This assumption is based on the fact that mainstem peak flows upstream from Rush Creek between 2011 and the 2015 survey were abnormally low. Rush Creek, however, is not the only source of gravel to the reach. Approximately 800 yd^3 of material was eroded from the terrace surface opposite the mouth of Rush Creek where surface elevations were lowered by as much as 12 ft (Figure 28). That eroded area included an uppermost layer of fine sediment 0.5 ± 0.1 ft thick that is assumed to have been transported out of the reach, but an estimated 600±40 yd^3 of clast supported gravel was transferred to the channel for possible redistribution within the reach. About 425 yd^3 of that material can be located immediately downstream from the eroded area along the left bank, and another 110 yd^3 of the eroded bank material appears to have been transported to depositional areas farther downstream along the left bank and on a riffle near the downstream end of the reach. The fate of the remaining 65 yd^3 is unknown, but some portion of it may have been redeposited within the reach. An additional 140 yd^3 of bed material derived from the patch of bed erosion in the downstream half of the reach (Figure 28) also contributed to the quantity of material available for redeposition within the reach. A volume balance calculation between these gravel sources and the remaining volume of deposition near the downstream end of the reach (110 yd^3) suggests that 95 yd^3 of coarse bed material exited the surveyed reach. Subtracting the net volume of material derived from within-reach erosion and deposited within the reach from the total deposition volume yields an estimated gravel delivery from Rush Creek of 3096 ± 465 yd^3.

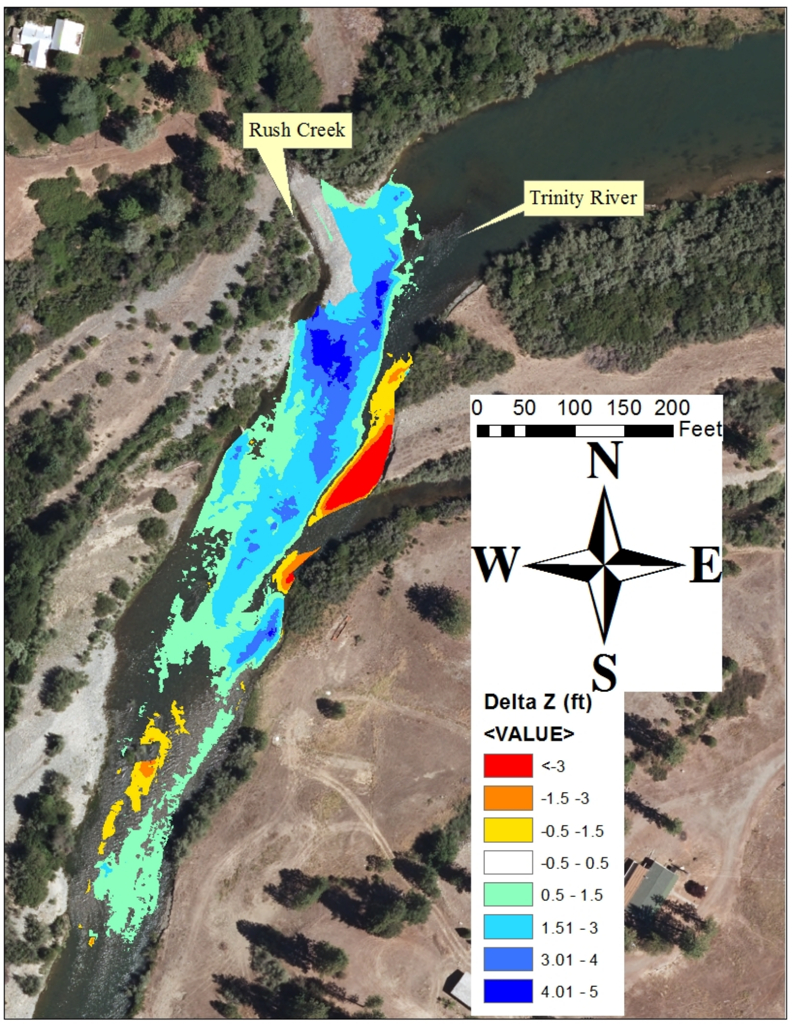

Figure 28: Change in elevation of gravel bed material at Rush Creek between summer of 2011 and April 2015. Flow in the Trinity River is from top to bottom.

Due to lateral confinement by a bedrock valley wall on river right, the Indian Creek delta consists of a discrete depositional lobe with a relatively simple morphology (Figure 29). Sediment dynamics near the mouth of Indian Creek are therefore easier to interpret than at Rush Creek. Topographic differencing at this site indicates that total deposition and erosion volumes in the area between the summer of 2011 and spring of 2015 were 1415 yd^3 and 40 yd^3, respectively. It is assumed that all of the erosion detected within the reach was redeposited within the reach. Field observations confirmed that the vast majority of the deposition consisted of clast-supported gravel and cobble. A thin layer of sand was observed in the downstream part of the depositional area, but its thickness was insufficient to cover the coarser particles. Thus the influence of sand deposition on the estimates of coarse sediment delivery from Indian Creek during this time interval is considered to be negligible. No mainstem flows believed to be capable of transporting coarse sediment through the mainstem backwater pool upstream from the delta occurred during the time period of interest, so the total net deposition in the delta area of 1375 ± 72 yd^3 is attributed to delivery from Indian Creek.

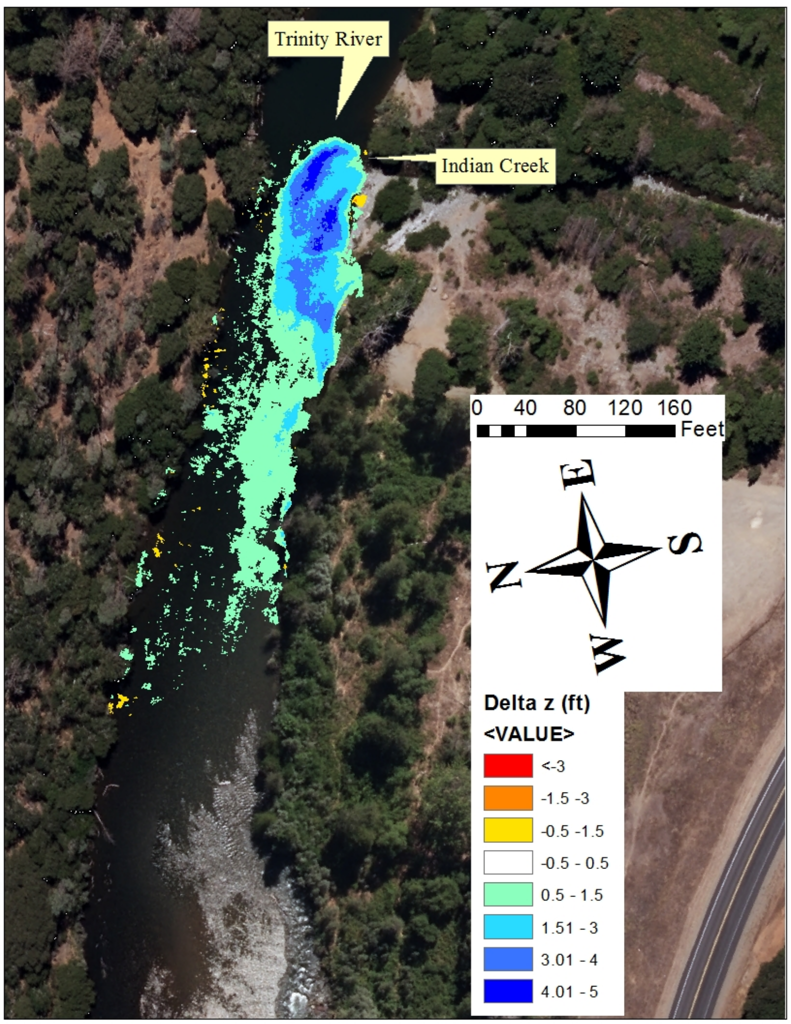

Figure 29. Change in elevation of gravel bed material at Indian Creek between the summer of 2011 and the spring of 2015. Flow in the Trinity River is from bottom to top.

A comparison between the estimates of gravel delivery from Rush and Indian Creeks in water years 2012 through 2015 based on delta survey and estimates computed using the methods of Gaeuman (2013) is presented in Table 7. Delta survey results indicate that gravel delivery during that time period was an order of magnitude larger than was computed with the long-term composite rating curves. The adjusted delta-based estimates presented in the table have been converted to tons using a conversion factor of 1.5 tons/yd^3 and uncertainty bounds have been increased to include an uncertainty in the conversion of $\pm$ 0.1 tons/ yd^3. The total uncertainties in these delivery estimates are ± 22% for Rush Creek and ± 12% for Indian Creek.

Because the delivery estimates for these creek are based on highly precise topographic data with relatively few error sources, these magnitudes of uncertainty are small compared to the rather large uncertainties associated with estimating sediment delivery with rating curves. This is especially true when the sediment transport data used to generate the rating curves is sparse and/or was collected during a different time period than the period it is being applied to. Both of these deficiencies are present for the rating curve estimates generated for water years 2012 through 2015. We therefore assert that the sediment delivery estimate for Rush and Indian Creeks based on the repeat topographic surveys is far superior to those developed from the long-term composite rating curves. We assume the surveyed estimates to represent the correct values, and the rating curve estimates to be erroneous. The magnitude of the errors is expressed in terms of an error ratio, E_t, that is analogous to the ratio, E, used in a previous section of this report to quantify errors in sediment load estimates. In the case of E_t, the error ratio is computed using the values that include the inner boundaries of the uncertainty margins. That is, the larger value in the ratio is the estimated delivery minus the uncertainty margin and the smaller value is the sum of the estimated delivery and the uncertainty margin. Even with these uncertainties considered, the rating curve estimates are between 6.4 and 14.5 times too small (Table 7).

Table 7: Tributary deliveries of gravel to the Trinity River from Rush Creek, Indian Creek and Weaver+Reading Creeks for water years 2012 through 2015, as estimated by two alternative methods.

Creek	Gravel Input Surveys (yd^3)	Gravel Input Adjusted Surveys (tons)	Gravel Input Rating Curve (tons)	E_t
Rush	3096 ± 465	4644 ± 1007	114 + 137,− 63	14.5
Indian	1375 ± 72	2123 ± 250	133 + 159,− 72	6.4
Deadwood	na	1950 + 1950,− 975	48 + 302,− 30	2.8
Weaver/Reading	na	5094 + 5094,− 2547	182 + 1642,− 164	1.4

Previous sediment budgets have computed the sediment inputs from Weaver Creek plus Reading Creek from the Indian Creek estimates according to the ratio of the total Weaver/Reading watershed area to the Indian Creek watershed area. That practice, which was introduced by Wilcock (2010) and adopted by Gaeuman and Krause (2011) and Gaeuman (2013) is continued here. Gravel delivery estimates for the Weaver and Reading

Creek basins developed using that method and the survey-derived loads for Indian Creek are included in Table 7. Uncertainty bounds for the estimated load were derived by increasing the 12% uncertainty in the Indian Creek estimate to 100% to account for uncertainty in the assumption that delivery characteristics are similar in the different basins. Similarly, inputs from Deadwood Creek have been estimated according to the ratio of its total watershed area to the area of the Rush Creek watershed. New gravel inputs from Deadwood Creek for 2012-2015 and 100% uncertainty bounds are also presented in the table.

The extremely large differences between the gravel input estimates derived from repeated topographic surveys and those derived from long-term composite rating curves raise the question as to whether any of the rating curve estimates for earlier years are reasonably close to the correct values. Although the results discussed here show that estimates of tributary sediment deliveries can be extremely inaccurate, they do not necessarily imply that the delivery rates estimated for the earlier years are incorrect. Sediment yields from upland watersheds are governed by many factors, including drainage area, topography, land cover, geology, and hydrology (Toy et al. 2002). Any change in watershed condition and/or episodic erosion events such as landslides can produce large shifts in the relationship between stream flow and sediment delivery from the watershed (Madej 2007). Sediment yields from tributary drainages can fluctuate enormously from years to year. For example, total annual sediment loads from these same tributaries estimated by GMA (2001) for water years 1981 through 2001 routinely deviate from the average estimated loads for the full time period by factors ranging from 14 to more than 200 (Table 8). Thus, it is possible that the gravel loads estimated from rating curves for Rush and Indian Creeks are more accurate for years near the time when the bedload samples used to create the rating curves were collected.

Table 8: Deviations of annual sediment yields estimated by GMA (2001) from the mean yield for the full time period from 1981 through 2001. E_{GMA} is computed as $Q_{s,GMA}/\mu_{GMA}$ for $Q_{s,GMA} > \mu_{GMA}$ and $\mu_{GMA} / Q_{s,GMA}$ for $Q_{s,GMA} < \mu_{GMA}$, where E_{GMA} is the total sediment yield for the year and μ_{GMA} is the mean for the time period.

Creek	E_{GMA} Maximum	E_{GMA} Standard Deviation
Rush	52.6	14.1
Indian	85.1	21.6
Deadwood	922.8	215.4
Weaver/Reading	97.9	24.9

Although it is clear that the rating relations changed substantially over time, it is impossible to determine when the change occurred. Substantial delta growth was noted in the late winter of 2006 and large changes in delta morphology were obvious to the casual observer in 2015, but we are aware of no such observations during the intervening years. This could perhaps be regarded as anecdotal information suggesting that actual sediment deliveries to those confluence areas was small during that time period, but no documentation or quantitative measurements are available to confirm that assertion. Nonetheless, in the absence of compelling evidence one way or the other, the estimated gravel deliveries reported by

Gaeuman and Krause (2011) for years prior to 2012 are retained herein. The updated tributary gravel delivery estimates described above and their uncertainties are tabulated in Table 9.

Table 9: Estimated tributary deliveries of gravel to the Trinity River for 2004-2015. Uncertainty factors (i.e. F2.2, etc.) can be converted to units of tons via equation (6).

	Deadwood Ck (tons)	Rush Ck (tons)	Indian Ck (tons)	Weaver+Reading Cks (tons)
2004	72 (F10)	171 (F2.2)	62 (F2.2)	149 (F10)
2005	1 (F10)	3 (F2.2)	166 (F2.2)	398 (F10)
2006	403 (F10)	960 ±480	490 ±245	1176 (F10)
2007	1 (F10)	1 (F2.2)	0	0
2008	0	0	13 (F2.2)	31 (F10)
2009	0	0	81 (F2.2)	194 (F10)
2010	0	0	143 (F2.2)	343 (F10)
2011	1 (F10)	2 (F2.2)	78 (F2.2)	187 (F10)
2012-15	1950 (F2)	4644 ± 1007	2123 ± 250	5094 (F2)

Gravel Budget Results

The cumulative gravel budget for WY 2004-2015 is tabulated for each budget cell in Table 10 and displayed graphically in Figure 30. Gravel storage since 2003 shows an increasing trend in budget cells 1-3, and a decreasing trend in budget cell 4.

Consolidating the cumulative changes through budget cells 1-3 permits a clearer summary of how the estimated gravel storage changes relate to the uncertainties in the estimates. As shown in Figure 31, cumulative storage increases through budget cells 1-3 total about 102900 tons and exceed the uncertainty margin by a factor of about nine. It can therefore be concluded with reasonable confidence that gravel storage increased by 92300 to 114400 tons. At the same time, the cumulative storage decrease in budget cell 4 is smaller than the uncertainty margin, such that a cumulative storage change of between −23800 and +5400 tons can be inferred with confidence. This range of uncertainty suggests that the probability that gravel storage in cell 4 decreased is about 4.4 time greater than the probability that it increased. Uncertainties are proportionally larger in budget cell 4 than in the upstream three cells due to the large uncertainties in the estimated gravel inputs from Indian, Weaver and Reading Creeks. As noted above, those uncertainties are extremely large for years in which no delta surveys were performed.

Table 10: Cumulative gravel (> 8 mm) storage changes for WY 2004-2012. All figures rounded to the nearest 100.

	Cell 1 Cumulative ΔS (tons)	Cell 2 Cumulative ΔS (tons)	Cell 3 Cumulative ΔS (tons)	Cell 4 Cumulative ΔS (tons)
2004	-1400^{+1100}_{-900}	500^{+700}_{-700}	0^{+700}_{-700}	-3300^{+2800}_{-2400}
2005	-800^{+1100}_{-900}	-700^{+1100}_{-1100}	-100^{+1100}_{-1100}	-6100^{+5200}_{-3600}
2006	-7100^{+5700}_{-4400}	18600^{+5600}_{-5600}	6400^{+4700}_{-4700}	-9800^{+14400}_{-9100}
2007	-4700^{+5800}_{-4400}	18600^{+5600}_{-5600}	6500^{+4700}_{-4700}	-10100^{+14400}_{-9100}
2008	3400^{+5800}_{-4500}	18700^{+5700}_{-5700}	7500^{+4700}_{-4700}	-11700^{+14500}_{-9200}
2009	11900^{+5900}_{-4600}	27700^{+5800}_{-5800}	7900^{+4700}_{-4700}	-12000^{+14600}_{-9200}
2010	13700^{+5900}_{-4600}	36100^{+5800}_{-5800}	10200^{+4700}_{-4700}	-12800^{+14900}_{-9200}
2011	12800^{+6800}_{-5700}	52600^{+6400}_{-6400}	26400^{+6100}_{-6100}	-16000^{+16600}_{-11600}
2012	12600^{+6800}_{-5700}	52500^{+6400}_{-6400}	26800^{+6100}_{-6100}	-17100^{+16600}_{-11600}
2013	12800^{+6800}_{-5700}	52500^{+6400}_{-6400}	26800^{+6100}_{-6100}	-17600^{+16600}_{-11600}
2014	12800^{+6800}_{-5700}	54600^{+6500}_{-6400}	26800^{+6100}_{-6100}	-17600^{+16600}_{-11600}
2015	15500^{+7100}_{-5800}	59600^{+6600}_{-6600}	27800^{+6100}_{-6100}	-11900^{+17400}_{-11900}

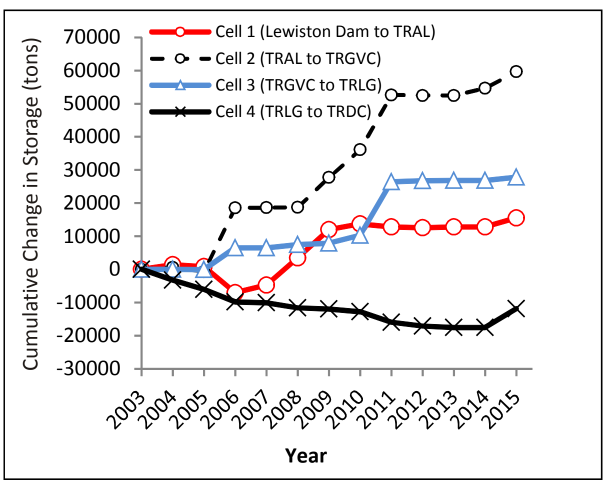

Figure 30: Cumulative changes in gravel storage by budget cell for WY 2004-2015 with zero budget balance assigned to WY 2003.

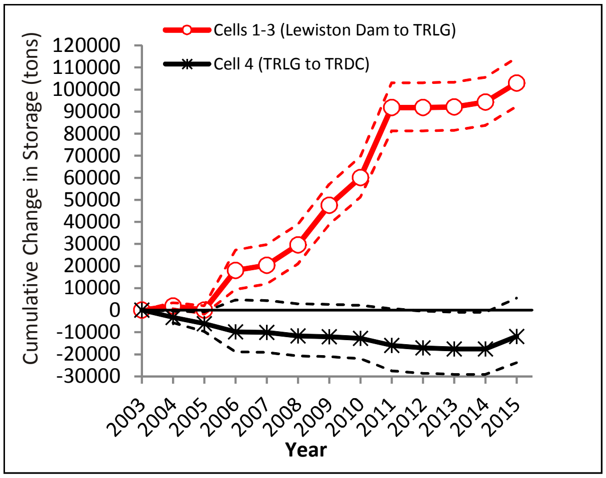

Figure 31: Cumulative changes in gravel storage since WY2003 in budget cells 1-3 and budget cell 4. Dashed lines indicate uncertainty envelops.

Implications for Gravel Management

The gravel budget indicates that recent TRRP management actions have produced an increase in gravel storage in three of the four sediment budget cells downstream from Lewiston Dam since 2003. The largest increase (about 59600 tons) is found in budget cell 2 (TRAL to TRGVC), where channel rehabilitation activities have been most concentrated over the past several years. Storage in budget cell 1 (Lewiston Dam to TRAL) decreased markedly in 2006 from a slight positive in 2005 balance to about −7100 tons as a result of the large spring release that year, which peaked at about 10300 ft^3/s. However, gravel augmentation activities in budget cell 1 after 2006 have since restored the budget to a positive balance near 15,500 tons. Storage increases in budget cell 3 (TRGVC to TRLG) since 2003 have been gradual through 2015, as very little gravel augmentation had been implemented in this cell. However, storage in cell 3 increased markedly in 2011, primarily due to gravel placements associated with the Lowden Ranch and Trinity House Gulch rehabilitation projects and extensive terrace erosion near the mouth of Grass Valley Creek. Contrary to the three upstream cells, budget cell 4 (TRLG to TRDC) showed a consistent decline between 2004 and 2014, but increased in 2015 due to large tributary inputs from Indian and Weaver Creeks to its current cumulative value of about −11900 tons.

The relative magnitudes of these storage changes can be more easily understood when expressed as equivalent bed elevation changes in each budget cell. In cells 1 and 3, storage increases in terms of bed elevation increases since 2003 are roughly equivalent, with average bed level changes of 0.21 to 0.14 ft (Table 11). The relative increase in cell 2 was about twice as much as in the neighboring cells, with an average bed aggradation of about 0.34 ft. These cumulative bed level increases are significantly larger than those reported for 2010 (Gaeuman and Krause 2011), with the differences being due to large gravel inputs associated with sediment additions and terrace erosion connected to the Lowden Ranch and Trinity House Gulch rehabilitation projects (Gaeuman 2013; Gaeuman 2014a), as well as to large tributary inputs in 2015. The smallest relative storage change occurred in cell 4 where the average bed elevation declined by about 0.06 ft. Channel areas reported here are based on the wetted channel area plus emergent in-channel bar area as mapped with airborne terrestrial LiDAR in April 2009 when discharge was 300 ft^3/s.

Table 11: Cumulative gravel storage changes since 2003 as equivalent bed elevation change (ΔZ). ΔZ is computed assuming a nominal bulk sediment porosity of 0.35.

	Cell 1	Cell 2	Cell 3	Cell 4
Cell River Length (miles)	2.0	5.3	6.1	6.4
Cell Channel Area (acres)	31.4	74.9	83.2	86.4
Cumulative ΔZ, feet	0.212	0.341	0.143	−0.061

The storage decrease observed in budget cell 4 reflects the fact that gravel transport fluxes exiting that cell at TRDC are considerably larger than the gravel fluxes entering the cell at TRLG. The average gravel export from cell 4 during 2004-2015 (3920 tons) is 3.1 times the average mainstem input from budget cell 3 (1260 tons), suggesting that the supply of mobile gravel increases substantially somewhere downstream from TRLG. That increase in the gravel supply is almost certainly due to inputs from Indian Creek, Weaver Creek and Reading Creek, all of which are located within budget cell 4 (Figure 26). Although the estimated annual quantities of gravel delivered from those tributaries are rather small relative to mainstem fluxes in many years, estimates for 2015 based on repeat surveys of tributary deltas show that tributary gravel inputs can be much larger in some years (Table 11). In addition, tributary inputs would have been comparatively large in the decades immediately following dam closure when mainstem flows competent to entrain gravel were rare (Gaeuman 2013; Gaeuman 2014b).

Assessment of the Sediment Budget Approach

The foregoing discussion touches on several issues that may cause one to question the utility of the “storage change” approach to assessing Program objectives. One deficiency in the use of storage as a measure of Program success is that it is an indirect proxy for the more basic objective to create spatially complex channel morphology (Essa Technologies, Ltd. 2009). In other words, the objective is to develop a topographically diverse bed composed of various types of bars and pools. In the opinion of the authors, this objective is better evaluated by direct examination of bed topography than by calculating change in the gravel storage quantities. In addition, storage changes have little meaning in the absence of a target. The Program documents that promote increasing gravel storage do not indicate what that storage level should be. The present budget indicates that gravel storage upstream from TRLG has increased by more than 102900 tons, 82 times the mean annual load at TRLG, since 2003. Yet, no accepted method exists to assess whether that increase is excessive, insignificant, or just right.

Another issue is that the basic notion of quantifying in-channel sediment storage is conceptually problematic. Gravel stored in the floodplains, terraces, and tailings piles are excluded from the storage totals mentioned in the Flow Evaluation Study (USFWS and HVT 1999), but it is unclear how those areas might function as sources and sinks of sediment in a dynamic fluvial landscape. Coarse sediment stored in the banks and floodplain areas is inactive – it is unavailable for fluvial transport and cannot contribute to the development of bars or influence physical habitat in the channel. Bank erosion transfers coarse sediment from inactive storage in the floodplain to an active state in which it can readily be entrained and re-deposited to alter in-channel topography and substrate characteristics. As this transfer fulfills a management objective, it is functionally similar to coarse sediment delivered from tributary sources or via coarse sediment augmentation. While defining sediment derived from bank erosion as an input to in-channel storage seems straightforward, the issue becomes more ambiguous in the context of planform change. For example, floodplain erosion on the outer bank of a meander bend can be reasonably interpreted as a sediment input to the channel, but then it would seem equally reasonable to regard the material deposited on the opposite bank as the channel migrates away as an export of sediment out of the channel. Clearly, a developing floodplain becomes distinct from the channel at some point, but precisely when that occurs is open to interpretation. Any attempt to parse sediment storage within a landscape will, to some degree, confront analogous issues regarding the definition of the storage reservoirs and the reasons for choosing them.

In light of the above considerations, it is recommended that the gravel budget be used only to guide the Program's long-term gravel augmentation activities. A budget approach can be effective for quantifying year-to-year gravel inputs and exports in the defined budget cells. It is obvious that to maintain a long-term sediment balance in any budget cell, augmentation quantities must equal the export at the downstream monitoring location minus the sum of the inputs from tributaries and the upstream cell. In this context, the total quantity of sediment contained in the storage reservoir, as well as sediment transfers between the channel and surrounding alluvium, become irrelevant.

Gravel Management Validation

TRRP gravel augmentation activities are intended to increase bed mobility and gravel transport rates in the reaches of the river upstream from Indian Creek. Gaeuman (2014b) identified a quantitative target for this objective by scaling transport rates at TRDC to the hydrology in the more upstream reaches. Since 2014, annual gravel augmentation quantities recommended by TRRP staff have been specified to match or slightly exceed transport rates at TRDC, thereby maintaining or gradually increasing gravel storage in the river upstream from that monitoring location (Gaeuman 2013). No gravel addition was recommended for water year 2014, because that year was designated as a critically dry year in which the maximum discharges released from Lewiston Dam were incapable of mobilizing gravel. In 2015, however, a release hydrograph peaking at 8500 ft^3/s was implemented, and a high-flow gravel injections totaling 1700 yd^3 was recommended. That total quantity was distributed between gravel injection sites at Upper Lowden Ranch (500 ft upstream from TRGVC) and at the Diversion Pool (about a mile downstream from Lewiston Dam), with the Lowden site receiving 700 yards and the Diversion Pool receiving 1000 yards.

According to bedload samples collected during the 2015 flow release, approximately 1920 tons (1325 yd^3) of gravel passed the TRDC sediment monitoring transect. Thus, the 2015 gravel augmentation exceeded the 2015 gravel flux at TRDC by 28%. The method used to develop that augmentation recommendation therefore successfully achieved the objective of replenishing or slightly exceeding the gravel volume transported downstream beyond TRDC. The same method was used to recommend a gravel augmentation quantity of 3600 yd^3 during the 2016 flow release. That flow release and the recommended augmentation were implemented in May of 2016, but 2016 gravel loads have not yet been computed so a comparison between those quantities cannot be presented at this time.

Conclusions and Recommendations

Sediment monitoring data are useful for addressing several of the questions noted in the introduction section of this report concerning spatial and temporal changes in fine and coarse bed material transport rates. In addition to the transport samples that support assessments of how transport rates and sediment fluxes vary by location and time, ancillary data collected along with the sediment samples provide information regarding the potential causes of the observed differences.

Spatial Differences in Sediment Transport Rates

Fine bed material loads increase with downstream distance from the Dam. Loads are smallest at TRAL, which is located 1.5 miles downstream from Lewiston Dam, and increase in downstream order by factors of 3.5 and 5.5 at TRGVC and TRLG, which are 7.5 and 13 miles downstream from the dam, respectively. Fine bed material loads at TRDC, located 19 miles from the dam, exceed loads at TRAL by a factor of more than 17 and are three and five times larger than the loads at TRGVC and TRLG. We recommend that suspended sediment sampling at TRAL be discontinued, as the quantity of fine bed material in transport at that location is negligible.

Gravel loads at TRAL exceed the loads at both TRGVC and TRLG by about 35%. The elevated gravel loads at TRAL above those at TRGVC and TRLG are related to the fact that TRRP has been implementing gravel augmentation projects upstream from that sampling location on a nearly annual basis over the past decade. The finding that loads at TRGVC remain smaller than those at TRAL suggests that the bulk of the gravel added to the river near Lewiston Dam has yet to reach TRGVC. TRRP has begun to address this apparent delay in gravel arrival at more downstream locations with gravel augmentations in the vicinity of TRGVC in 2010, 2011, and 2015.

Gravel loads at TRLG were slightly larger than at TRGVC in all years prior to 2007, but loads at TRGVC have surpassed the loads at TRLG in all but one year since. This shift can likely be attributed to the gravel augmentations near Lewiston Dam and the more recent augmentations near TRGVC. These augmentations appear to have begun to increase gravel transport rates at TRGVC, but have yet to influence transport rates at TRLG.

Temporal Changes in Sediment Transport Rates

Bed material transport rates show large temporal fluctuations, with the fluctuations in the fine and coarse sediment fractions following similar patterns. It is hypothesized that the close correspondence between the temporal fluctuations in the transport rates of both size fractions is due to the influence of fine sediment abundance on the mobility of both.

Bed material loads and transport rates appear to have decreased over the past decade at three of the four monitoring locations. At TRAL, fine bed material transport rates for a reference flow decreased by about 35% and gravel transport rate decreased by about 77% between 2004 and 2015. Decreases in the fine bed material and gravel transport rates computed for a reference flow at TRGVC and TRLG decreased by between 55% and 160% since 2004. Transport rates at TRDC, however, increased over the same time period.

The causes of temporal trends in transport are unclear. The sampling transects at TRGVC and TRDC have been subject to wholesale modifications imposed during recent channel rehabilitation projects, which likely contributed to the observed changes. However, the primary driver of change appears to be fluctuations in the fine sediment supply delivered to the channel, which alters the transport rate of gravel as well as fine material, and gravel augmentations implemented by TRRP. Temporal trends in gravel transport rates do not appear to be strongly linked to changes in the size of gravel particles on the stream bed.

Sediment fluxes obtained with long-term composite rating curves can be several times too large or too small in a given year. Because the magnitude of inter-annual fluctuations in gravel transport characteristics is similar to the magnitude of the changes that monitoring is intended to detect, multiple years of sampling are necessary to demonstrate that management has successfully altered the sediment regime at a particular sampling location. We recommend that bedload sediment monitoring efforts be maintained at or above the current level in normal or wetter years, although we suggest that, to save costs, bedload monitoring be skipped in years when peak flows do not exceed 5000 ft^3/s because gravel fluxes in such years are negligible.

The Program's gravel augmentation strategy has evolved to focus on maintaining scaled coarse sediment transport rates near the dams at levels similar to those observed in downstream reaches where tributary-derived sediment supplies are considered adequate. Gravel augmentation volumes designed to meet that objective were implemented for the first time in water year 2015. Sediment monitoring results from that year indicate that the 2015 gravel augmentations approximately matched the gravel flux past TRDC, thereby maintaining or slightly increasing gravel storage upstream from that location. We recommend continuing to specify gravel augmentation quantities with the method used in 2015, but that the method be refined as more data quantifying gravel fluxes at TRDC and tributary confluences are obtained.

Hysteresis

The discussion of hysteresis presented in this report is a first step toward addressing questions about how hydrograph shape affects sediment transport rates. Each year, TRRP scientists are tasked to develop a peak flow release that uses a limited volume of water to maintain or improve aquatic and riparian habitats into the future. A better understanding of the circumstances that affect when flows are most effective for transporting sediments is needed to optimize hydrograph design.

Bedload sample data from individual monitoring sites show some evidence of hysteresis over annual flow releases in about 60% of the datasets evaluated. Clockwise hysteresis is by far the most common type, especially for fine bedload transport at the two most upstream sampling locations. In most of these cases, decreased transport rates are observed in the first two to four days after attaining the peak flow bench. Anticlockwise and figure-8 hysteresis loops are almost entirely confined to the TRDC sediment monitoring location, where just half of the instances of hysteresis are clockwise in form. We hypothesize that anticlockwise behavior occurs when fine sediment derived from sources far upstream reach TRDC during extended periods of high flow.

These observations suggest that relatively short peak flow durations may be able to flush excess fine bed material sediment from the stream reaches upstream from TRGVC, but that long periods of high flow may be needed to flush fine sediments past TRDC. Likewise, the dominance of clockwise hysteresis in gravel transport at upstream locations suggests that short flood durations accomplish geomorphic work more efficiently than long duration floods.

Gravel Budget

The Trinity River gravel budget indicates that gravel storage between Lewiston Dam and TRLG has increased by about 102900 tons since 2003. Gravel augmentation accounts for about two-thirds of the total increase.

We recommend that annual gravel budgets continue to be computed, but only to inform gravel augmentation activities. The gravel budget should focus on balancing gravel inputs with downstream transport rather than on quantifying storage changes. The use of gravel storage as a primary management objective is discouraged. The core Program objective to create spatially complex channel morphology is better assessed by direct evaluation of bed topography.

Closing the gravel budget for the mainstem Trinity River requires estimates of the gravel inputs delivered from several principal tributaries. Effectively monitoring of tributary sediment delivery with physical bedload samples is impractical, and computing sediment loads from the sparse data that can be obtained with less intensive monitoring can result in errors spanning two orders of magnitude. We recommend estimating gravel deliveries from Rush Creek and Indian Creek, and perhaps at additional locations, with repeat topographic surveys.

We no longer compute a fine sediment budget because we lack the tributary input data required to close the budget. In addition, TRRP has yet to identify a clear link between a fine sediment budget and particular management actions. We therefore recommend that suspended sediment transport monitoring be discontinued until a management need and new funds to support it are identified.

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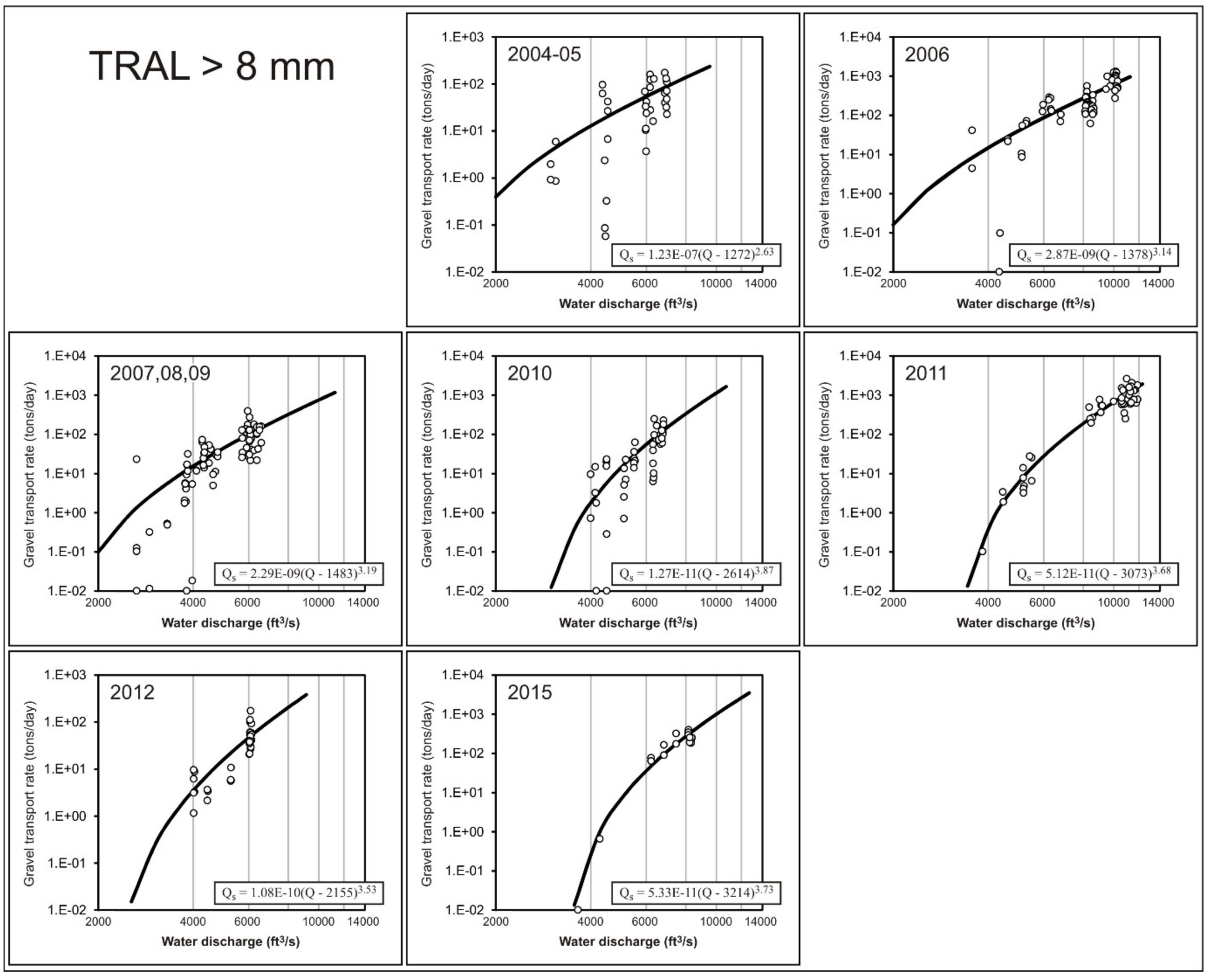
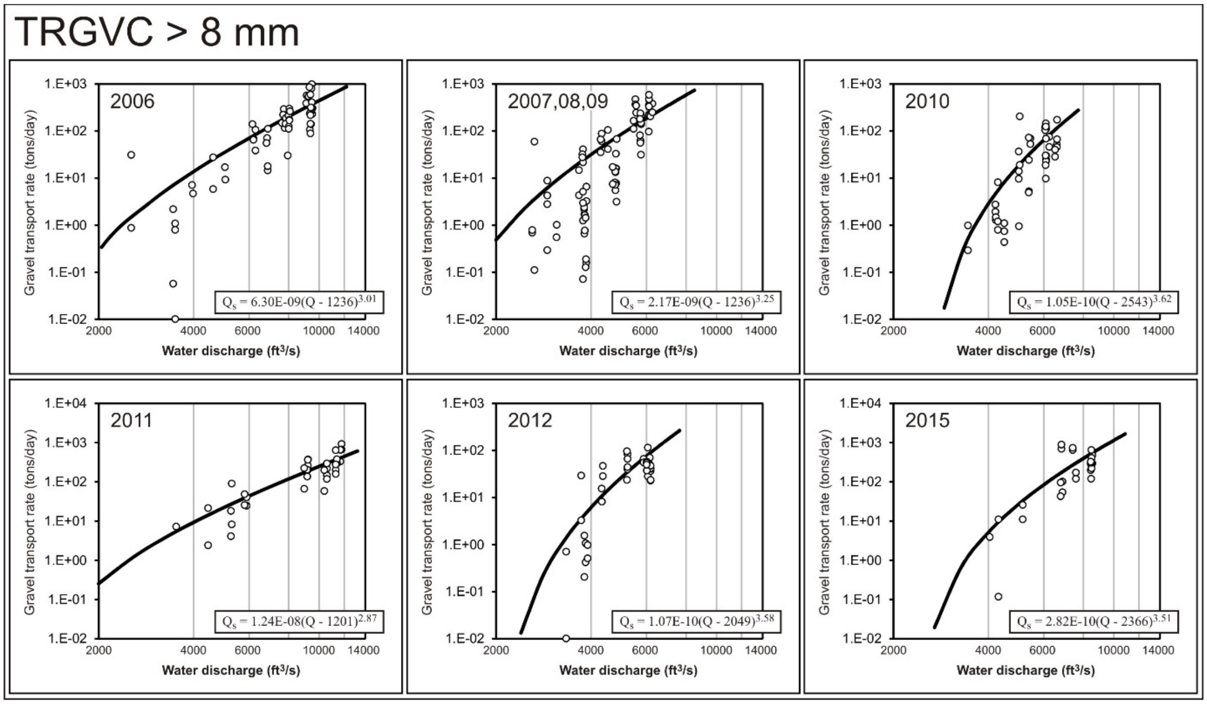
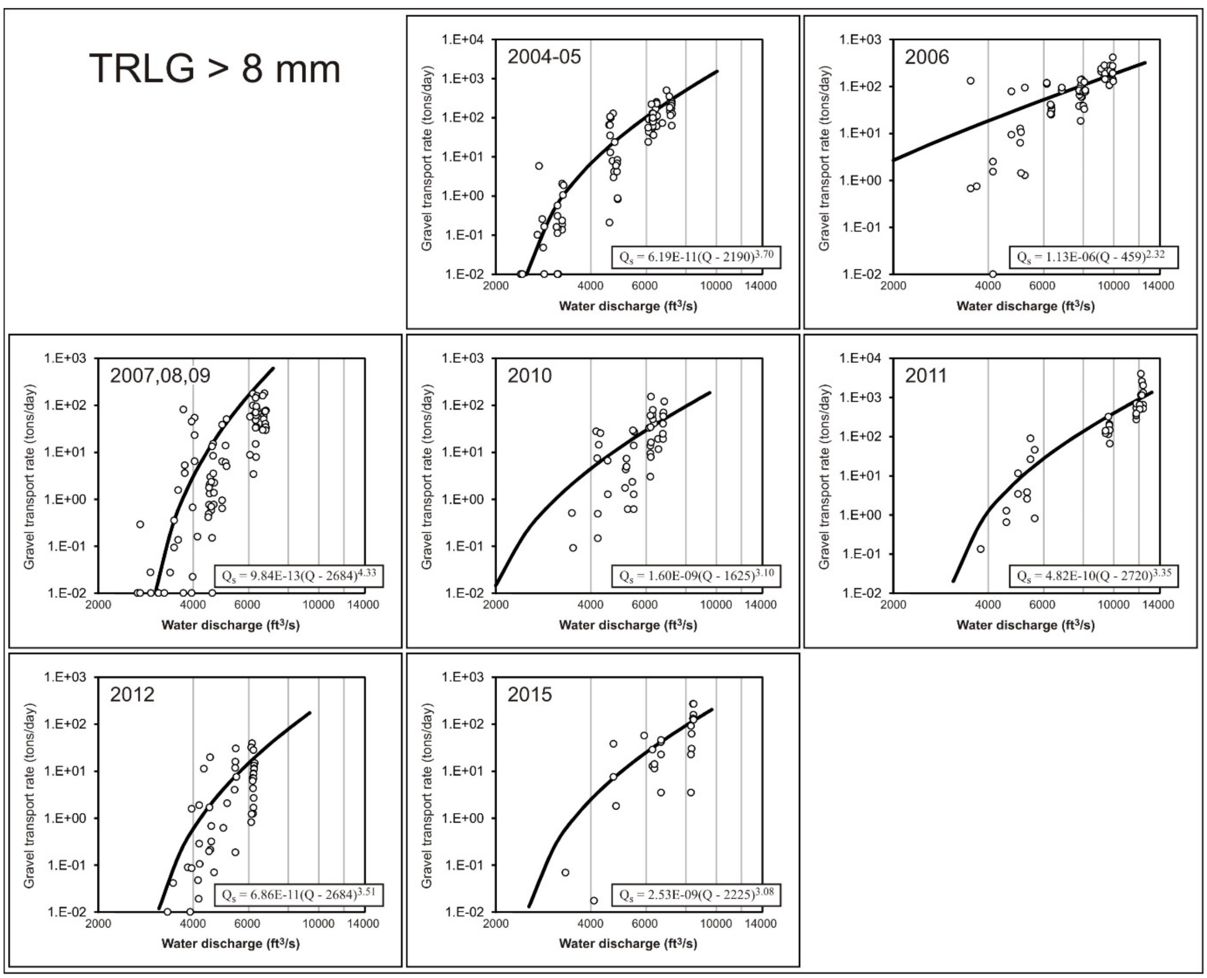
Appendix A

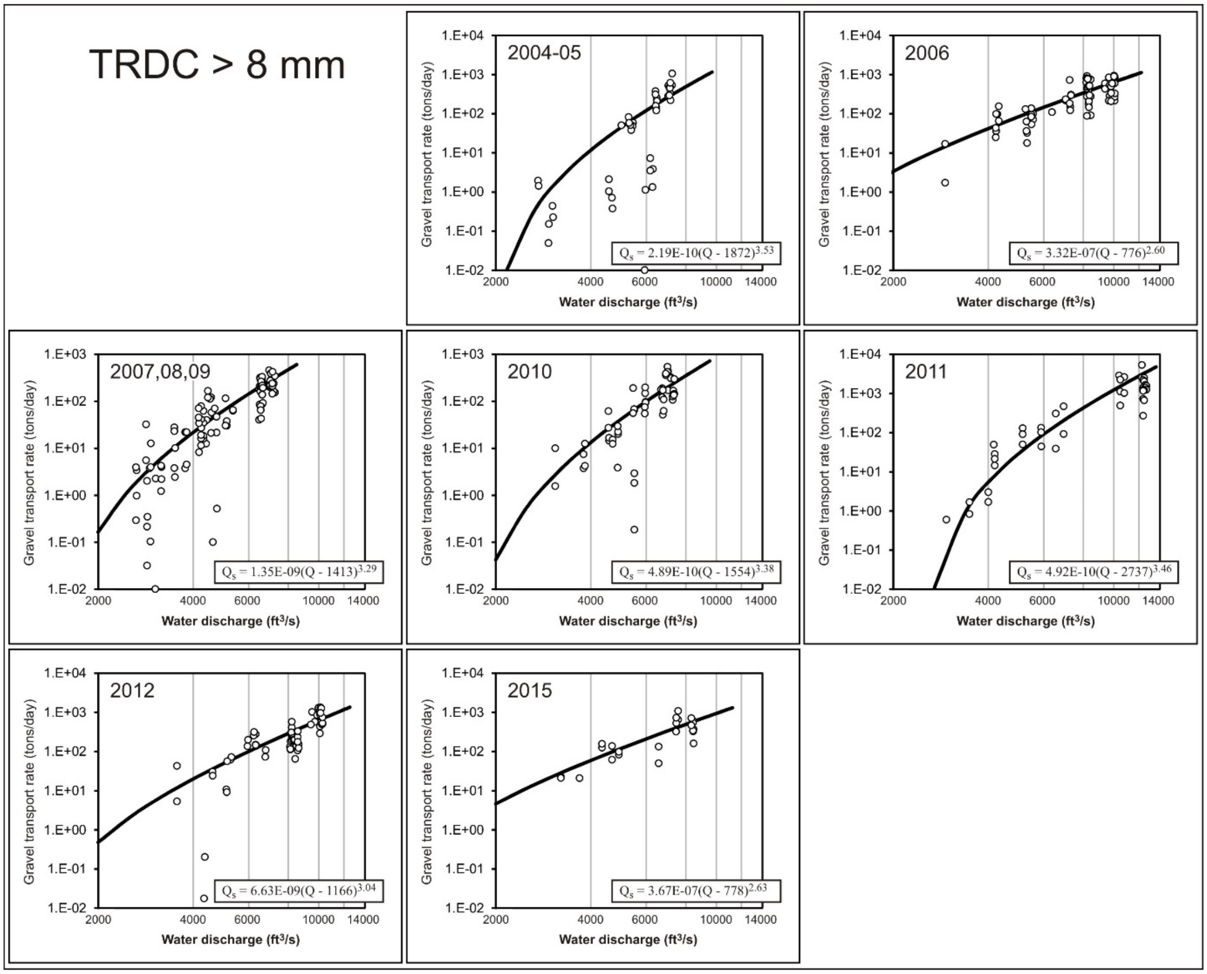
Period-specific Rating Curves

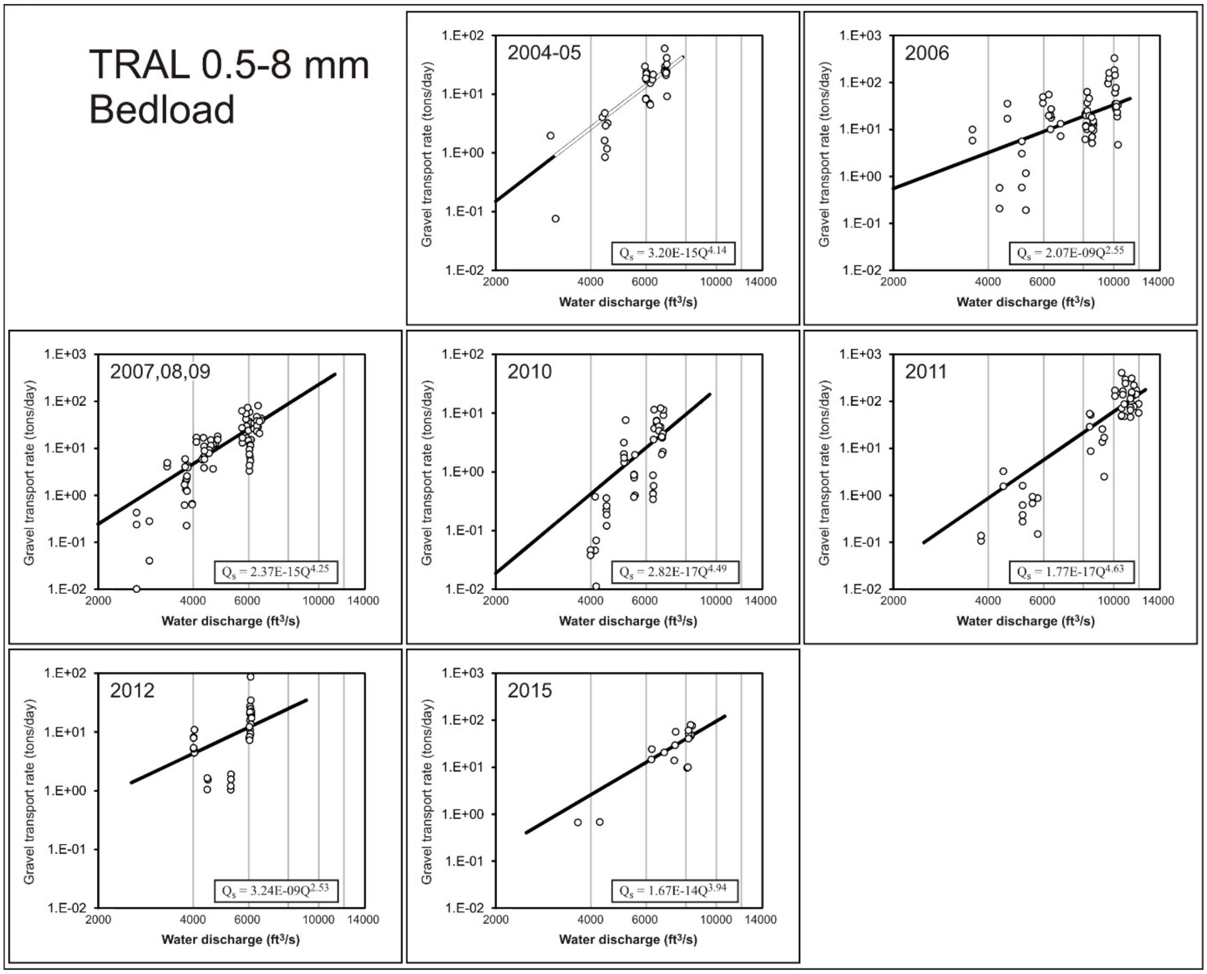
Period-specific rating curves were developed for seven time interval: 2004-05, 2006, 2007 through 2009, 2010, 2011, and 2015. Power function curves for fine bed material (0.5-8 mm) were developed separately for suspended and bedload sediments using non-linear LAR regression. Three-parameter coarse bedload curves (> 8 mm) were fit using a maximum likelihood parameter estimation procedure. Several sets of suspended bed material data consisted mostly or entirely of samples with zero transport, making it impossible to fit a rating curve. Zero samples were otherwise retained in the optimization procedures, but were replaced with 0.01 for display on the log-log graphs presented in this appendix.

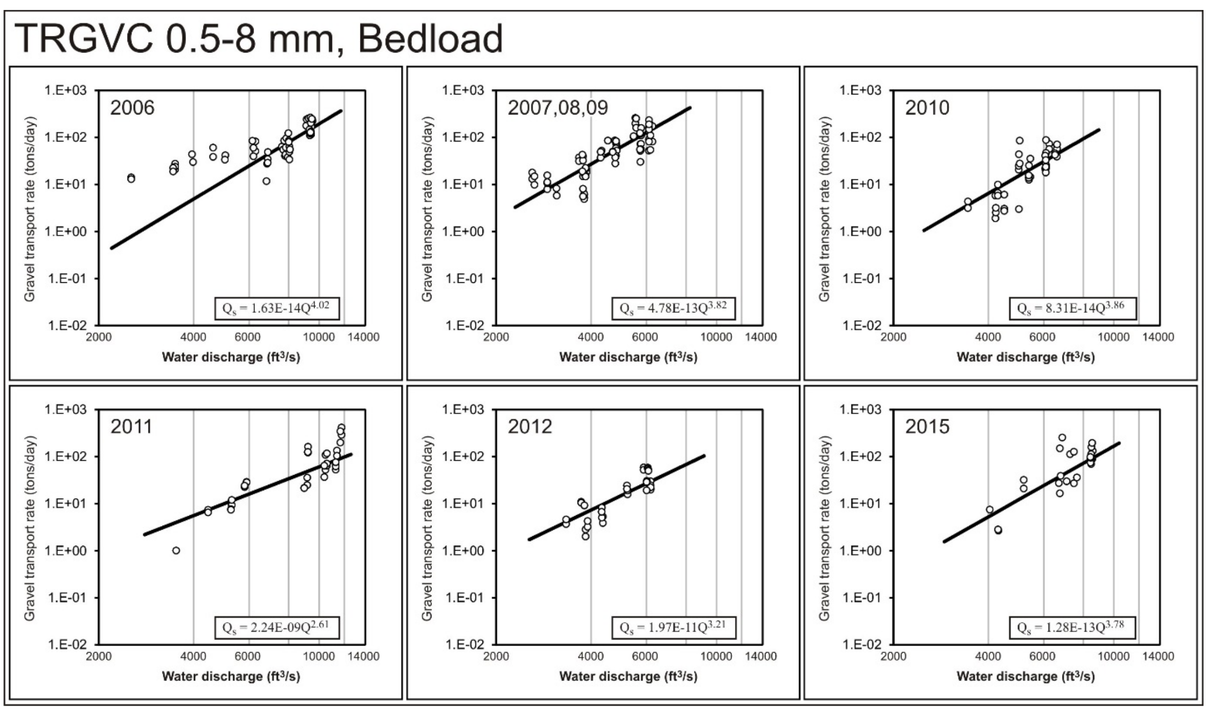


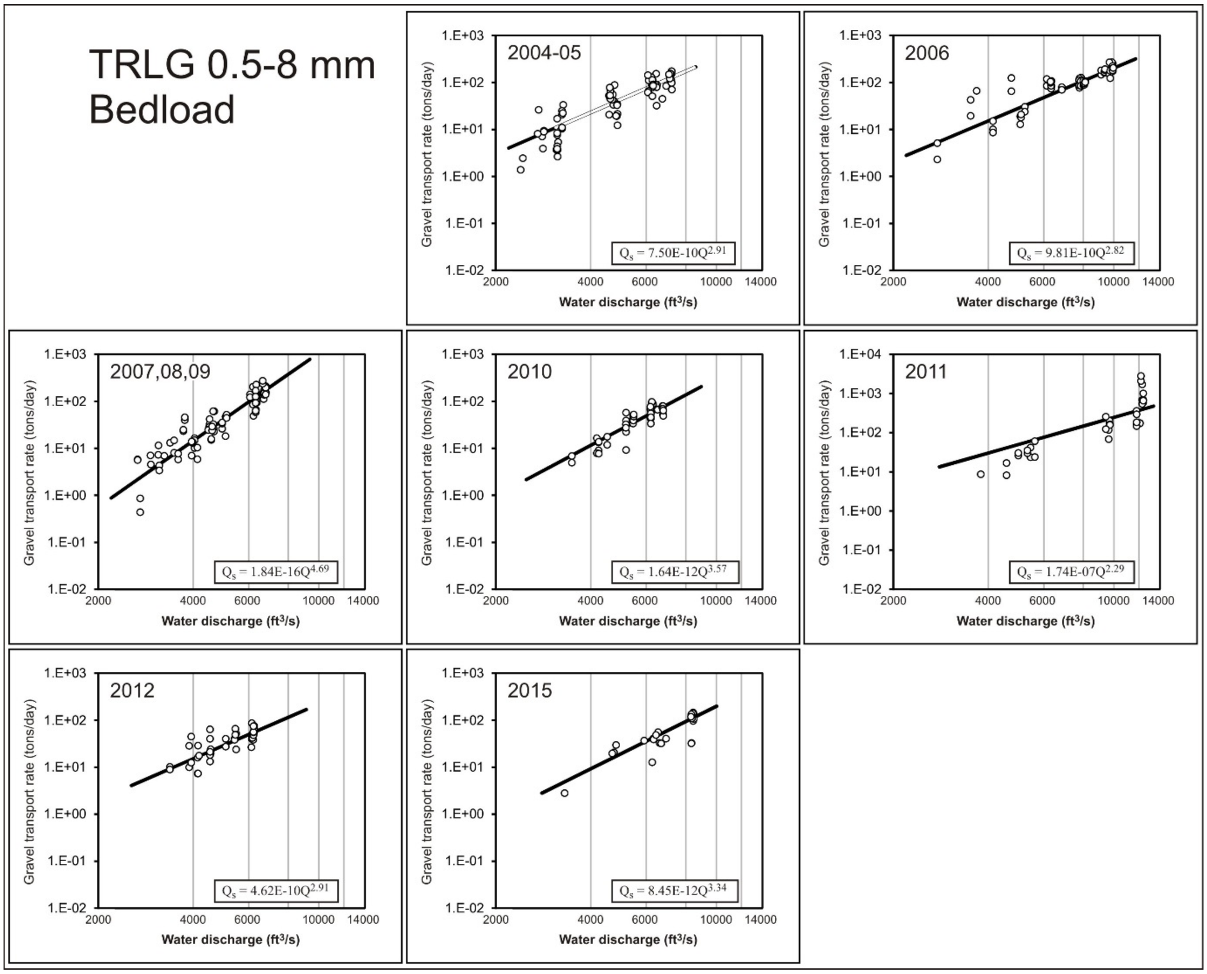

TRGVC > 8 mm
2006
Qs = 6.30E-09(Q - 1236)^3.01
2007,08,09
Qs = 2.17E-09(Q - 1236)^3.25
2010
Qs = 1.05E-10(Q - 2543)^3.62
2011
Qs = 1.24E-08(Q - 1201)^2.87
2012
Qs = 1.07E-10(Q - 2049)^3.58
2015
Qs = 2.82E-10(Q - 2366)^3.51
Gravel transport rate (tons/day)
Water discharge (ft3/s)

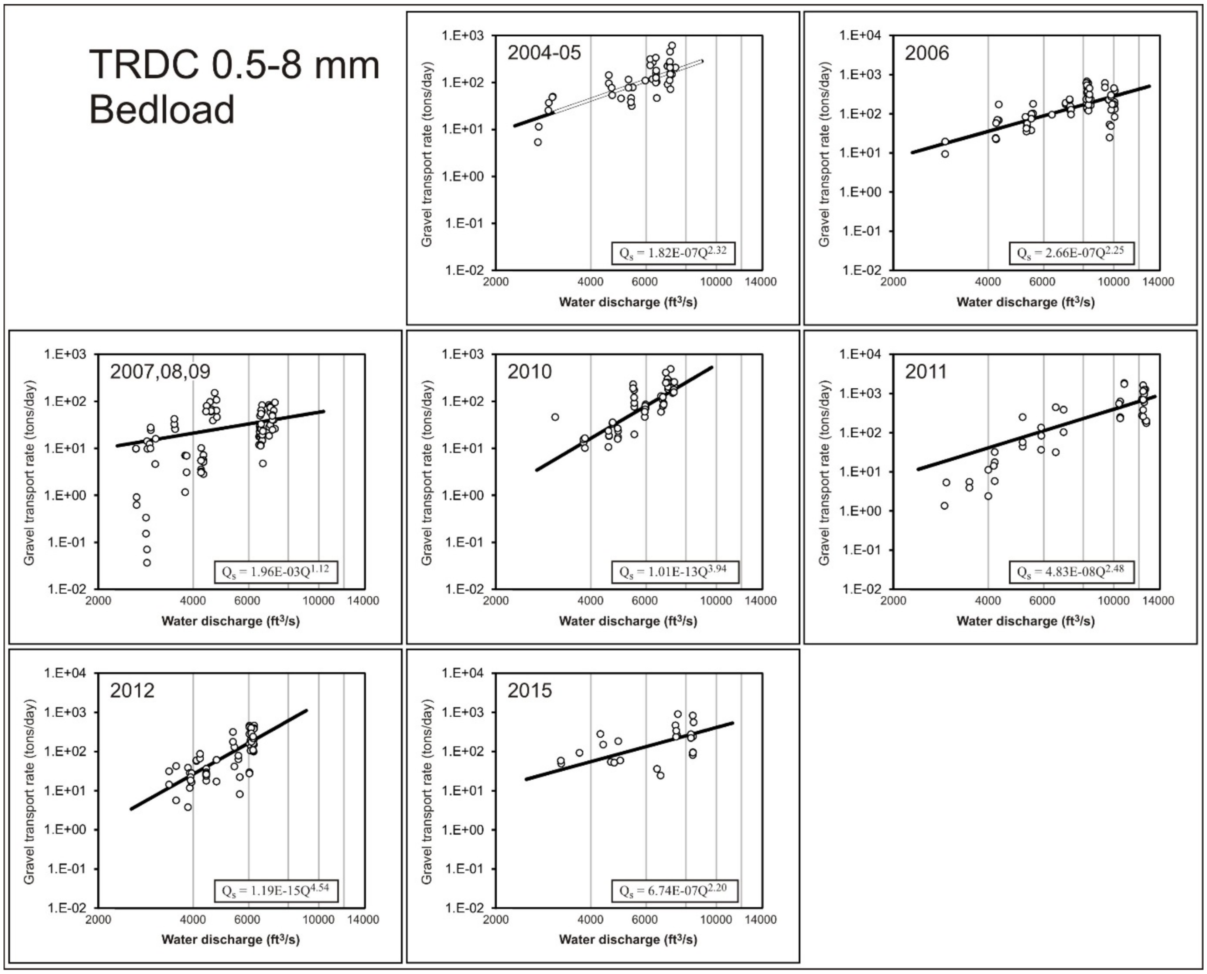

TRLG > 8 mm
2004-05
Qs = 6.19E-11(Q - 2190)^3.70
2006
Qs = 1.13E-06(Q - 459)^2.32
2007,08,09
Qs = 9.84E-13(Q - 2684)^4.33
2010
Qs = 1.60E-09(Q - 1625)^3.10
2011
Qs = 4.82E-10(Q - 2720)^3.35
2012
Qs = 6.86E-11(Q - 2684)^3.51
2015
Qs = 2.53E-09(Q - 2225)^3.08
Gravel transport rate (tons/day)
Water discharge (ft3/s)

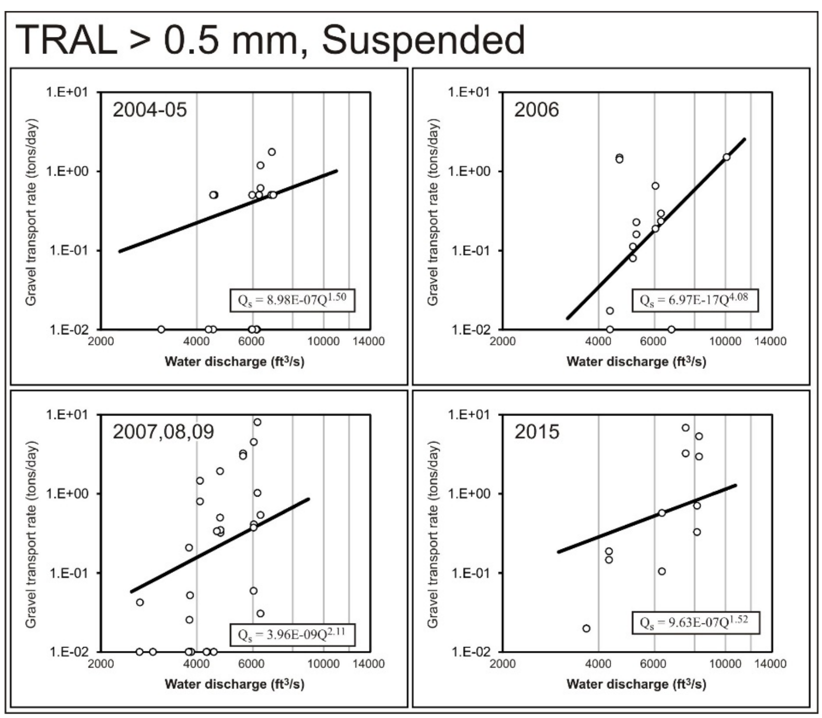

TRDC > 8 mm
2004-05
Q_s = 2.19E-10(Q - 1872)$^{3.53}$
2006
Q_s = 3.32E-07(Q - 776)$^{2.60}$
2007,08,09
Q_s = 1.35E-09(Q - 1413)$^{3.29}$
2010
Q_s = 4.89E-10(Q - 1554)$^{3.38}$
2011
Q_s = 4.92E-10(Q - 2737)$^{3.46}$
2012
Q_s = 6.63E-09(Q - 1166)$^{3.04}$
2015
Q_s = 3.67E-07(Q - 778)$^{2.63}$
Gravel transport rate (tons/day)
Water discharge (ft^3/s)
1.E-02
1.E-01
1.E+00
1.E+01
1.E+02
1.E+03
1.E+04
2000
4000
6000
10000
14000

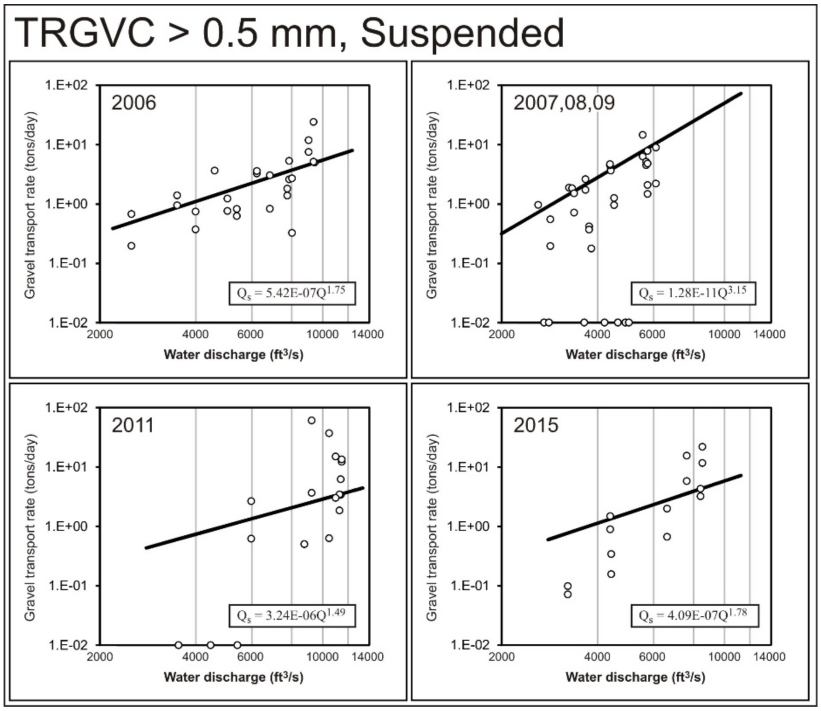

TRAL 0.5-8 mm Bedload
2004-05
Q_s = 3.20E-15$Q^{4.14}$
2006
Q_s = 2.07E-09$Q^{2.55}$
2007,08,09
Q_s = 2.37E-15$Q^{4.25}$
2010
Q_s = 2.82E-17$Q^{4.49}$
2011
Q_s = 1.77E-17$Q^{4.63}$
2012
Q_s = 3.24E-09$Q^{2.53}$
2015
Q_s = 1.67E-14$Q^{3.94}$
Gravel transport rate (tons/day)
Water discharge (ft³/s)

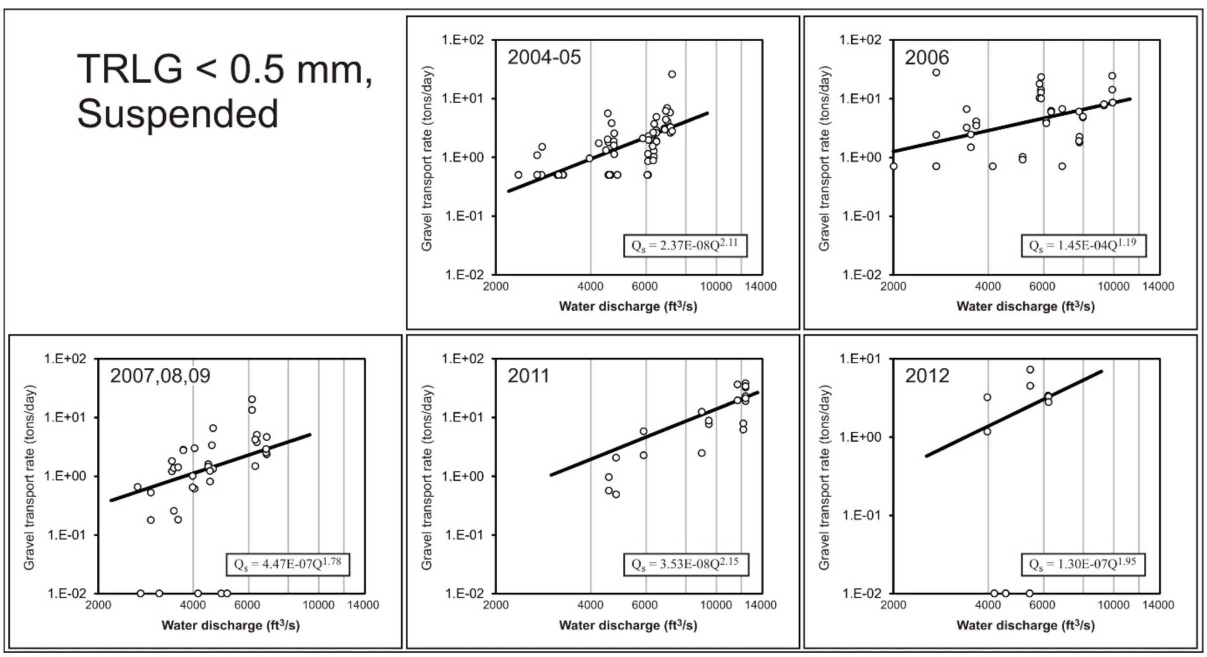

TRGVC 0.5-8 mm, Bedload
2006
Q_s = 1.63E-14$Q^{4.02}$
2007,08,09
Q_s = 4.78E-13$Q^{3.82}$
2010
Q_s = 8.31E-14$Q^{3.86}$
2011
Q_s = 2.24E-09$Q^{2.61}$
2012
Q_s = 1.97E-11$Q^{3.21}$
2015
Q_s = 1.28E-13$Q^{3.78}$
Gravel transport rate (tons/day)
Water discharge (ft³/s)

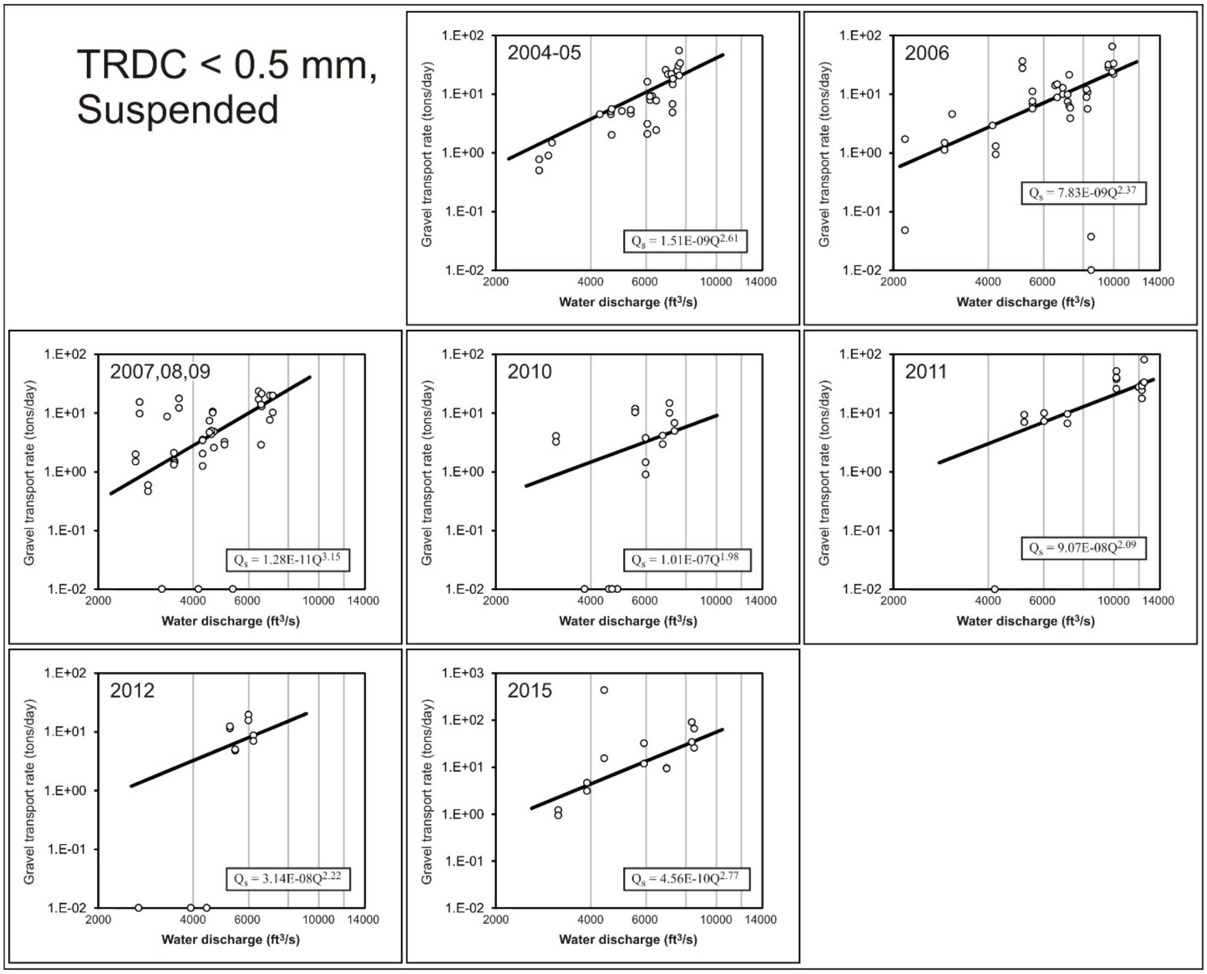

TRLG 0.5-8 mm
Bedload
2004-05
$Q_s = 7.50E\text{-}10Q^{2.91}$
2006
$Q_s = 9.81E\text{-}10Q^{2.82}$
2007,08,09
$Q_s = 1.84E\text{-}16Q^{4.69}$
2010
$Q_s = 1.64E\text{-}12Q^{3.57}$
2011
$Q_s = 1.74E\text{-}07Q^{2.29}$
2012
$Q_s = 4.62E\text{-}10Q^{2.91}$
2015
$Q_s = 8.45E\text{-}12Q^{3.34}$
Gravel transport rate (tons/day)
Water discharge (ft^3/s)


TRDC 0.5-8 mm Bedload
2004-05
$Q_s = 1.82E\text{-}07Q^{2.32}$
2006
$Q_s = 2.66E\text{-}07Q^{2.25}$
2007,08,09
$Q_s = 1.96E\text{-}03Q^{1.12}$
2010
$Q_s = 1.01E\text{-}13Q^{3.94}$
2011
$Q_s = 4.83E\text{-}08Q^{2.48}$
2012
$Q_s = 1.19E\text{-}15Q^{4.54}$
2015
$Q_s = 6.74E\text{-}07Q^{2.20}$
Gravel transport rate (tons/day)
Water discharge (ft^3/s)
2000
4000
6000
10000
14000
1.E-02
1.E-01
1.E+00
1.E+01
1.E+02
1.E+03
1.E+04


TRAL > 0.5 mm, Suspended
2004-05
$Q_s = 8.98E\text{-}07Q^{1.50}$
2006
$Q_s = 6.97E\text{-}17Q^{4.08}$
2007,08,09
$Q_s = 3.96E\text{-}09Q^{2.11}$
2015
$Q_s = 9.63E\text{-}07Q^{1.52}$
Gravel transport rate (tons/day)
Water discharge (ft^3/s)
2000
4000
6000
10000
14000
1.E-02
1.E-01
1.E+00
1.E+01


TRGVC > 0.5 mm, Suspended
2006
2007,08,09
2011
2015
Gravel transport rate (tons/day)
Water discharge (ft³/s)
$Q_s = 5.42E\text{-}07Q^{1.75}$
$Q_s = 1.28E\text{-}11Q^{3.15}$
$Q_s = 3.24E\text{-}06Q^{1.49}$
$Q_s = 4.09E\text{-}07Q^{1.78}$


TRLG < 0.5 mm, Suspended
2004-05
2006
2007,08,09
2011
2012
Gravel transport rate (tons/day)
Water discharge (ft³/s)
$Q_s = 2.37E\text{-}08Q^{2.11}$
$Q_s = 1.45E\text{-}04Q^{1.19}$
$Q_s = 4.47E\text{-}07Q^{1.78}$
$Q_s = 3.53E\text{-}08Q^{2.15}$
$Q_s = 1.30E\text{-}07Q^{1.95}$



TRDC < 0.5 mm, Suspended
2004-05
Qs = 1.51E-09Q2.61
2006
Qs = 7.83E-09Q2.37
2007,08,09
Qs = 1.28E-11Q3.15
2010
Qs = 1.01E-07Q1.98
2011
Qs = 9.07E-08Q2.09
2012
Qs = 3.14E-08Q2.22
2015
Qs = 4.56E-10Q2.77
Gravel transport rate (tons/day)
Water discharge (ft3/s)
1.E+03
1.E+02
1.E+01
1.E+00
1.E-01
1.E-02
2000
4000
6000
10000
14000

Appendix B

Long-term Composite Rating Curves

Long-term composite rating curves were developed from all sediment samples collected in 2004 through 2015. Separate power function curves for suspended fine bed material (left column) and fine bed material transported as bedload (middle column) were developed using non-linear LAR regression. Numerous zero-valued suspended bed material samples were retained in the LAR optimization procedures and are displayed on the arithmetic plots. Power function curves were developed for coarse bedload (right colum) using OLS. A small number of zero-valued coarse bedload samples were removed from the dataset to accomodate log transformation.