Overview of Bedload Estimates Based on Seismic Monitoring at the ephemeral Arroyo de los Pinos tributary of the Rio Grande, New Mexico

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Abstract

The field of environmental seismology encompasses the use of seismic ground motion records produced by shallow-earth processes, such as glacial motion, subsurface water flow, and bedload transport, to better understand those processes. Seismic monitoring of these phenomena has several advantages over more traditional surficial process measurements, as seismic data can provide continuous recording over multiple events, potentially at several different positions safely away from the event of interest. Early applications using seismic data to track bedload transport in rivers focused on opportune recordings in the vicinity of high energy perennial rivers; these studies suggest that seismic energy within certain frequency bands is linked to bedload discharge. Theoretical models of bedload transport in these high energy systems demonstrate the potential for seismic signal frequency characteristics to distinguish bedload transport of different size material. With the relative success of seismic methods in predicting coarse bedload transport in high energy rivers, interest has shifted towards other river systems, such as ephemeral streams that move large quantities of mixed sand-and-gravel sediment during short-lived flash flood events. Even though ephemeral streams in arid regions are common, they are generally data poor because of the infrequency of flood events and their localized occurrence. The Arroyo de los Pinos sediment observatory located in an ephemeral tributary of the Rio Grande is unique in combining a variety of in-channel bedload and water monitoring measurements with dense seismic recording alongside the channel. We have seismic records for over 15 flow events ranging from a few centimeters to over one meter of water depth, encompassing bedload flux in the range 0.2 - 12 kg s^{-1} m^{-1}. Our efforts to date have focused on identifying the noise sources within the seismic record, characterization of the seismic properties of the site, and determining the seismic frequency ranges best correlated with the monitored bedload flux. Within the frequency range of 30-80 hertz (Hz), we find a linear relationship between seismic power and bedload flux. We hypothesize that variations in linear fit statistics between flood events are due to varying grain size distributions in transport and morphological changes in the channel.

Introduction

An important question in the Earth sciences is the magnitude of bedload transported in river systems, a process that affects large-scale landscape evolution and erosion, with practical applications for river management. Various methods and data are used, with data collection both within and outside of the active channel, to characterize the flux of transported sediment.

However, in-channel sampling can be costly, especially if hardened infrastructure is required for trapping material, or dangerous if it requires personnel for manual sampling of material (e.g., Reid et al., 1980; Bunte et al., 2004).

Other proxy measurements have been used, such as plate geophones and in-channel microphones that measure impacts, or the sounds of impacts, as water and bedload move in the channel (e.g., Rickenmann et al. 2012; Mizuyama et al. 2010). Measurements with these instruments can be automated to capture data without human intervention. However, these instruments are still located within the channel itself and at risk of damage during large floods.

Another proxy measurement is seismic ground motion associated with the impacts of bedload on the channel bed. Seismic instrumentation has many advantages for bedload recording; the instrumentation can be placed outside the channel and can record continuously at a high sampling rate (up to 1000s of samples per second) without manual intervention. An early example of monitoring bedload transport with seismic recording repurposed data originally collected for a tectonic project in the Himalayan Mountains to study ground motion associated with changes in water flow along the high-energy Trisuli River (Burtin et al., 2008). These seismic data, specifically those ground motions within the 5-15 Hz frequency band, had larger amplitudes during the local summer monsoon period. Temporal variations of seismic power within the monsoon season were attributed to the river having more sediment available for transport early in the season relative to the season's end, providing indirect evidence of bedload transport (Burtin et al., 2008).

Other seismic studies have focused attention on the diversity of signals associated with the related processes of water discharge and precipitation, as well as the structure of the channel (e.g., Govi et al., 1993; Hsu et al., 2011; Roth et al., 2014; 2016; 2017; Schmandt et al., 2013, 2017; Dietze et al., 2019; Bakker et al., 2020; Lagarde et al., 2021). These related processes and channel bed roughness influence the seismic recordings; thus these studies have tried to isolate the frequency content of the seismic signals associated with water flow and those due to bedload transport. Many of these studies have suggested different frequency bands associated with these processes, with turbulent water flow generating seismic energy at 2-20 Hz frequencies and bedload transport generating signals at somewhat higher (20-100 Hz) frequencies (e.g., Gimbert et al., 2014; Roth et al., 2016; Schmandt et al., 2017).

Theoretical models have also been developed to link seismic observations to bedload flux and water turbulence (Tsai et al., 2012; Gimbert et al., 2014), thus providing a framework to use the less costly and less hazardous out-of-channel seismic data collection to determine bedload discharge or flux. The theoretical models that link the seismic data to bedload transport include several assumptions appropriate for the high energy, bedrock rivers most commonly studied with these techniques. However, other river systems, such as those ephemeral streams common around the world, including in the southwestern U.S., can have very different geologic settings, with much finer grained sediment available for bedload in the channels and much more limited time periods of flow. Seismic instrumentation in these areas have also been lacking, so it is difficult to test the theoretical models for bedload transport in these regions. Here we report on a unique seismic experiment woven within a state-of-the-art sediment transport research station in a southwestern US ephemeral channel, providing some of the first seismic data collected during flash floods common in the summer monsoon season.

Study Site

The Arroyo de los Pinos sediment monitoring station, located at an ephemeral tributary of the Rio Grande River in central New Mexico, provides detailed sediment, hydrologic, and seismic data during flash floods resulting from southwestern US monsoon seasons (Figure 1). Limited seismic and sediment data exist from the site as early as 2017, and the full sediment monitoring station construction was completed in 2018 (see Stark et al., 2021 for overview of the site). The sediment data consists of bedload transport rates and suspended sediment measurements. Water depth and water velocity data are also routinely collected, in addition to grain size characterization and digital elevation data from drone flights following flood events.

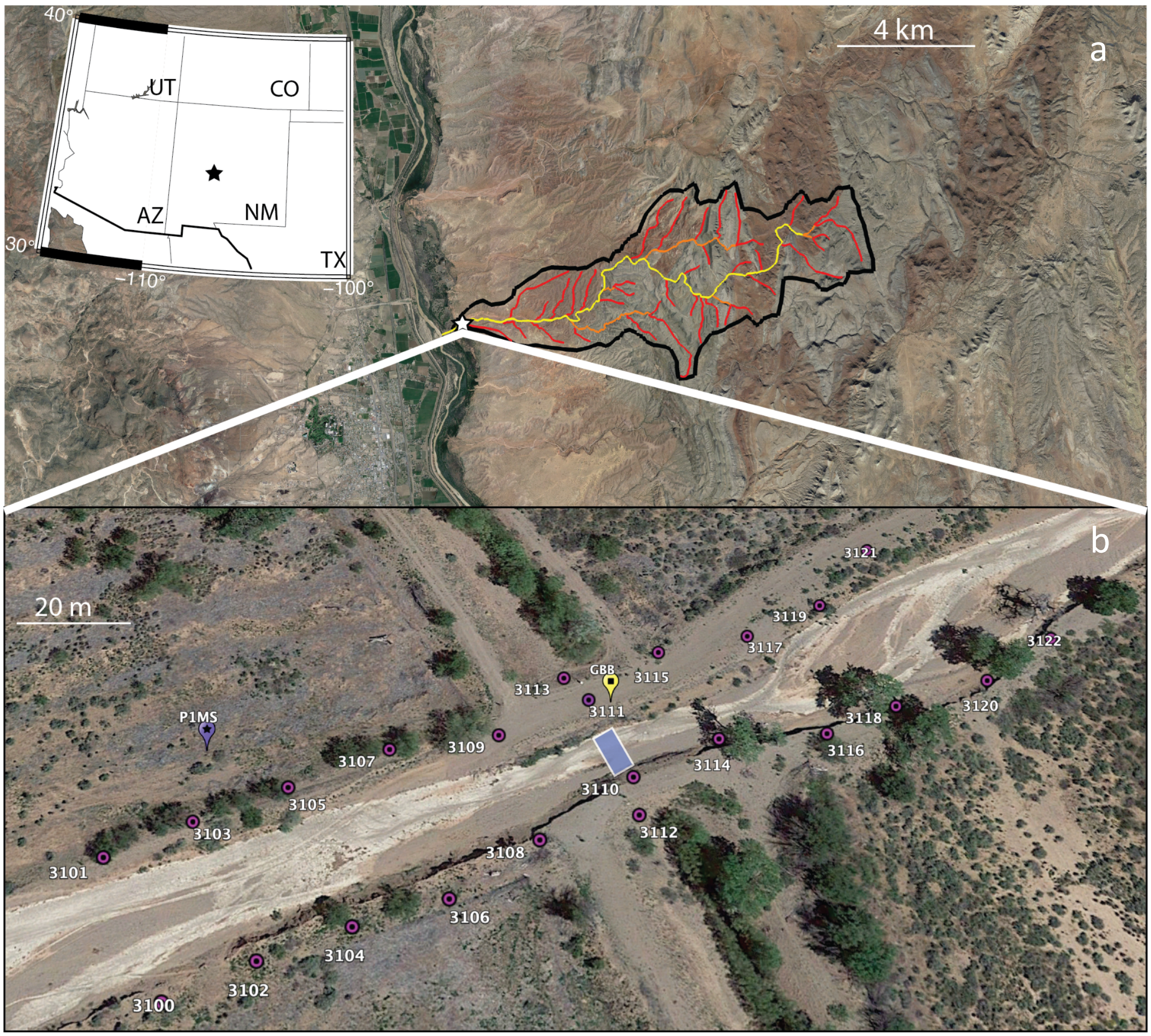

Figure 1. Location of the Arroyo de los Pinos research station in central New Mexico, USA. a) Outline of the ADLP watershed (black outline) with minor tributaries (red) and primary channel (yellow), located within central NM (inset). Star indicates location of outlet research station, shown in b. b) Location of the in-channel sediment monitoring research station (blue rectangle) and distribution of the seismic stations deployed during 2021 along the channel (purple circles, seismic nodes, P1MS and GBB are broadband stations).

Seismic Instrumentation and Data

The density of seismic instrumentation at the ADLP site has increased significantly since the first instrument was deployed in 2017 (Figure 1). The initial seismic station (GBB in Figure 1, moved to current location in 2018) is a broadband three-component Nanometrics Trillium Compact ground motion sensor paired with a Taurus datalogger that records at 1000 Hz during the summer monsoon period. The sensor is buried within the channel bank, ~17 m from the center of the channel. Beginning in 2019, we deployed an additional three component broadband seismic station (P1MS, Guralp CMG-3T sensor and RT130 data logger, recording at 500 Hz) located ~32 m from the channel center and further downstream from GBB. In addition to these broadband stations, we also deployed a variable number of seismic nodal stations at distances of 4 - 25 m from the channel center each summer between 2019 and 2022. These nodes are all-in-one seismic stations with a high frequency three-component ground motion sensor with onboard GPS timing, power, and data logger, also recorded at 1000 Hz. The full seismic experiment also includes three additional broadband stations and additional seismic nodes further upstream in the watershed. We will focus here on seismic data from the primary research site to compare with measured bedload flux from the Reid slot samplers.

Data Analysis

We retrieve the raw seismic data from the stations at each site and convert the raw recorded ground motion time series (counts) into ground velocity (m/s) using instrument response functions developed by the manufacturer and IRIS-PASSCAL. We then extract windows of ground motion data during time periods of flood events to examine the ground motion amplitudes and frequency content associated with the flow events (Figure 2).

The seismic time series are also converted to the frequency domain to examine the seismic power at different frequencies (up to the Nyquist frequency, or one half of the sampling rate) over the time period of the flood, typically displayed in spectrograms. Standard Fourier transform algorithms were used to convert into the frequency domain, computing the amplitude spectra using overlapping windows of 60 s duration with 50% overlap. We also compute seismic power spectral density (PSD) using the closest broadband seismic data (GBB, vertical component) and the cross spectral density function. Using these PSDs, we compute the median PSD power within selected frequency bands and compare the median power of that frequency with measured bedload flux at the research station to determine linear regression fit statistics for each frequency band comparison.

Comparisons between seismic power and measured bedload flux are time-limited because the Reid slot samplers typically fill within the initial rising limb portion of the flood, at least for larger flow events. In these cases, we determine another parameter, the average cross-sectional bed shear stress, to extend our comparisons with the seismic data over the full flow period. Bed shear stress is computed using

$$\tau = \rho R g S \tag{1}$$

where τ is the bed shear stress, ρ is the water density, R is the hydraulic radius, g is acceleration due to gravity, and S is the channel bed slope. Previous work at the Pinos has found that bedload transport has been correlated with bed shear stress (Stark et al., 2021).

Results

The seismic instruments successfully recorded signals associated with a flood wave moving downstream in the ADLP towards its outlet to the Rio Grande. Here we show one example of a moderate to small flow event (Figure 2). We observe larger ground motion amplitudes above the background noise during this flood time window (2021-08-23 09:00-13:00 UTC time, Figure 2a). The arrival of the flood event is also apparent in the spectrogram, with elevated seismic power in a broad range of frequencies (10-100 Hz), similar to previously published estimates, relative to times before and after the event.

Other processes can also generate seismic noise, such as distant earthquakes, rainfall, wind, and traffic. The frequency content of these signals needs to be characterized such that they can be removed from signals that are associated with the local flood and bedload transport processes (see McLaughlin et al., submitted for a review of noise characterization at ADLP).

To narrow down the frequency range most representative of bedload flux in the ADLP floods, we take advantage of the measured bedload flux at the research station, co-located with the seismic recordings. Using data from several years of flood events, we find that the seismic PSD in the 30-80 Hz frequency band has the highest correlation with the measured bedload flux. We use that frequency band in our results for the flow event (2021-08-23 09:00-13:00 UTC) in our example.

This event had low water depths (maximum of ~20 cm, Figure 2a) relative to other flow events captured at the ADLP, although the bedload flux measurements reached over 3 kg s^{-1} m^{-1} prior to the filling of the bedload samplers (Figure 3). The median seismic power ranged from a low of -150 dB within the first few minutes of flood arrival to over -135 dB near peak measured bedload flux. Within the time period of observations, we find a good quality (R^2=0.65) linear fit between measured bedload flux and recorded seismic power.

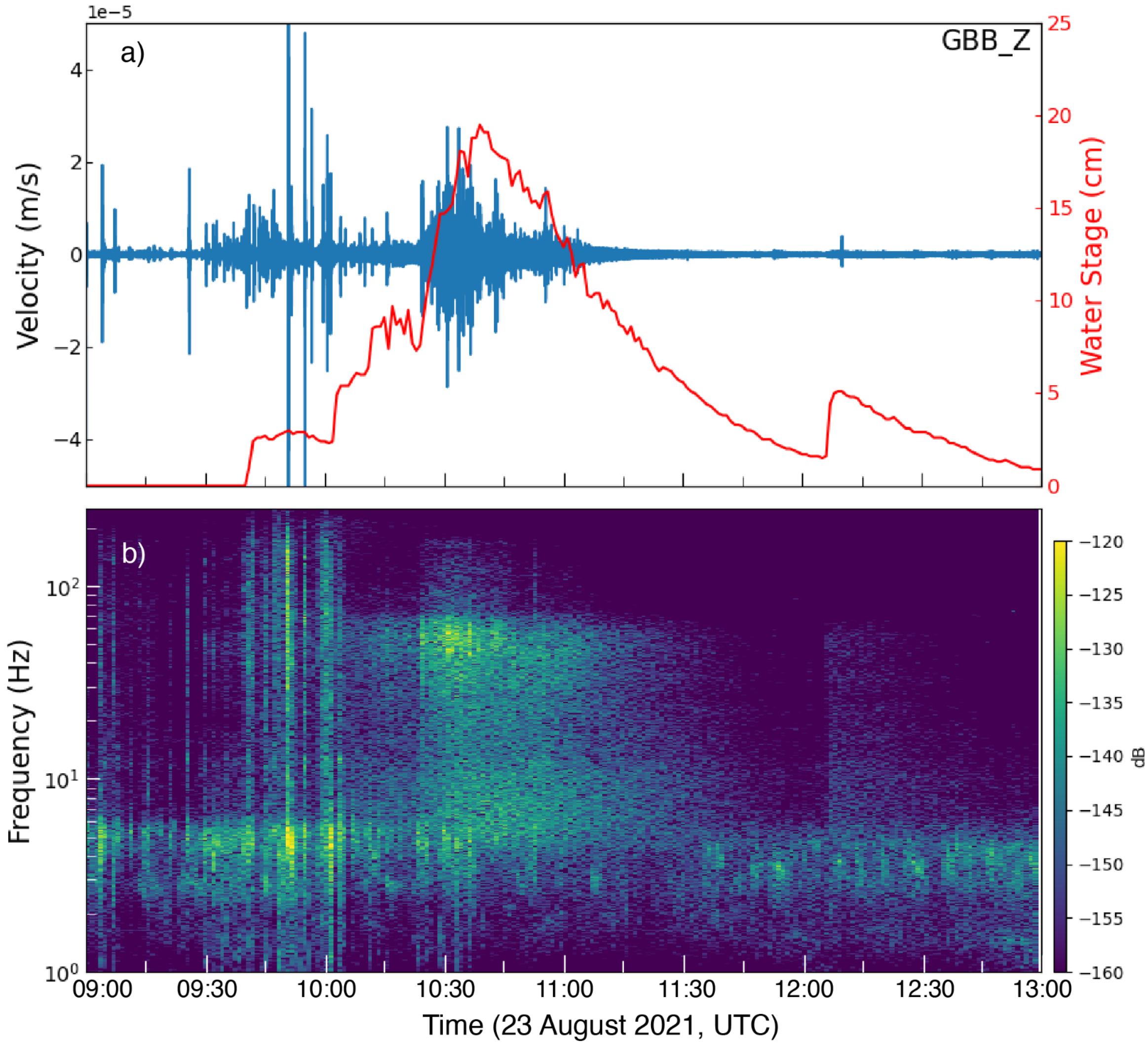

Figure 2. Example seismic and water stage data for a flow event on 2021-08-23 (09:00-13:00 UTC). Seismic data from broadband station GBB and water discharge at the research station. a) Ground velocity seismic data (blue, m/s) and water stage (red, cm) over duration of the flood event. Flow event appears in the seismic data as a longer duration, moderate amplitude seismic signal. Large spikes in the seismic data may due to discrete collapse of channel bank as no field crew was at the site at this time. b) Spectrogram of the seismogram (panel a), with color scale reflecting seismic amplitude spectral value in units of dB ($10\log_{10}$ (m^2/s^2)/Hz). Flood duration is apparent with larger seismic power over a large frequency range (~8-100 Hz), with peak power occurring at ~30-80 Hz during the time of the highest water stage.

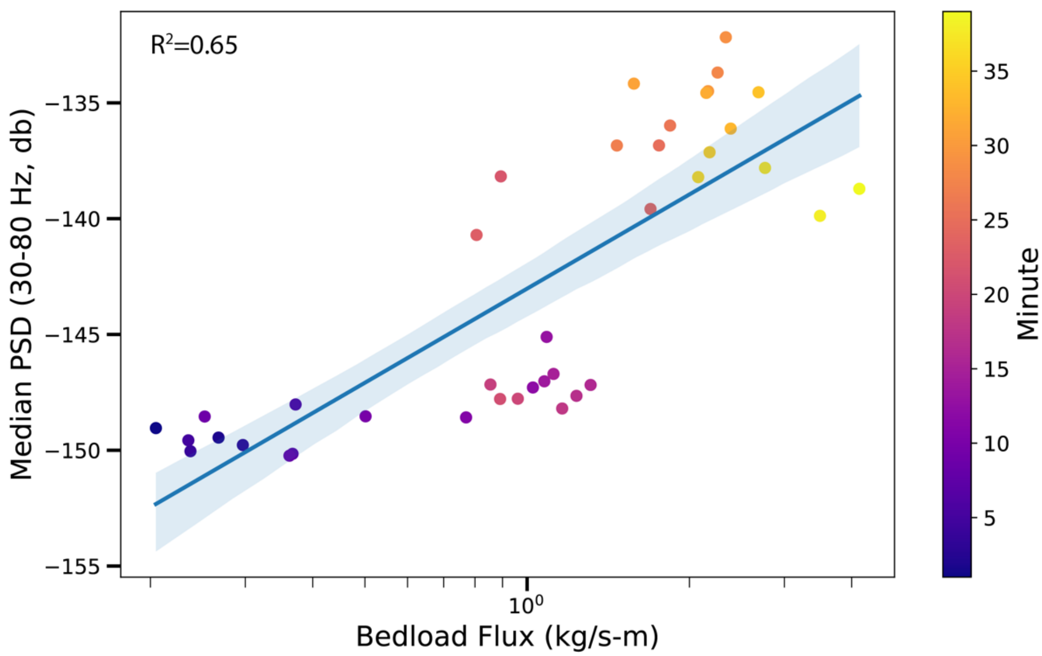

Figure 3. Median seismic PSD within the 30-80 Hz frequency band as a function of measured bedload flux during the 2021-08-23 09:00-13:00 UTC flood event, using data from station GBB. Circles are colored by minute following the start of bedload flux measurement; note this is only a small portion of the overall flood duration shown in Figure 2. Best fit regression line included (blue line) with 95% confidence interval (blue shading).

Bedload flux measurements ceased when the slot samplers filled after 39 minutes before the peak water depth at the site, so we also compare the median seismic power (30-80 Hz frequency band) with the computed bed shear stress for the entire flow period (Figure 4). Again, we find a roughly linear fit between the observed seismic power and the bed shear stress, although with a more complex pattern indicating hysteresis. In this case, we find higher power in the early, rising limb of the event, with lower seismic power observed later for the same shear stress levels. The R^2 value for a linear fit to the entire dataset (R^2=0.57) is reduced over that found for the comparison with bedload flux, however, we would obtain a better R^2 with shear stress if we limited the data to the peak and falling limb portion of the flood to remove the hysteresis effect.

Discussion

Our comparisons between observed seismic power and measured bedload flux for a representative, albeit small, ADLP flow event are a strong indication that seismic measurements can serve as a useful out-of-channel proxy for bedload transport. One of the valuable aspects of the ADLP is the collection of bedload flux during flow events through the Reid slot samplers; these co-located measurements provide a critical calibration for future predictive relationships using seismic observations. However, one issue is the premature filling of the samplers prior to the end of the flood. This is an important limitation, as the larger bed particles, which are likely to generate the most seismic energy (Tsai et al., 2012), may move later in the flood event, closer to peak water depth. These particles are likely to be omitted by the current sampling operations. Modifications to the sampler slots to allow for covering until later in the flood event will be implemented in upcoming field seasons.

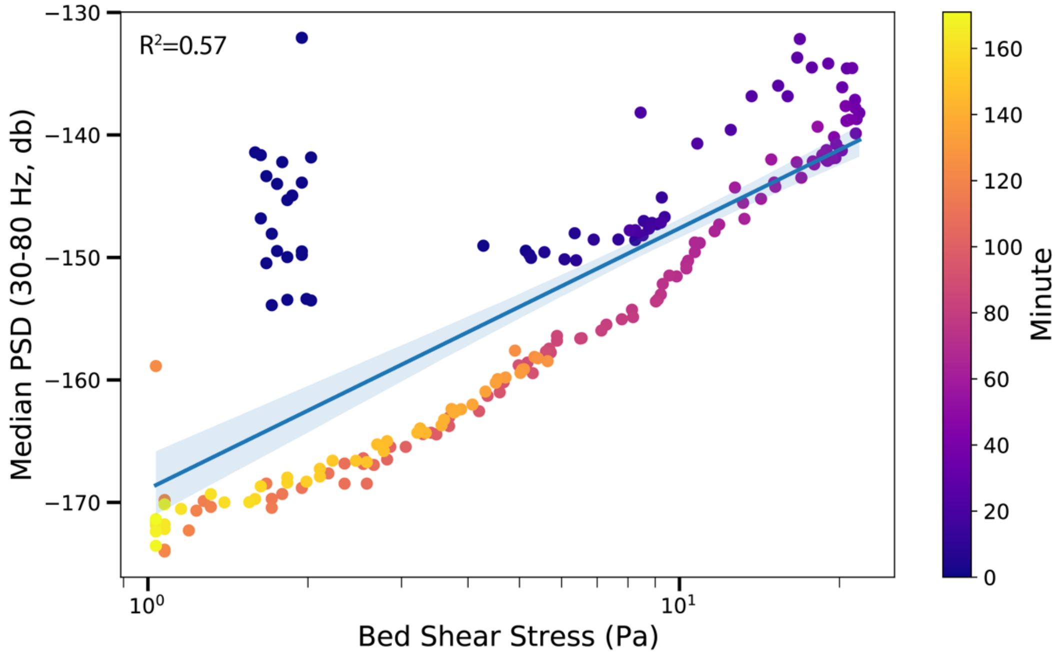

Figure 4. Median seismic PSD within the 30-80 Hz frequency band as a function of calculated bed shear stress during the 2021-08-23 09:00-13:00 UTC flood event using data from seismic station GBB. Circles are colored by minute following the start of water depth measurement. Best fit regression line included (blue line) with 95% confidence interval (blue shading).

Theoretical models have been developed to link seismic PSD observations to bedload flux and water turbulence (Tsai et al., 2012; Gimbert et al., 2014). These models have typically focused on perennial rivers with higher energy and larger grain sizes than the ADLP system. Application of these models requires geologic site characterization for the structure of the subsurface seismic velocity and attenuation. We have collected various active seismic source (hammer surveys and rock drop experiments) datasets in the ADLP to determine these important site-specific parameters. Initial analysis suggests that our site parameters sufficiently differ from those used in the existing theoretical models such that model assumptions may need to be adjusted for ADLP-like systems (Luong et al., submitted).

Although we present only one flood example here, the seismic instrumentation at the ADLP site has recorded over 25 floods since the initial installation. We observe linear trends between bedload and seismic power with this larger dataset as well, but the details (overall power for given flux, slopes of the trends for example) vary between flood events. It is possible that grain size distribution can explain these variations, and inclusion of grain size distribution into our analysis is an ongoing effort. Other future analyses include use of the spatial density of seismic instrumentation along the channel at this primary site, as well in upstream locations, to explore spatial variations in seismic power tied to channel geometry and geological settings.

Conclusions

A diverse set of sediment, hydrologic, and seismic data collected at the Arroyo de los Pinos sediment monitoring station in central New Mexico allows us to investigate the relationships between seismic signals generated from water flow and sediment transport during flash floods in the ephemeral tributary of the Rio Grande River. We demonstrate the seismic analysis for a representative 2021 flood event, finding a linear correlation (R^2=0.65) between median seismic power over the 30-80 Hz frequency range and measured bedload flux over the time period of rising limb sampling. Similar correlations exist between seismic power and bed shear stress, a bedload proxy that can be computed over the full flood time period. Hysteresis is apparent in this comparison, with higher seismic power observed earlier in the flood period for similar bed shear stress signals. These results suggest seismic observations are a useful proxy for bedload transport, and the unique co-located measurements at the ADLP provide an invaluable calibration for future predictive relationships.

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