Quantifying bedload transport in ephemeral channels using seismic methods

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Abstract

The transport of sediment is one of the fundamental geomorphic processes governing the evolution of landscapes. Reliable sediment flux forecasts are necessary for a variety of applications such as sedimentation engineering, river restoration, and flood risk mitigation. Quantifying bedload driven by flood events in ephemeral channels is notoriously difficult because of the scarcity, irregular nature, and high intensity of flash floods. Seismic methods appear to be a promising tool to characterize such fluvial processes, as they continuously record the ground motions caused by bedload and water movement while located outside of the active channel.

We evaluated the performance of the Tsai et al. (2012) physics-based model estimates of bedload flux by comparison to continuous monitoring of bedload flux. The Tsai model estimates the power spectral density (PSD) of the Rayleigh waves produced by vertically impulsive impacts from saltating particles based on the rate of impacts of fluvial sediment for a given bedload flux and grain size distribution. As a test of this model, we collected seismic data during flow events and compared the seismically-estimated bedload flux with high-precision bedload flux observations. These data derive from a multi-year campaign of monitoring an ephemeral, sand-and-gravel bed channel reach of the Arroyo de los Pinos, central New Mexico, USA. Based on seismic data analysis, we find bedload transport correlates to signals in the 30-80 Hz frequency range, whereas rainfall correlates to signals at all observed frequencies but especially at > 100 Hz. Inverting seismic data for bedload flux using the vertical impact model results in overestimates of the observed bedload flux by ~2 orders of magnitude. We explore three hypotheses to explain this mismatch. First, the process of rolling and/or sliding particles, as opposed to saltating particles, may be the predominant cause of model discrepancy. Rolling particles are perhaps a very significant contributor to bedload at this study site. Second, the fine-grained alluvial characteristics of this riverbed, as contrasted to a rigid bedrock substratum conceptualized in the model, lead to significant attenuation of seismic energy as a result of the inelastic impact of bedload particles. Third, the bedload impact frequency model may not fully characterize the rate and angle of impact of particles onto the riverbed in this environment. By thoroughly examining bedload transport mechanisms and considering alternative impulse functions for seismic noise generation, we intend to construct a modified physics-based model within the framework of the existing models to quantify bedload transport in the ephemeral environment.

Introduction

In arid and semi-arid regions worldwide, ephemeral channels are responsible for delivering water, sediment, and nutrients, as well as being the main contributor to the local watershed and local water cycle. Understanding the water movement in ephemeral channels is crucial not merely academically – to understand how these rivers erode landscapes in drylands – but also for water management. Furthermore, reliable sediment flux forecasts are required for a variety of applications, such as sedimentation engineering, river restoration, and flood risk mitigation (Wilcock, 2004; García, 2008; Totschinig et al., 2011). The fundamental processes by which sediment is entrained and carried by flowing water are referred to as sediment transport. Typically, sediment transport can be divided into two modes: suspended load and bedload. Suspended load pertains to sediment particles that move in suspension by the energy from flowing water and turbulence. Bedload represents the fraction of sediment particles that move along the streambed by rolling, sliding, or saltating. Several sediment transport models are proposed in the literature, but none can completely and effectively model the underlying physics of bedload transportation. Model development and parameterization is especially difficult in ephemeral rivers, where flow is periodic and, in the semi-arid Southwest, depends on rainfall during the monsoon season. So far, the knowledge on bedload transportation in ephemeral channels/rivers is limited and has been primarily developed based on sediment transport equations derived from perennial river and flume experiment data.

Various studies have been made to empirically estimate average bedload transport rate in different geomorphology conditions. Many have failed to provide general applicability to a wide range of river conditions. Several indirect methods (i.e., hydrophones, pipe and plate microphones, geophones) can monitor bedload transport (Bogen and Møen, 2003; Rickenmann et al., 2014; Roth et al., 2016). Recently, seismic approaches have been used to record the seismic noise generated by bedload transport and turbulent flow in several regions worldwide. With the data recorded from the Arroyo de los Pinos sediment station, we intend to validate several physics-based models available in the literature, specifically two models that rely on seismic signals generated by bedload (Tsai et al. 2012) and by turbulence (Gimbert et al. 2014).

Environmental seismology has been widely adopted to quantify many surface processes, such as fluvial processes, ocean tides, ice vibrations, and landslides (e.g., Larose et al., 2015). According to recent studies (e.g., Burtin et al., 2016; Chao et al., 2014; Bakker et al., 2019; Lagarde et al., 2021; Nasr et al., 2021), seismic and acoustic approaches for monitoring fluvial processes have been deployed across many regions to study sediment transport, river geomorphology, and landscape evolution Seismic noise induced by bedload transport, turbulent flow, and other ambient processes such as wind and rain can be characterized at distinctive frequencies (e.g., Burtin et al., 2008; Tsai et al., 2012; Gimbert et al., 2014). As such, a physical model aimed at relating bedload flux to seismic noise should be an effective means to quantify bedload transport as well as other fluvial characteristics.

Study site

The Arroyo de los Pinos watershed has a drainage area of 32 km^2. The channel is a direct tributary of the Rio Grande. Sediment transport data have been collected at the station since

2018. The geologic setting varies throughout the basin, with confined channel morphology in the Permian and Pennsylvanian lithologies of the upstream portion of the watershed and an anastomosing morphology as it crosses the Pliocene and Pleistocene ancestral Rio Grande floodplain and alluvial fan deposits in the lower watershed (Stark et al., 2021). In addition to a monitoring station at the basin's outlet, the watershed is also equipped with an extensive network of rain gauges and pressure transducers to record rainfall and runoff throughout the channel network. Some construction and improvements have been added each year from the initial monitoring in 2016.

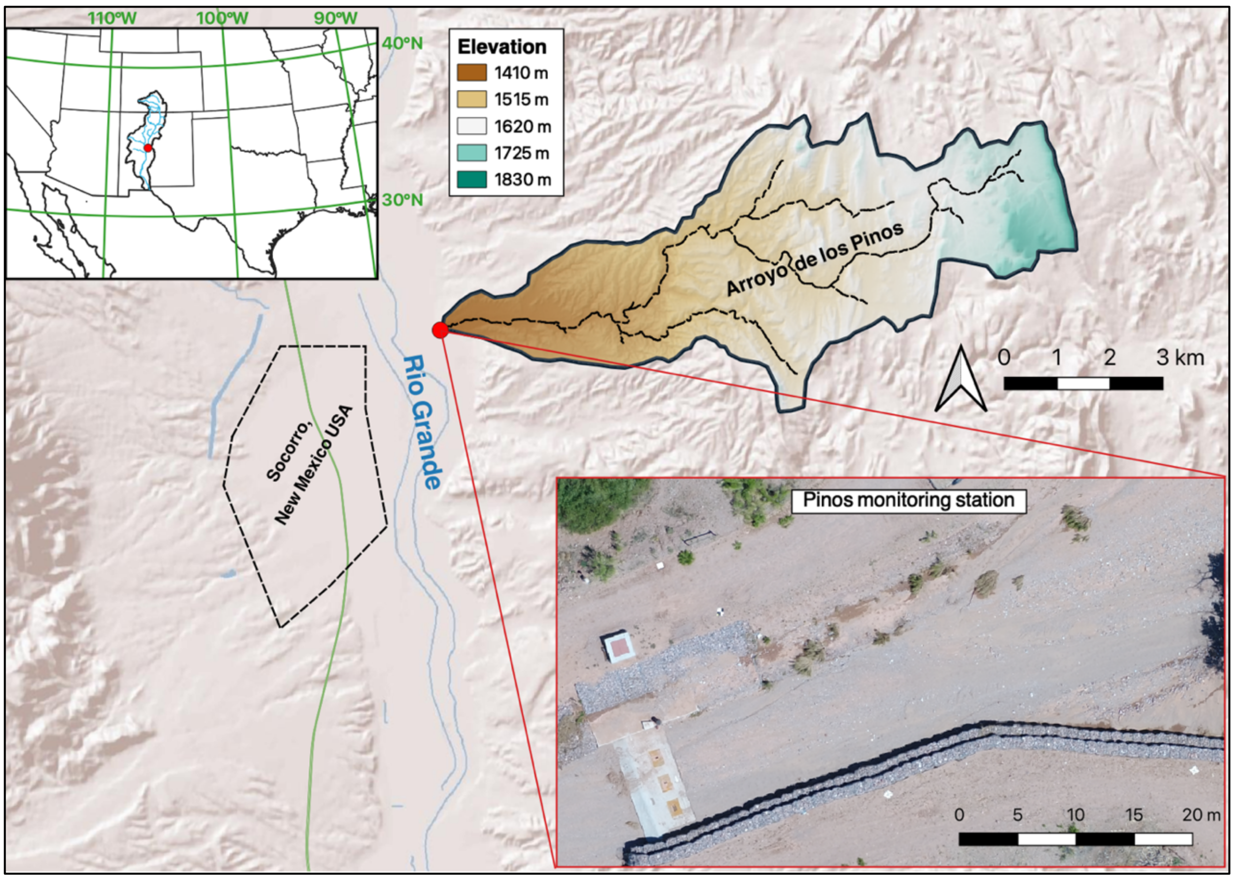

Figure 1. Study site location and monitoring station at the Arroyo de los Pinos (Stark et al., 2021)

The Arroyo de los Pinos research station is one of the few stations where sediment and water flow are monitored using such a broad variety of instruments. We deployed three Reid-type slot samplers for direct bedload monitoring in 2018, in conjunction with pipe microphones embedded in the channel that record sediment impacts upstream of the samplers and pressure transducers that record water depth. One broadband seismic station was installed in 2017 on the channel bank, and additional seismic instrumentation was installed during 2019-2022 (Bilek et al., 2023). We deployed two hydrophones to record the acoustic signals within the water column in 2020. This combination of direct and surrogate methods will help us advance the understanding of sediment transportation, river morphology, and dynamics.

Methodology

Physics-based model

A physical model for seismic noise generation by bedload transport (Tsai et al. 2012) was implemented to estimate bedload flux during a flash flood in the Arroyo de Los Pinos. Equation 1 below illustrates the seismic power spectral density (PSD) function as it varies due to elastic or seismic parameters (f, v_c, v_u), bedload parameters ($q_{bD}, \rho_s, \overline{w}_s, H_b, U_b$), channel parameters ($W$), and the attenuation of seismic waves ($\chi(\beta)$).

$$P_v(f;D) = \frac{C_1 W q_{bD} \overline{w}_s}{V_p U_b H_b} \cdot \frac{\pi^2 f^3 m^2 w_i{}^2}{\rho_s{}^2 v_c v_u} \cdot \chi(\beta) \qquad \text{Eq. 1}$$

The model assumes that individual particles that impact vertically on the river-bed generate an impulse that travels as seismic energy through the subsurface to nearby seismic stations. In the bedload model, W is the average channel-bed width, $\overline{w}_s$ is depth-averaged particle settling velocity, V_p is the particle volume, U_b is vertically averaged streamwise particle velocity, H_b is the bedload layer height, C_1 is a constant factor ~0.66 (Tsai et al., 2012), and q_{bD} is the volumetric sediment flux per unit channel width for particles of grain size D transported as bedload. In the seismic model, f is the frequency of the seismic wave, m is the particle mass, w_i is the vertical particle speed, and ρ_s is the particle density. Empirical equations are used to estimate bedload and channel parameters. Group and phase velocity (v_c, v_u) of the seismic waves are obtained from rock drop experiments.

The total PSD is computed by integrating the equation over a grain size distribution *D*:

$$P_v^T(f) = \int_D P_v(f;D)\, dD \qquad \text{Eq. 2}$$

Incorporating the attenuation of seismic waves ($\chi(\beta)$) into equation 1 and integrating equation 2 on a grain size distribution *D*, the sediment flux can then be inverted once the PSD is estimated from the seismic signals recorded by seismometers near the river.

Inversion scheme

We follow the inversion scheme from Lagarde et al. (2021) to invert bedload fluxes from seismic data. The following equations are used to obtain the inverted bedload fluxes.

$$PSD_{computed} = PSD^* \times q_{bD} \qquad \text{Eq. 3}$$

$$PSD^* = \frac{C_1 W \overline{w}_s}{V_p U_b H_b} \cdot \frac{\pi^2 f^3 m^2 w_i{}^2}{\rho_s{}^2 v_c v_u} \cdot \chi(\beta) \qquad \text{Eq. 4}$$

The PSD^* is calculated based on equation 1 without considering the bedload flux term (q_{bD}). If the model accurately quantifies the sediment transport physics, then the observed seismic power spectral density is approximately equal to the computed seismic power spectral density. Therefore, bedload flux can be calculated by the ratio between the observed seismic power spectral density and PSD^* as follows:

$$q_{bD} = \frac{PSD_{observed}}{PSD^*} \qquad \text{Eq. 5}$$

Results

During several years of Arroyo de los Pinos research station operation, we collected data from flash floods including water depth, bedload flux, bedload grain size distribution, rainfall, and seismic signals. For simplification, we only present here a representative flood, which occurred on July 05, 2021 (Figure 2). Vertical component ground velocity seismic data were used for the PSD calculation, assuming dominant seismic energy associated with Rayleigh waves. The ground motion time series were converted to the frequency domain by computing Fourier transforms in one-minute windows to obtain the power spectrum. The hydrograph for this flood is typical of arid and semiarid environments, in which the rising limb is sharp and quickly reaches the peak, whereas the recession has a longer tail, although still short in comparison with hydrographs in perennial settings. The lower panel depicts the spectrogram associated with this flood. A spectrogram describes the temporal variation of seismic energy distributed within different frequency ranges, in this example during the course of this flood. The flood event is the most prominent feature on the spectrogram in comparison to other non-active periods that occurred before and after the flood. Local rainfall occurred before and during the rising limb of this flood, which we interpret as the increased power at the broad range of frequencies, up to ~200 Hz.

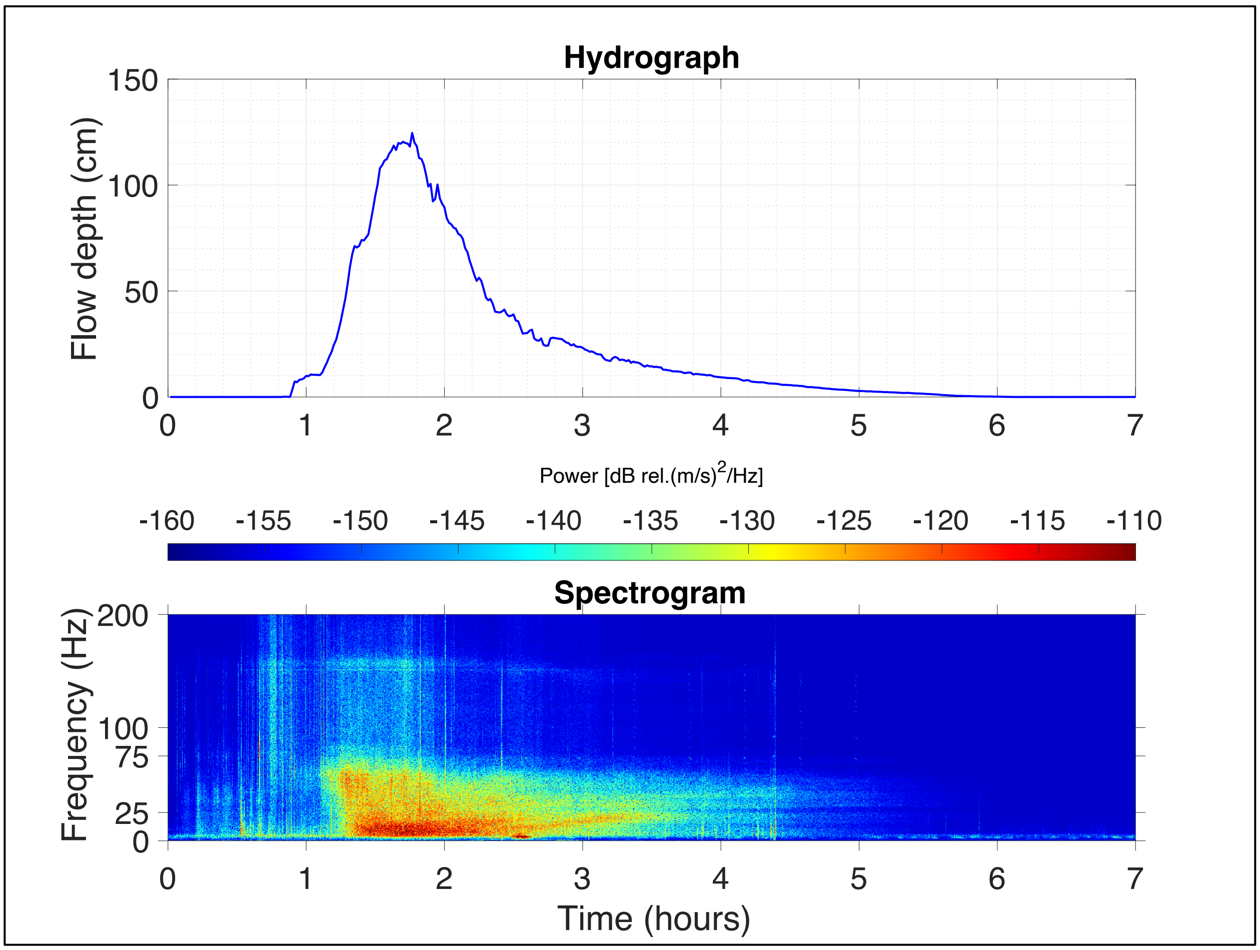

Figure 2. Hydrograph (top) and spectrogram (bottom) of the 2021-07-05 flood.

Other concurrent fluvial and meteorological processes occur simultaneously during flow events, such as a hydraulic jump that resulted from an abrupt increase in channel slope, turbulence, rainfall, or complicated interaction between flood and vegetation. By performing a wide range of regression analyses, we found that bedload transport is well explained by signals in the 30-80 Hz frequency range, whereas rainfall generates signals across all observed frequencies and especially at > 100 Hz (McLaughlin et al., 2023). Seismic signals in the 1-10 Hz range are likely due to anthropogenic noise, for example from the interstate highway or railroad across the valley from the monitoring station (McLaughlin et al., 2023).

The PSD of the model strongly depends on the grain size diameter; PSD is approximately proportional to D^3 (Tsai et al. 2012; Farin et al. 2019). Therefore, constraining the grain size distribution (GSD) is essential to obtain an accurate inversion of bedload flux. To determine the GSD of this flood, we fitted a log-raised cosine distribution to the bedload-material grain size data from >10 samples collected during this flood. The cumulative distribution function (cdf) is matched with field grain sizes, and the probability density function (pdf) is derived from the cdf (Figure 3). We prioritized matching the cdf with the largest grain sizes, because it is anticipated that particles of larger grain size disproportionately generate seismic energy. The median grain size of bed material (not necessarily bedload in transport) at the station is approximately 5 mm. Approximately 30% of the sediment is sand sized (< 2 mm), while the remaining 60% and 10% are respectively gravel (2-64 mm) and cobbles (64-256 mm). Using the grain size distributions mentioned above, we inverted to the bedload fluxes for the 2021-07-05 flood. Figure 4 shows the inverted bedload fluxes from observed seismic power.

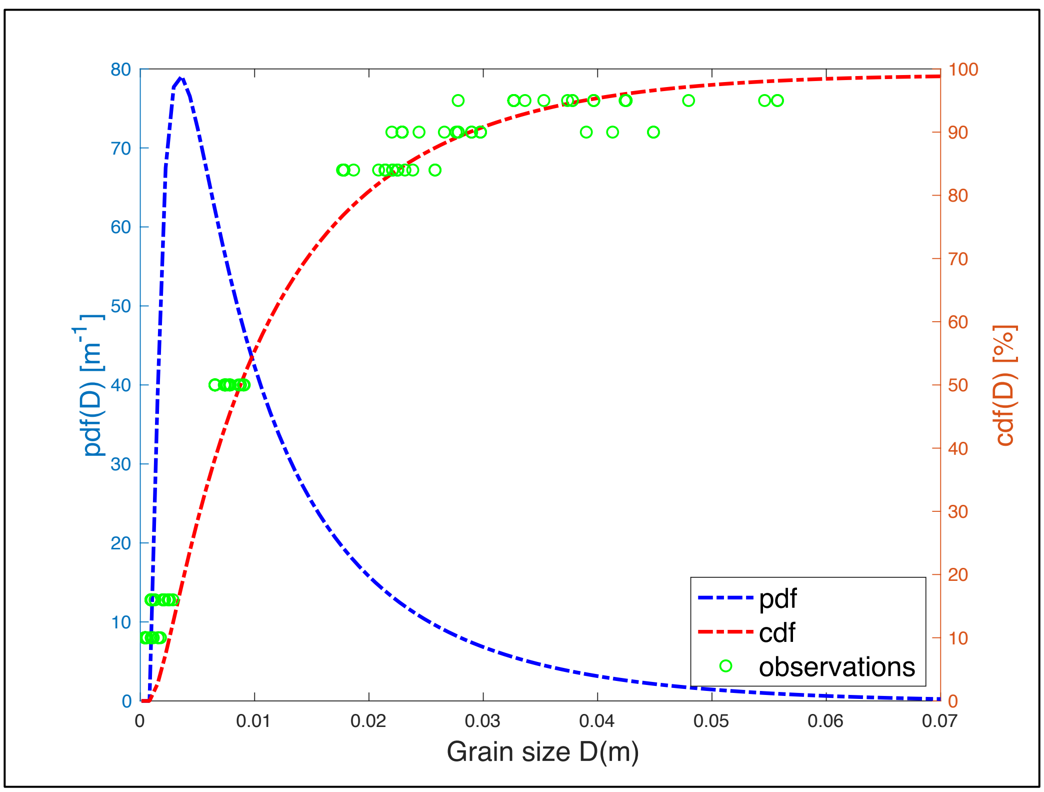

Figure 3. Grain size distribution for bedload in transport during the 2021-07-05 flood.

On the rising limb, seismic power rises as water depth reaches a peak of ~ 1 m, then decreases during the recession. There is an anomalous peak of seismic power at a flow depth of 1.1 m that is likely caused by a passing train or bank collapse (Figure 5). We also observed hysteresis over many floods in 2021 (Figure 7). The hysteresis patterns in the bedload flux versus flow depth suggests the viability of the seismic method for quantifying sediment transport as shown elsewhere (Burtin et al., 2008) independently of stage and flow conditions, despite the fact that the model significantly overestimates our bedload fluxes.

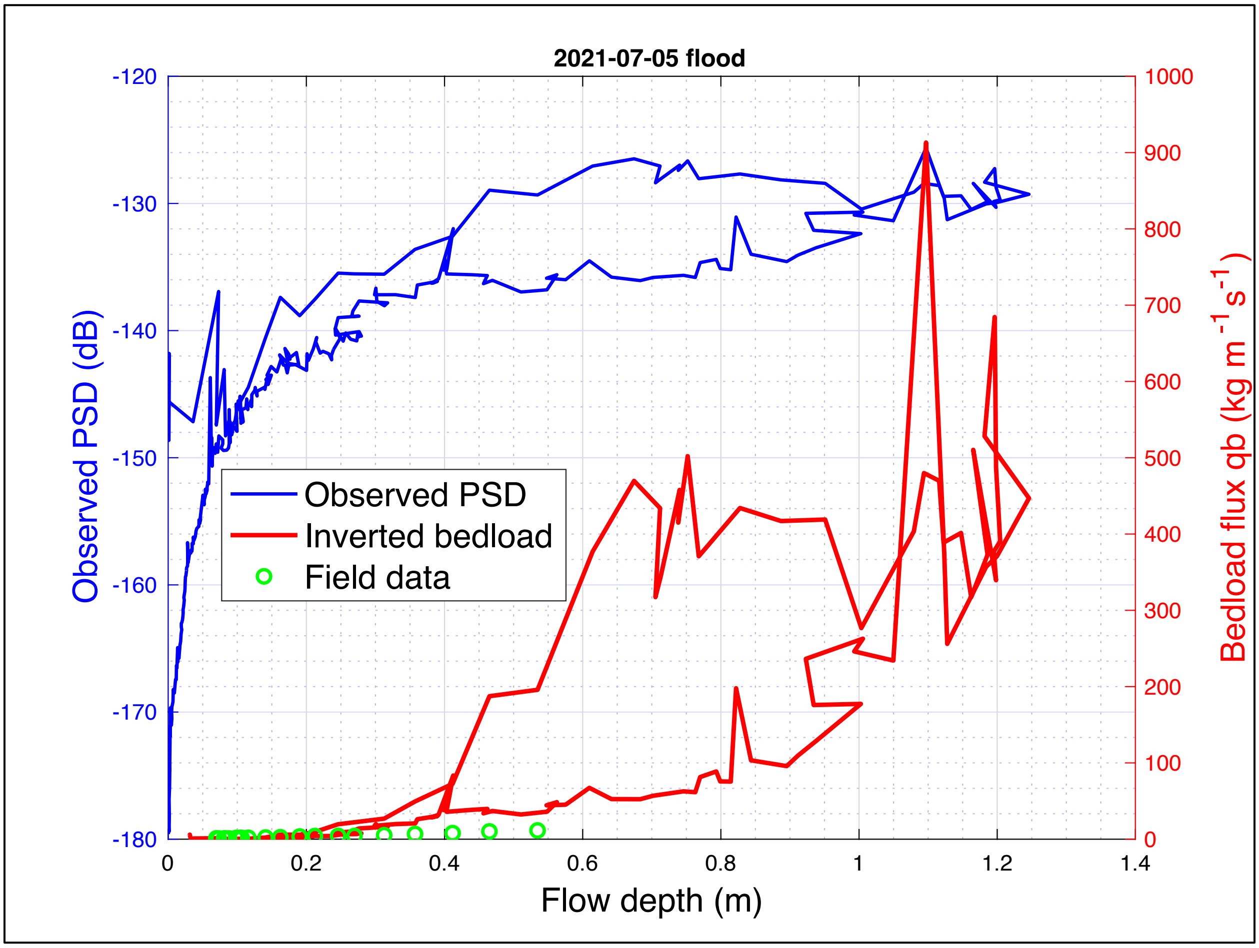

Figure 4. Inverted bedload flux from observed seismic power.

At our monitoring station bedload particles are physically captured by samplers, and the maximum capacity of the samplers is filled during an intensive or prolonged flood. Due to the capacity limitations of the pit traps, bedload measurements are only captured during the early portions of a flood. We were unable to compare the prediction across the entire bedload transportation profile. However, it is evident that predictions are significantly greater than observed values (Figure 5).

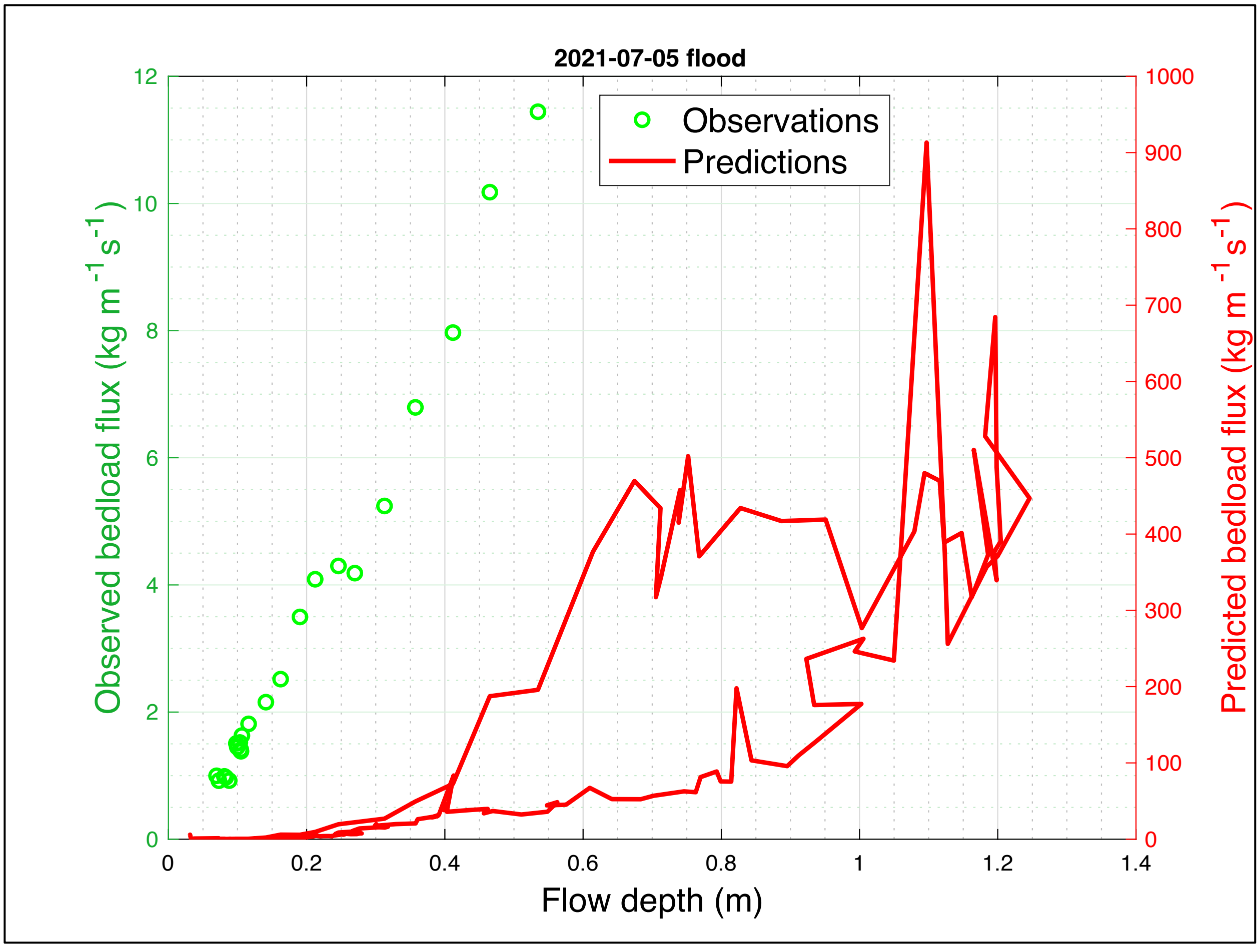

Figure 5. Comparison between bedload predictions and observations. Note the differing y-axis scales.

Comprehensive results for all floods in 2021

We have compiled a comprehensive comparison of all floods measured in the 2021 monsoon season (Figures 6 and 7). On July 06, we did not collect bedload measurements due to the samplers being full of sediment from the July 05 flood. For small events (flow depth less than 10 cm), we captured nearly complete time series of bedload flux for the events, whereas for moderate and large flows (depth > 20 cm), we obtained bedload data from the first 10 – 25 min of the events. For all floods in 2021, inverted bedload fluxes fluctuated depending on flow conditions at ~100-1000 kg/m/s (Figure 7), much higher than the field measurements (Figure 6, red lines).

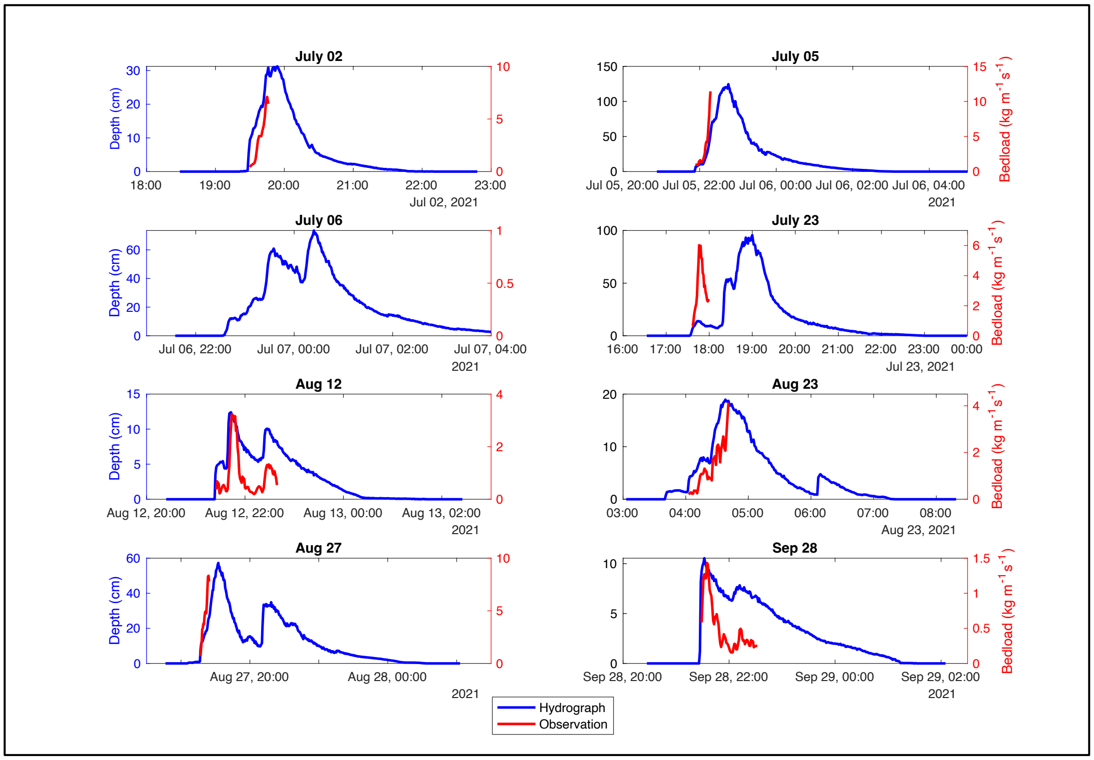

Figure 6. Hydrographs and observed bedload flux for all floods in 2021.

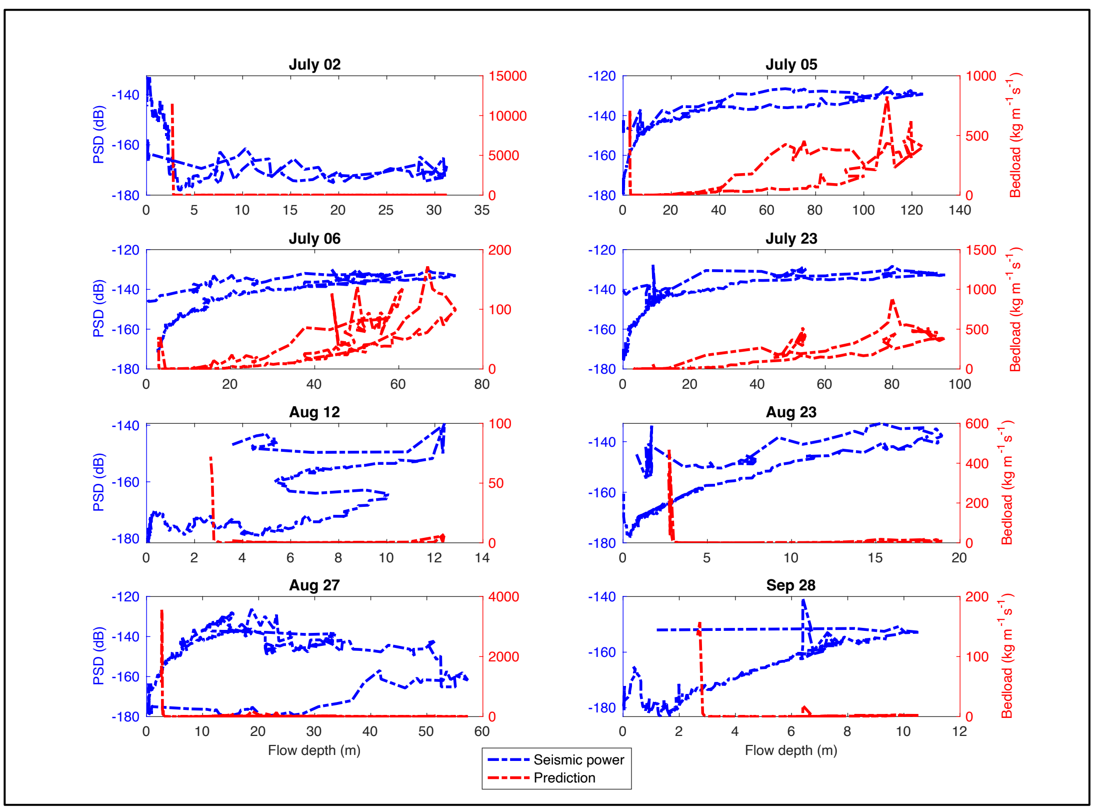

Figure 7. Inverted bedload flux based on the seismic PSDs for all floods in 2021.

Discussion and conclusions

The model is sensitive to elastic parameters: rock density, phase, and group velocities of Rayleigh waves. To quantify these parameters, we performed a series of active source experiments by dropping rocks of varying sizes onto the ground at well-defined distances along the riverbed. We found that group and phase velocities in alluvial environments are much lower than those in bedrock settings (Tsai et al., 2012), which is consistent with results from Bakker et al. (2020). We also ran sensitivity analyses for various combinations of model parameters and validated our implementation with some results from Tsai et al. (2012). Theoretical research suggests that sediment transport and other fluvial processes such as turbulence generate seismic energy in distinct frequency bands, although there may be some overlap. Even though we assumed that the 30-80 Hz frequency band is dominated by bedload impacts, there are some uncertainties associated with the dominant seismic frequency ranges that captures effects of turbulence (Schmandt et al., 2013; Gimbert et al., 2014) and rainfall (Roth et al. 2016).

The predicted bedload fluxes are approximately two orders of magnitude larger than our field measurements. This suggests that the model does not fully capture the physics of bedload transport under these grain size and flow conditions. We hypothesize that there are several potential reasons for the discrepancy between model prediction and observed data. The riverbed is composed of thick alluvial sediments, in contrast to the bedrock channel conceptualized in the original model development. Hence, seismic energy is lost and quickly dissipated due to the inelastic impact of sediment on the fine-grained substratum (Tullos et al., 1969). However, this is only expected to alter the modeled impulse energy by a factor of one-half, since elastic rebound acts to double the calculated impulse from a falling particle. Additionally, the model ignores rolling and sliding particles, which, based on observations by researchers standing in the channel during moderate flows, might be a common form of bedload transport at our station. Additionally, the bedload impact frequency model may not accurately represent the impact of particles on the riverbed. The assumption of vertical impacts onto the riverbed is reasonable for a starting point to derive the first-order relationship between bedload movements and seismic noise generation. However, in reality, the impacts of particles are more complicated due to the interaction of different grains (Lajeunesse et al. 2010; Farin et al., 2019), as well as the non-vertical impact (impact angle), bed roughness, and irregular shape (Gimbert et al. 2019).

We observed that seismic signals attenuated very quickly in fluvial sediments, especially those at higher frequencies. This observation is consistent with theory and prior studies that seismic attenuation increases with frequency (Quan & Harris, 1997; Tsai et al., 2012; Bakker et al., 2019). The relatively fine-grained sediment in this river reach, relative to the coarse bedload at the mountainous streams on which most prior fluvial seismology studies have focused, is therefore expected to produce signals that attenuate more rapidly. Relevantly, we have placed our seismometers closer to the channel bank (1-4 m) than most previous studies. Although this should not affect the theoretical basis of the Tsai method, it may influence empirical comparisons to other prior studies.

In conclusion, results from the inversion compared to our field data demonstrate significant overestimation using Tsai et al.'s (2012) model. Therefore, relevant bedload transport mechanisms should be examined together with seismic noise generation to improve the model and better quantify bedload transport in alluvial settings.

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