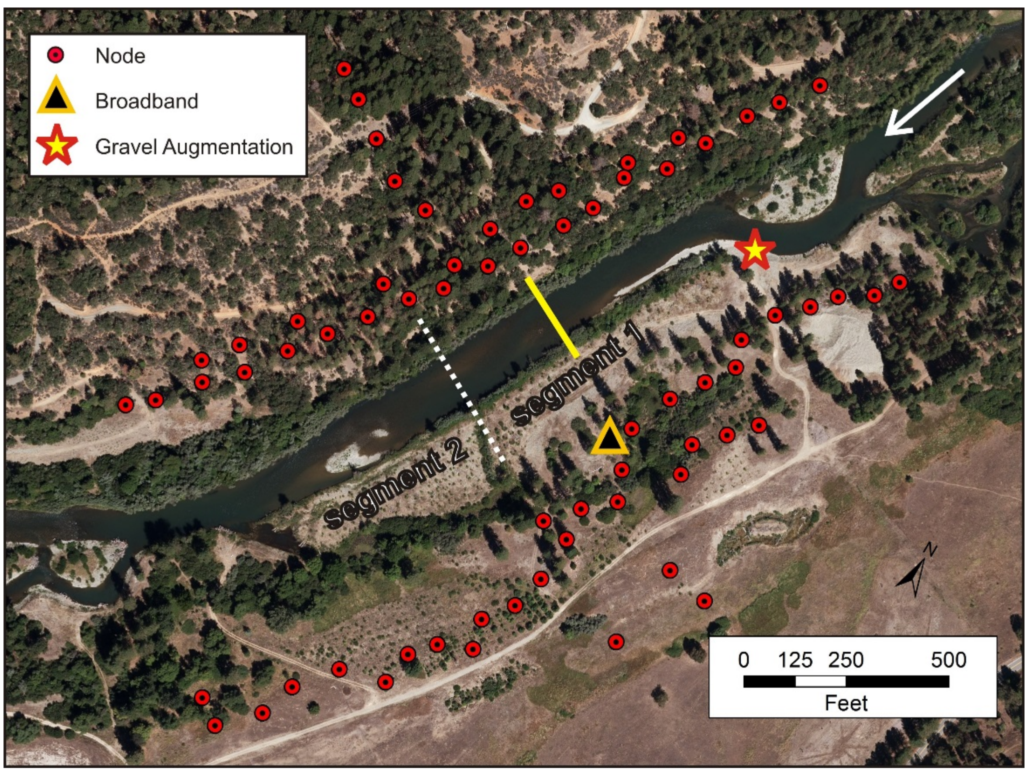
RECLAMATION

Managing Water in the West

Seismic Monitoring of Bedload Transport in a Large Gravel-bed River

Research and Development Office
Science and Technology Program
Final Report ST-2016-5561-1



U.S. Department of the Interior
Bureau of Reclamation
Research and Development Office

August 2016

Mission Statements

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The mission of the Bureau of Reclamation is to manage, develop, and protect water and related resources in an environmentally and economically sound manner in the interest of the American public.

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14. ABSTRACT *(Maximum 200 words)*

Several recent studies have shown that seismic energy generated by bedload transport in rivers can be detected by seismometers deployed outside the channel. This report presents the results of a comparison between seismic observations, changes in streambed topography, and measured bedload transport rates obtained during a dam-controlled flood in the Trinity River of Northern California. Seismic data were collected using an array of 77 seismometers spanning both sides of a reach of river nearly half a mile long. Seismic amplitudes reached maxima shortly after gravel augmentations at the upstream end of the study reach, followed by amplitude decay lasting 7 to 10 hours. The frequencies of the bedload-generated signals were found to be in the range of 20 to 100 Hz. Seismic amplitudes were greatest in the section of channel immediately downstream from the gravel augmentation location, where migrating bedforms were detected and net gravel deposition was greatest. These results demonstrate the potential for out-of-stream seismic monitoring to detect spatial and temporal variations in coarse sediment transport at the sub-reach scale. Potential applications include sediment transport monitoring in remote watersheds and exploration of how coarse sediment slugs produced by hillslope failures or other abrupt changes in sediment supply are propagated downstream.

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Executive Summary

Bedload transport is a primary driver determining river channel morphology, but obtaining sufficient physical samples to accurately quantify bedload fluxes is logistically difficult. Bedload transport rates are known to be highly variable in both time and space due to numerous factor, including stochastic variations in hydraulic forcing associated with turbulent flow, heterogeneous flow over bedforms, or changes in the quantity or grain size distribution of sediment supplied to a stream reach. Direct sampling of bedload transport rates is time consuming, expensive, sometimes dangerous, such that the number of samples collected in many bedload monitoring campaigns is insufficient for capturing the inherent variability and developing reliable estimates of bedload flux.

One emerging surrogate technology for monitoring bedload activity is the use of seismometers to detect bedload-induced seismic vibrations. Seismometers can be deployed outside the channel have been shown to have the potential to discriminate and quantitatively track the intensity of wave energy generated by bedload transport. Seismic monitoring of sediment transport has the potential to detect transport during transient or unexpected events that physical sampling would be unlikely to capture.

This project investigated the use of seismic ground vibrations to detect and quantify bedload transport in the Trinity River of California. Seismic observations were compared with bedload samples and repeated sonar surveys documenting topographic changes during a controlled flow release that included gravel augmentations upstream from the study reach. Seismic data were collected using an array of 77 seismometers spanning both sides of a reach of river nearly half a mile long. Gravel augmentations implemented at the upstream end of the study reach during the flow release produced significant temporal variability in gravel transport rates. Seismic amplitudes reached maxima shortly after the gravel augmentations, then decayed over periods lasting 7 to 10 hours. The frequencies of the bedload-generated signals were found to be in the range of 20 to 100 Hz. Seismic amplitudes were greatest in the section of channel immediately downstream from the gravel augmentation location, where migrating bedforms were detected and net gravel deposition was greatest.

These results demonstrate the potential for out-of-stream seismic monitoring to detect spatial and temporal variations in coarse sediment transport at the sub-reach scale. Potential applications include sediment transport monitoring in remote watersheds and exploration of how coarse sediment slugs produced by hillslope failures or other abrupt changes in sediment supply are propagated downstream.

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Introduction

Bedload transport is a primary driver determining channel morphology and aquatic habitat quality in gravel-bed streams. Accurately predicting bedload transport rates or quantifying bedload fluxes, however, is challenging. Bedload transport rates are known to be highly variable in both time and space due to numerous factors, including stochastic variations in hydraulic forcing associated with turbulent flow, heterogeneous flow over bedforms, or changes in the quantity or grain size distribution of sediment supplied to a stream reach [Gray et al. 1991; Kleinhans and Ten Brinke 2001; Singh et al. 2009]. Direct sampling of bedload transport rates is time consuming, expensive, and sometimes dangerous (Gaeuman and Jacobson 2006; Gray et al. 2010), such that the number of samples collected in many bedload monitoring campaigns is insufficient for capturing the inherent variability and developing reliable estimates of bedload flux.

Various researchers have attempted to improve bedload transport monitoring through the use of surrogate technologies, including acoustic Doppler bottom tracking (Rennie et al. 2002; Rennie and Villard 2004; Gaeuman and Jacobson 2007; Gaeuman and Pittman 2010), passive acoustics (Thorne et al. 1989; Barton et al. 2010; Marineau et al. 2016), and various types of impact sensors (Rickenmann and McArdell 2007; Rickenmann et al. 2013; Hilldale et al. 2015). These types of technologies make it possible to continuously monitor transport during transient or unexpected events that conventional sampling would be unlikely to capture. Another emerging method for monitoring bedload activity is the use of seismometers to detect bedload-induced seismic vibrations (Hsu et al. 2011; Schmandt et al. 2013; Roth et al. 2014; Roth et al. 2016). These studies demonstrate that seismometers deployed outside the channel can discriminate and quantitatively track the intensity of wave energy generated by bedload transport. Seismic methods also allow for spatially-explicit data acquisition, such that spatial variability in bedload transport rates can be resolved at the reach scale, thereby opening a new avenue for exploring bedload dynamics.

Although seismic measurements show promise as a useful method for qualitatively assessing bedload transport, a thorough calibration study in a setting where established methods are currently being employed is needed to establish its utility as a quantitative measurement technique. This report presents the results of a comparison between seismic observations and physical bedload transport samples collected during a high-flow dam release in the Trinity River of Northern California. In addition, multiple multibeam sonar surveys tracking changes in bed topography were obtained over the course of the flow release. These data identify areas of locally high bedload transport activity, which can be compared with reach-scale spatial variability in the observed seismic activity.

Study Area

This investigation was conducted in the Lowden Ranch reach of the Trinity River, a large gravel-bed river in Northern California (Figure 1). A pair of dams, Lewiston Dam and the larger Trinity Dam, have regulated flows and eliminated bed material delivery from the upper basin since 1960. Decreases in anadromous fish populations associated with dam operations led to establishment of the Trinity River Restoration Program (TRRP), a multi-agency partnership that currently manages environmental flow releases and bed material supplies downstream from the dams (USDOI 2000). The 2-year recurrence peak flow downstream from the dams is in the neighborhood of 7000 ft^3/s and bankfull channel widths typically range between 100 and 160 ft.

The Lowden Ranch site is located about 7 miles downstream from Lewiston Dam (Figure 1). TRRP implemented a channel rehabilitation project in this reach in 2010. That project consisted of terrace lowering, side channel construction, construction of a meander bend, and establishment of a long-term gravel augmentation location (Gaeuman 2014). The gravel augmentations are performed by dumping gravel and small cobbles into the flow with a loader near the upstream end of the site during high-flow dam releases. An initial augmentation was performed in the spring of 2011, when 2050 yd^3 of coarse sediment between about 12 and 125 mm in intermediate diameter were introduced during a 3-day period when flows were between about 11000 and 12000 ft^3/s. A second augmentation performed in conjunction with this study is described below.

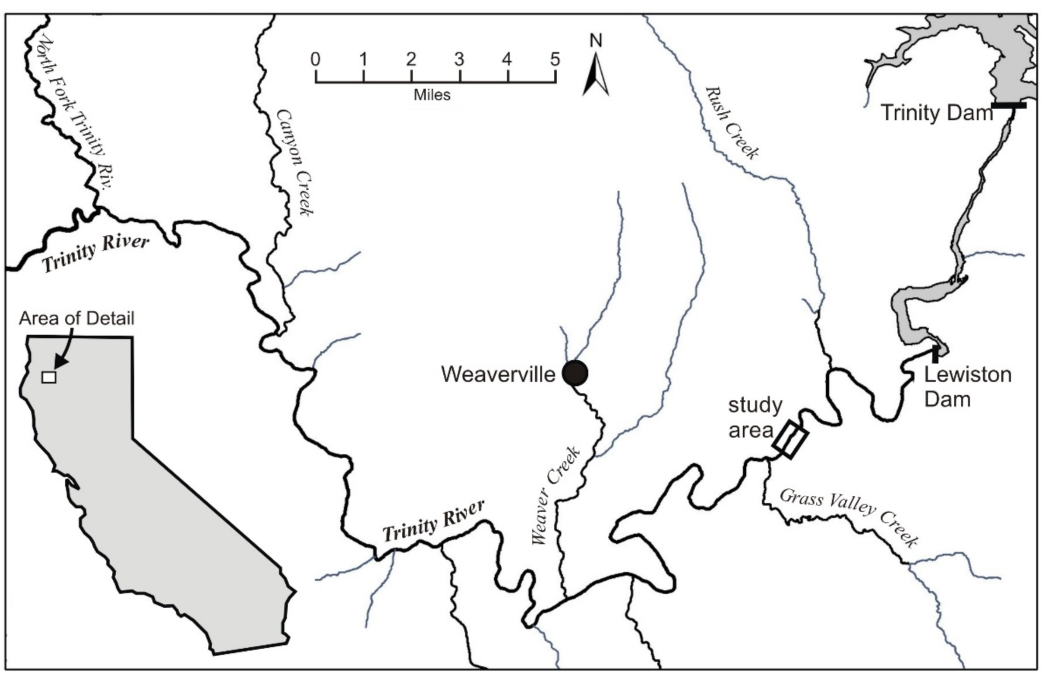

Figure 1: Map showing the study area location in northern California.

Methods

Data used in this study were collected in the Lowden Ranch reach before, during, and after a high-flow release that peaked in early May of 2015. Water discharge during the flow release was measured at the Trinity River above Grass Valley Creek gaging station (USGS station 11525540), which is located within the Lowden Ranch site. A gradual rise from a winter baseflow near 300 ft^3/s beginning in mid-April reached 5000 ft^3/s, a discharge near the onset of significant gravel transport, by about noon on May 4 (Figure 2). Flows then increased rapidly to a peak near 8500 ft^3/s by midnight. The flow was maintained near that peak level for slightly more than 2 days before beginning to decline early on May 7. Flows dropped back below 5000 ft^3/s by noon on May 8.

Bedload transport rates were monitored during the release at a sampling transect approximately 150 yards downstream from the gravel augmentation point (Figure 3). A total of 27 single-pass bedload samples were obtained over the course of the release, including 6 samples collected each day on May 4 through May 7 (Figure 2). As defined here, a single-pass sample consists of 1 pass across the channel using the equal distance sampling protocol described by Edwards and Glysson (1999). Sampling was conducted using a TR-2 bedload sampler with a 6 by 12 inch intake nozzle and a 0.5 mm mesh bag (GMA 2016). Samples were subsequently dried and sieved into half-phi size classes, but only the total bedload transport rates and loads are considered herein.

The 2015 gravel augmentation at this site was accomplished in two sessions, each of which consisted of 340 yd^3 of gravel introduced over the course of 2 to 3 hours. The first augmentation session took place between about noon and 15:30 PDT on May 4, as flows were rapidly rising from about 5000 to about 7500 ft^3/s (Figure 2). The second augmentation began at about noon and ended at 14:15 PDT on May 5, while flows were held steady at about 8500 ft^3/s.

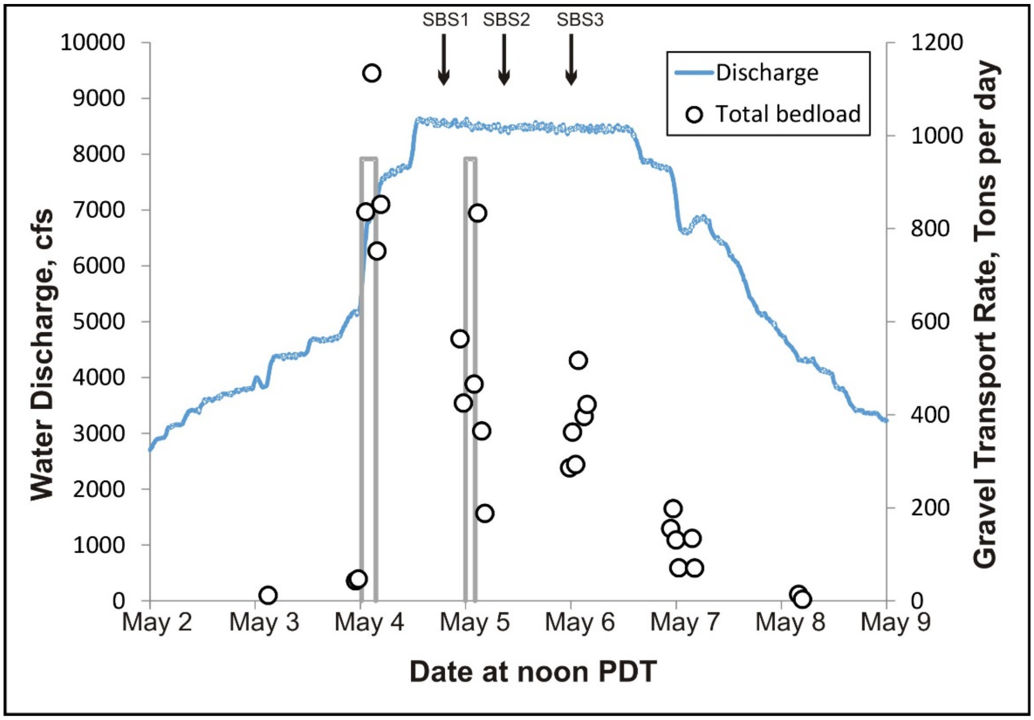

Figure 2: Flow hydrograph in the days surrounding the flow release peak superimposed with timing and magnitudes of the bedload samples (open circles) and gravel augmentations (grey bars). Approximate times of sonar bathymetric surveys during the release are also indicated. The initial and final bathymetric surveys (SBS0 and SBS4) occurred prior to and after the time period shown.

The seismic data were collected using an array of 76 small cable-free seismometers referred to as nodes, each of which contained a 10-Hz geophone sensitive to vertical ground motion (Schmandt et al. *submitted*). The node array spanned a distance of nearly half a mile on both sides of the river (Figure 3). Data were recorded with a sample rate of 250 Hz, allowing analysis up to 100 Hz. An additional three-component broadband seismometer was installed in the middle of the array. Analysis was restricted to nighttime measurements, 7 pm to 7 am local time (GMT-7 hours), because of human activity within the study area and on nearby roads during the day. The amplitudes of the seismic signal recorded at individual nodes were corrected for signal decay with distance from the river using a locally estimated attenuation factor. Attenuation of surface waves, which are assumed to be the dominant wave type produced by the river, is estimated according to:

$$A(d) = A_0 e^{-\omega d/2cQ} \qquad (1)$$

where A_0 is the signal amplitude at the source, d is the propagation distance orthogonal to the river, ω is angular frequency of the seismic signal, c is the shear velocity associated with the floodplain material, and Q is a quality factor that quantifies energy dissipation (Aki and Richards 2002). A local shear velocity of 1280 ft/s was estimated by generating signal sources within the node array with a sledge hammer. *Q* was estimated from median hourly amplitudes recorded between midnight and 3:00 a.m. on the first night of peak discharge. The recorded waveforms were filtered to 20–30 Hz because those frequencies had the highest amplitude responses following gravel augmentations. Statistical optimization to minimize the misfit to $\log_{10}$ seismic amplitudes yielded $Q = 19$, with a 95% confidence interval encompassing $14 < Q < 29$ (Chatterjee and Hadi 1986). This value of *Q* implies that the amplitude of a 20 Hz signal would decay by a factor of 10 over about 650 ft.

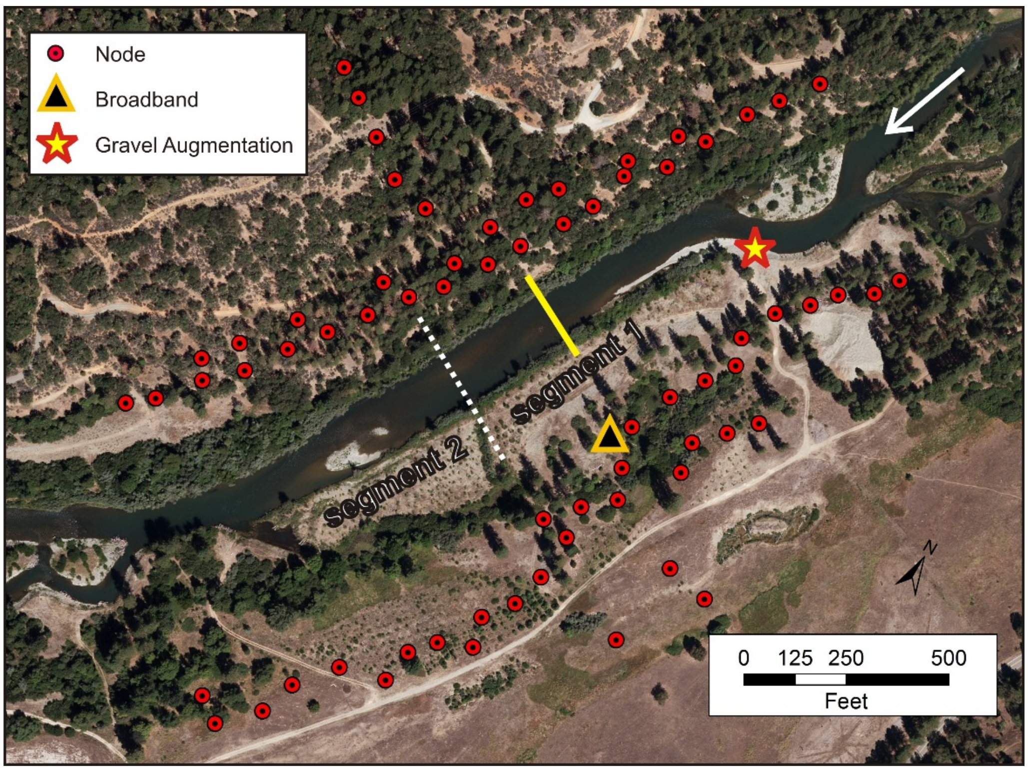

Figure 3: Map of the Lowden Ranch reach showing the locations of seismic nodes and the broadband seismometer. The yellow line indicates the bedload sampling transect and the white dashed line is the boundary between channel segments 1 and 2. The white arrow shows the direction of flow.

Bounds on bedload transport were derived from repeated sonar bathymetric surveys (SBS) of the river bed. The initial bed topography prior to the 2015 flow release is represented by a terrain model based on data collected with an array of 7 sonar transducers mounted on a jet boat (GMA 2012) in the summer of 2011. This initial survey is denoted by SBS0. Although close to four years elapsed between SBS0 and the start of the 2015 release, flows large enough to generate large gravel transport rates were nearly absent in that time interval (Figure 4). Thus, the bed topography depicted by SBS0 is believed to approximate the topography that existed just prior to the 2015 release. Topography was surveyed four more times during the flow release using a Norbit wideband multibeam sonar system. The first two multibeam surveys, SBS1 and SBS2, were collected on May 5 (Figure 2), one in the morning before the second gravel augmentation (8:30 to 10:15 PDT) and one in the evening following the augmentation (17:00 to 18:30 PDT). The third multibeam survey, SBS3, was obtained on the morning of May 6 (10:30 to 11:30 PDT) while streamflow remained steady at the release peak of 8500 ft^3/s, and the fourth survey capturing the final bed topography at the end of the release (SBS4) was performed in the early evening of May 10 after flow had dropped to about 3000 ft^3/s.

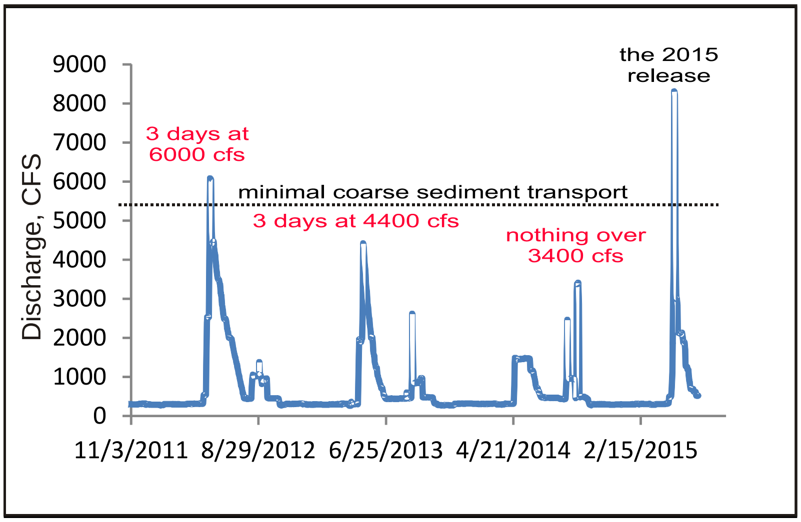

Figure 4: Hydrology at the Lowden Ranch location since the summer of 2011. Flows were below the threshold for significant gravel entrainment throughout 2012-2014 except for three days in 2012 when flows exceeded that threshold by a relatively small margin.

Results

The mean estimated bedload transport rate from physical samples during the three days of peak discharge (May 4 through May 6) was 370 tons/day, and the maximum transport rate was 1140 tons/day. Sampled bedload was primarily gravel, with about 75% of the sampled mass consisting of grains larger than 4 mm in diameter. Transport rates were greatest during and immediately following the first gravel augmentation on May 4, which coincided with a rapid increase in flow to about 7500 ft^3/s (Figure 2). Transport rates during the second gravel augmentation on May 5 were approximately half those observed on the previous day, despite the fact that the flow was 15% to 20% higher. Transport rates continued to decrease slightly on the last day of the peak and declined to about a sixth of the average value observed during the first gravel augmentation as flows decreased to between 6000 and 7000 ft^3/s on May 7. Transport rates measured at flows less that about 5000 ft^3/s prior to the first gravel augmentation and after

May 7 were negligibly small. The D_{50}, D_{90}, and D_{94} of sampled grains were 32, 82 and 94 mm, respectively.

The broadband seismograph's vertical component amplitude spectra during three time periods illustrate the frequencies dominantly excited by fluid and sediment transport (Figure 5). Estimates of amplitude spectra were calculated using the multi-taper method (Thomson 1982). The S1 amplitude spectrum was observed at 23:00 PDT prior to the controlled flood when discharge was about 3800 ft^3/s. It serves as a reference spectrum because little or no gravel transport occurs at this discharge level. The S2 spectrum was observed on May 5 during the peak discharge of 8500 ft^3/s and 1–2 hours after the second gravel augmentation was completed. It approximates the maximum 3–100 Hz amplitudes recorded by the broadband seismograph during the experiment and contains strong signals from both water and bedload transport. The occurrence of gravel augmentation during constant discharge provides an opportunity to isolate the frequency range that responds to variations in bedload supply. The S3 spectrum was recorded six hours after S2 while discharge remained constant. The strength of the bedload signal decays with time after the gravel augmentation, with the S2 spectrum at least 2 dB stronger than the S3 spectrum at frequencies above 20 Hz. Consequently, we focus on frequencies greater than 20 Hz as a potential bedload transport proxy.

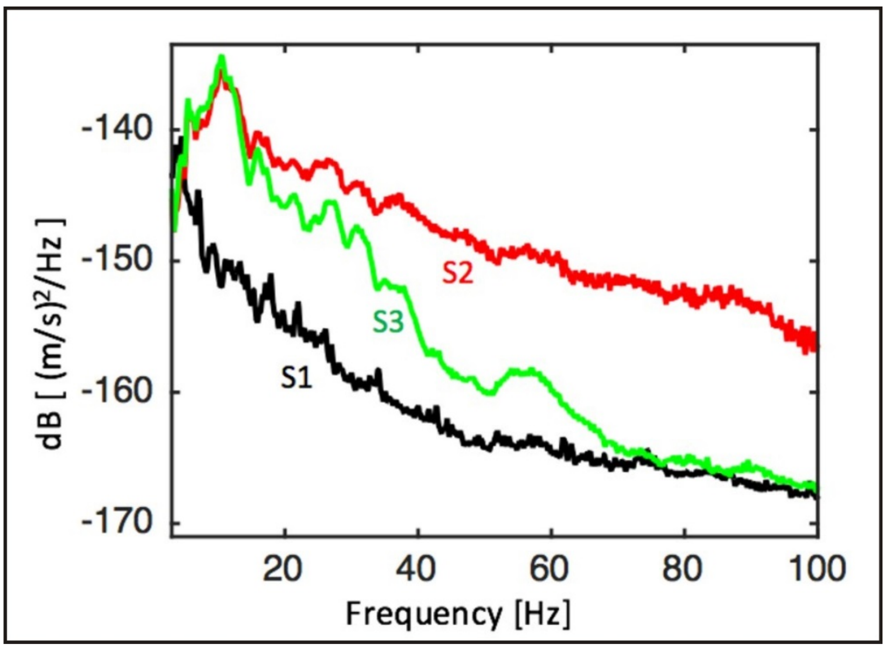

Figure 5: Amplitude spectra of the vertical component of the seismic signal received at the broadband seismograph during three time periods. The times at which these three spectra were recorded is indicated on panel A of Figure 7.

Distinct temporal variations in seismic amplitude in two frequency bands further illustrates their dominant sensitivity to fluid and bedload transport, respectively.

Hourly seismograms were bandpass filtered between 3–12 Hz and 20–100 Hz, and hourly median amplitudes were computed for each node and averaged over all nodes in the array. The resulting hourly amplitudes for the 3–12 Hz frequency band varies smoothly with water discharge and does not exhibit strong responses to the gravel augmentations (Figure 6). In contrast, the 20–100 Hz hourly amplitudes exhibited local maxima after each gravel augmentation followed by amplitude decay extending up to 7–10 hours after augmentation. The first episode of post-augmentation amplitude decay occurred during rising discharge and the second occurred during constant discharge so these transients are unambiguously linked to bedload rather than water transport (Figure 7).

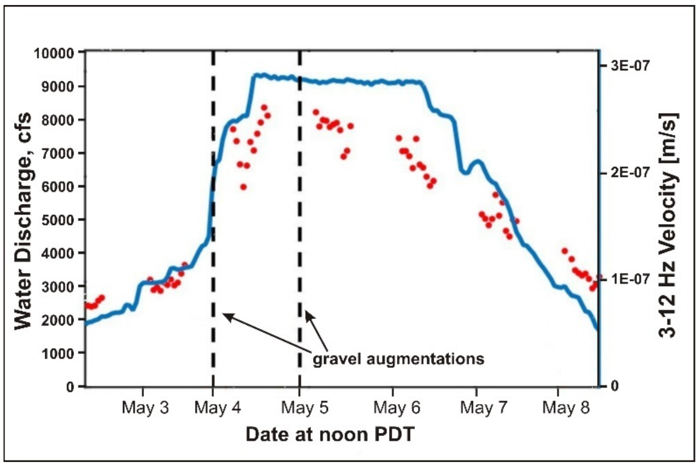

Figure 6: Hourly mean amplitudes of the vertical component of the seismic signal at 3 to 12 Hz, averaged over the full study area.

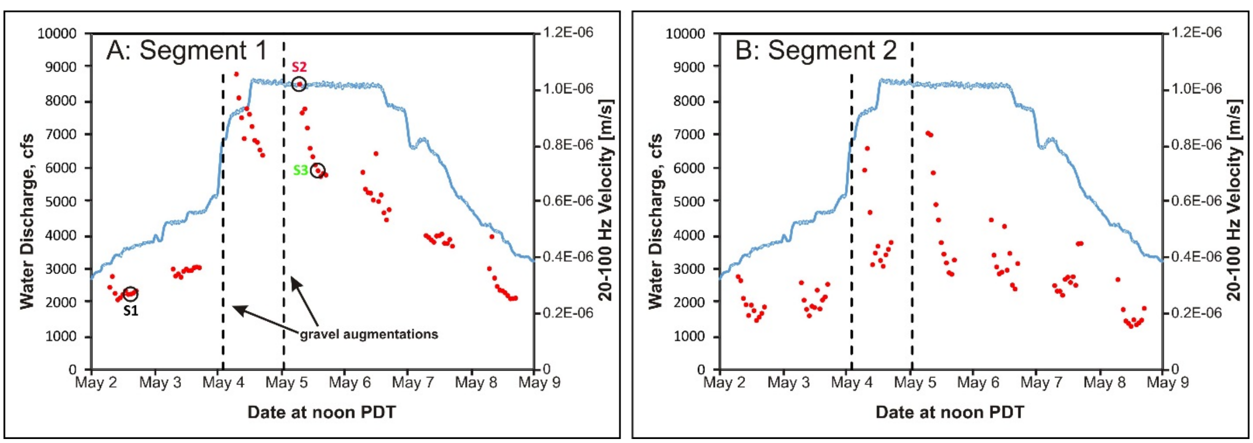

Figure 7: Hourly mean amplitudes of the vertical component of the seismic signal 20 to 100 Hz, averaged over A) channel segment 1, and B) channel segment 2. The locations of the channel segments are indicated in Figure 3.

The array of nodes was separated into two segments to investigate the extent of the reach affected by gravel augmentation (Figure 3). Channel segment 1 begins at the gravel augmentation location and extends about 800 ft downstream from there. Channel segment 2 begins at the downstream boundary of segment 1 and extends another 500 ft downstream. Each segment contains more than 27 nodes within about 600 ft of the thalweg. Seismic waves from the river propagate in all directions so signals in the two segments are not entirely independent. However, observed amplitude decay with distance to the channel indicates that the amplitudes of frequencies greater than 20 Hz decay by a factor of 10 or more over a distance of about 650 ft. Consequently, the mean hourly amplitudes for each segment are dominated by sources located within the segment. Both segments exhibited amplitude maxima following gravel augmentations, but the range in amplitudes following gravel augmentation was smaller in segment 1 (Figure 7). The transient responses in segment 2 exhibit a more pronounced decreases in amplitude over time, reaching levels of about 50% of the maxima recorded shortly after the augmentations were completed (Figure 7). Post-augmentation amplitude decays occurred over the first 4 to7 hours of the night, which corresponds to 7 to 10 hours after augmentation.

Maps of signal amplitude at each node illustrate along-stream variations (Figure 8). A similar pattern was observed for the first night of peak discharge and the 3-night mean. The highest amplitudes were observed in channel segment 1. Migrating bedforms about 1 to 1.5 ft high were detected by topographic differencing in this portion of the channel (Figure 8a). Seismic amplitudes were relatively small farther downstream in channel segment 2, as well as in the bend upstream from the augmentation location. Bedform activity was absent in both of these locations. The mean amplitude in segment 1 was 66% greater than in segment 2 after correction for signal decay with distance from the channel, per equation (1).

Both segments of the reach accumulated gravel during the flood, with a cumulative total increase in gravel storage of about 1580 yd^3 according to topographic differencing. The bed of the Trinity River is composed of clast-supported gravel and cobbles (Viparelli et al. 2011), so the contribution of sand to changes in bathymetry is considered negligible because it occupies the pore spaces between larger grains (Gaeuman 2014). The total volume of the gravel augmentations was 680 yd^3, so about 900 yd^3 of gravel appears to have been transported into the reach from upstream. This represents a lower bound on the cumulative transport into the reach because some portion of the gravel transported into and within the reach may have passed beyond the downstream boundary of the surveyed area. The bathymetric models generated from the sonar surveys, however, indicate that bed topography near the downstream end of the study area was essentially static over the course of the flow release, suggesting that gravel fluxes in that part of the river were negligible. Most of the net gravel deposition, about 1280 yd^3, occurred in segment 1. Gravel storage in segment 2 increase by just 300 yd^3. Thus, assuming a negligible gravel flux past the downstream boundary of the study area, the repeat sonar surveys indicates that gravel transport rates were as much as 5.3 times larger in channel segment 1 than in segment 2. This result is consistent with the hypothesis that along-stream differences in high frequency seismic amplitudes are due to spatial differences in gravel transport rates.

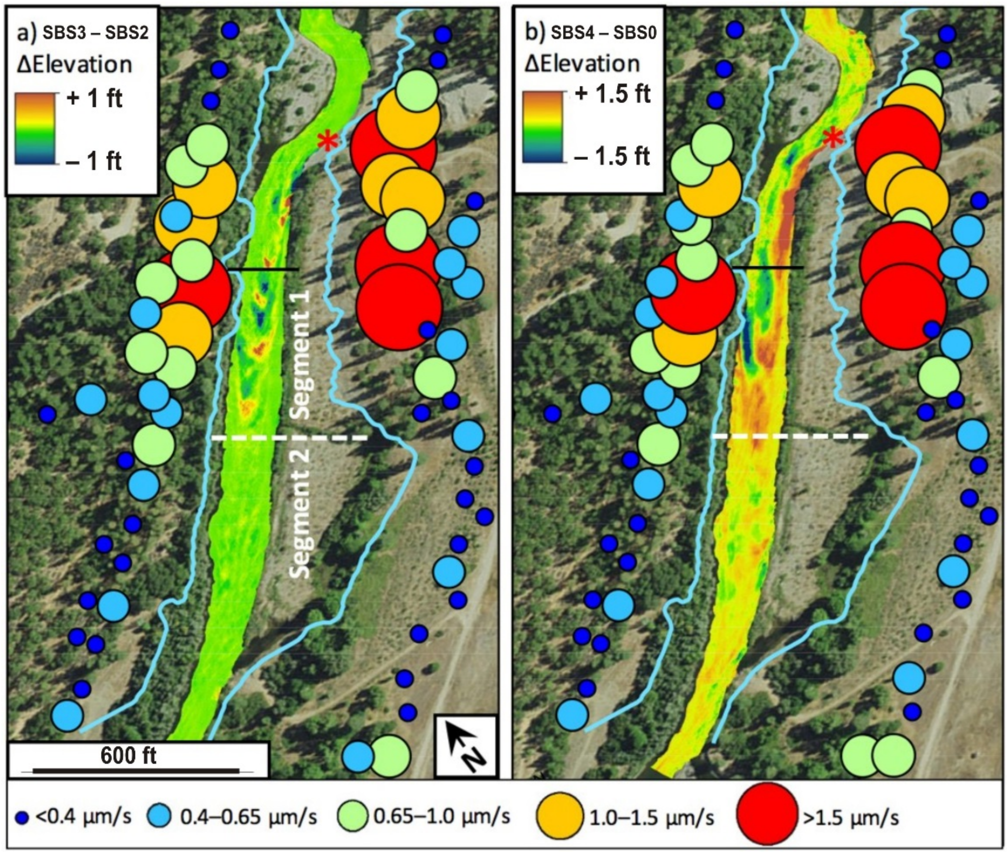

Figure 8: Maps showing the spatial distributions of the mean hourly seismic amplitudes and topographic changes. A) Bed level changes between sonar surveys SBS3 and SBS2 corresponds to changes during the nighttime following the first day of the flood. Node seismographs symbol size and color corresponds to nighttime amplitudes in the 20–100 Hz frequency band following the first day of the flood. The red asterisk denotes the gravel augmentation point. B) Bed level changes between sonar surveys SBS4 and the initial survey, SBS0, and mean hourly seismic amplitudes averaged over the three nights of highest discharge.

Discussion

The temporal response of the seismic array to the gravel augmentations provides additional insights into the temporal and spatial scales affected by the augmentations. The similar timing of the increases in seismic amplitudes in both the upstream and downstream halves of the reach suggest that the augmentations stimulated a nearly immediate short-term (7 to 10 hour) increase in bedload transport through most of the Lowden Ranch site. This is inconsistent with the notion that a discrete pulse of excess gravel propagated through the reach, one segment at a time. However, transient seismic amplitude increases in the downstream half of the reach decayed more rapidly than in the upstream half, suggesting a longer term effect within about 800 ft of the augmentation point where migrating bedforms were observed (Figure 8).

Differential pre- and post-flood bathymetry demonstrating that gravel transport decreased by a factor of about 5.3 in the downstream half of the site provides an opportunity to test theoretical models of seismic sensitivity to bedload transport. A simple model of seismic wave generation by bedload saltation over exposed bedrock proposed by Tsai et al. (2012) predicts that seismic power is linearly proportional to the mass transport rate, assuming a constant grain size distribution. The distance-corrected power ratio between channel segments 1 and 2 in the 20–100 Hz range is 1.9, which is less than half the ratio of the transport rates inferred for the two channel segments from topographic differencing. Additionally, the model predicts an absolute power level for frequencies in the 20 to 100 Hz range up to 15 dB greater than the power observed in segment 1. The fact that the model overestimates the seismic power in this reach of the Trinity River is not surprising because the model assumes an exposed bedrock channel rather than a gravel bed. The source of the difference between observed and predicted along-stream variations, however, is more difficult to identify.

According to the model of Tsai et al. (2012), seismic power is proportional to the cube of the characteristic grain size (the D_{94}) of the bedload. The bedload samples collected near the center of channel segment 1 provide the only information available for estimating the D_{94} of the bedload in the study reach. Given that the D_{94} at the sampling transect is estimated to be about 94 mm, the difference between the observed power ratio of 1.9 and the estimated flux ratio of 5.3 could be explained by a downstream decrease in the bedload D_{94} to about 67 mm. Although a spatial difference in the bedload grain size of this magnitude seems plausible, no direct observations of bedload grain sizes in segment 2 are available to assess this possibility. It is also possible that the difference between the seismic power ratio and the estimated bedload transport rates is partly an artifact of assuming that little or no gravel was transported beyond the downstream boundary of the study area. The ratio of the estimated gravel fluxes in channel segments 1 and 2 decreases if one invokes the possibility that there was a non-zero quantity of gravel passed out of the study. In particular, the ratio of the estimated gravel fluxes can be made to match the seismic power ratio by assuming that the gravel flux out of the study area totaled about 1100 yd^3. Although a gravel flux of this magnitude is plausible, the available evidence suggests that the gravel flux exiting the study area was much smaller. As already noted, an almost complete lack of topographic change in the downstream portion of the study area suggests that gravel fluxes in that area were small. In addition, gravel load computations based on the physical bedload samples also suggest that little or no gravel left the study area. According to GMA (2016), a total of about

940 yd^3 of gravel flux passed the sediment monitoring transect during the flow release. When parsed into regions upstream and downstream from that transect, the net bathymetric changes derived from the sonar surveys indicate that about 1190 yd^3 of gravel was deposited within the study area downstream from the sampling transect. The close agreement between the estimated flux at the sampling transect and the deposition volume measured downstream from the sampling transect is strong evidence that most of that material remained in the study area.

Conclusions

Seismic signals with frequencies of 3 to 12 Hz were found to vary smoothly with water discharge and exhibited little response to gravel augmentations. In contrast, seismic signals with frequencies of greater than 20 Hz reached maximum amplitudes after gravel augmentations near the upstream end of the reach, followed by amplitude decay lasting 7 to 10 hours after augmentation. We therefore conclude that the frequencies of bedload-generated seismic signals are in the range of 20 to 100 Hz. The amplitudes of these frequencies were found to decay by a factor of 10 or more over a distance of about 650 ft at the Lowden Ranch site.

The rapid rate of signal decay relative to the length of the study reach made it possible to assess spatial differences in the bedload-generated seismic signal. The largest seismic amplitudes were observed in a section of channel extending about 800 ft downstream from the gravel augmentation location. Migrating bedforms about 1 ft high were detected by differential bathymetry in this portion of the channel (Figure 8a). Seismic amplitudes were relatively small and decayed more rapidly following augmentation in the section of channel located farther downstream, suggesting that gravel transport rates were greatest in the upstream part of the study area.

Estimated changes in bed material storage based on repeat sonar surveys and topographic differencing corroborate the seismic results, in that net gravel deposition was greatest in the upstream portion of the study area. About 1280 yd^3 of net deposition was detected in the first 800 ft downstream from the gravel augmentation locations, whereas just 300 yd^3 of net deposition was detected in the downstream half of the site. This implies that bedload transport rates were about 5.3 times larger in the upstream half of the study area than in the downstream half.

The distance-corrected power ratio in the 20 to 100 Hz frequency range between the upstream and downstream segments of the study area was found to be less than half the ratio of the transport rates inferred for the two segments from topographic differencing. This result differs from the predictions of a published theoretical model of bedload-generated seismic activity, but the apparent discrepancy could be due to spatial changes in the bedload grain size distribution.

These results demonstrate the potential for out-of-stream seismic monitoring to detect spatial and temporal variations in coarse sediment transport at the sub-reach scale. They also highlight the importance of developing empirical or mechanistic models of the seismic signal generated by bedload transport under specific riverbed conditions, which may vary over short along-stream distances. Potential applications include sediment transport monitoring in remote watersheds and exploration of how coarse sediment slugs produced by hillslope failures or other abrupt changes in sediment supply are propagated downstream.

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Data Sets that support the final report

If there are any data sets with your research, please note:

- Share Drive folder name and path where data are stored: https://drive.google.com/drive/folders/0B1kG9U-E0F0gV1kwdnJoSzBlR1k

- Point of Contact name, email and phone: David Gaeuman, dgaeuman@usbr.gov

- Segment1.csv and segment2.csv contain hourly mean seismic amplitudes (vertical component) between 20 and 100 Hz averaged over channel segment 1 and 2. Time is given in ordinal days, Greenwich Mean Time.

  LowdenArray.csv contains the geographic coordinates of the seismic node locations (decimal degrees).

  TRGVC_WY15_fractional_bedload_transport.csv contains fractional bedload transport data collected with a TR-2 bedload sampler.

  Multibeam.zip contains the gridded bed elevations collected with multibeam sonar. Grids numbered 1 through 4 correspond to the first through fourth surveys discussed in the report.

- Keywords: bedload transport, seismic monitoring

- Approximate total size of all files: 2.43 MB