***Flow and Sediment Transport Monitoring using Seismic and Infrasound Signals***

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## Introduction

Most people associate seismic waves with geologic processes like earthquakes and volcanic eruptions, and many have even felt the ground motion associated with these geologic events. Few, however, are aware that subtle ground vibrations, measureable with seismometers, occur as a result of common Earth surface processes such as ocean waves, water discharge, and sediment movement in rivers. As a result, application of shallow, subsurface geophysical instruments offers unique opportunities to measure fluvial processes in a safe, non-invasive and continuous manner. A streamside technique for monitoring flow and sediment transport is especially useful during high discharges when flow depth and turbulence are too great to safely work in rivers.

Over the past decade researchers have seismically monitored bedload transport in gravel bed rivers and documented seasonal variations in signals using seismic observations of discharge and sediment transport rates. Additionally, measurements of a controlled experimental flood in the Grand Canyon identified bedload transport through an observed increase in seismic energy on the rising limb compared to the falling limb of flow. Here, we deployed seismometers and infrasound sensors on two small rivers (drainage area 29-183 $km^2$) in Colorado to test the applicability of quantifying flow and sediment transport using ground vibrations or river ‘noise’. Very limited seismo-acoustic research has been conducted on smaller rivers. Discharge on the South Fork is only 1-17 $m^3/s$, which is more than two orders of magnitude lower than those observed during the Grand Canyon controlled flood.

*Study Sites*

Geophysical instruments were deployed along the South Fork Cache la Poudre and Upper Colorado Rivers (Figure 1) in 2015, and along the Upper Colorado River only in 2016. Flow and sediment transport data on the South Fork, collected in collaboration with Sandra Ryan of the USFS Rocky Mountain Research Station to assess post-High Park Fire burn effects provides the basis for comparison of river flux and ground vibrations over the 2015 snowmelt hydrograph, during a short-duration, high-intensity rain storm, and in response to a small dam release. The Colorado River in Rocky Mountain National Park (RMNP; Figure 1) has ongoing discharge, suspended and bedload data related to research on channel response and restoration following a 2003 debris flow.

## Methods

Three, three-channel seismographs and two, three-element infrasound arrays were installed in late May 2015 along the South Fork Cache la Poudre River (Figure 2). In addition, two three-channel seismographs were deployed along the Upper Colorado River in RMNP in early June 2015. At both locations, seismometers were deployed in shallow holes close to the water table approximately 1 m from the high-water bank. This is possibly the first sediment transport and monitoring study to place seismometers within the floodplain directly adjacent to a fluvial system. Proximity to Ft. Collins and river access via a footbridge enabled flow and sediment transport to be monitored multiple times per week spanning snowmelt along the South Fork. In contrast, access to the Upper Colorado River site was more limited in early season because of high, unwadable discharges. As a result, Upper Colorado flow and sediment transport measurements were collected after peak discharge in 2015 when flows were sufficiently low to cross the river.

In 2016, four, three-channel seismographs were installed in the late spring on the Upper Colorado River in RMNP. Discharge and sediment transport data were collected over the snowmelt hydrograph and into the fall.

**Results and Interpretation**

We present results of correlations between seismic power and discharge collected on the South Fork in 2015 only because i) discharge and suspended sediment are strongly correlated, ii) bedload transport was measured non-continuously so is not conducive to time series analysis, and iii) flow and sediment transport data from the Upper Colorado River in 2015 span the receding limb, which generates lower ground vibrations, and 2016 data are still being collected.

Analysis of seismographic data from the South Fork (Figure 3) shows strong river signals across the instrumental response band (~2 to 100 Hz). Seismic energy at peak runoff on the South Fork site is over 100 times that observed during low flow conditions. Spectra show strong peaks that vary with stream flow and with seismic component (e.g., systematic differences occur between vertical and horizontal components of motion). This suggests different underlying mechanisms for the excitation of compressional and shear/surface wave components of the seismic wavefield.

High frequency H/V ratios (Figure 4) remain constant over varying discharge and are likely generated by a resonance frequency within the low velocity finer-grained floodplain sediments adjacent to the seismometer. In contrast, the low frequency ratios change by several orders of magnitude, which may indicate sensor tilt in response to elevated discharge. A logarithmic transfer function was generated between discharge and low frequency, horizontal component seismic energy. This enabled discharge rates to be estimated solely from seismic energy, with an accuracy of $< 0.3\ m^3/s$ (Figure 5).

**Conclusions**

Seismometers are able to measure the shaking or river noise created during snowmelt runoff, a short-duration rain storm and a small dam release during 2015 on the South Fork Poudre River. Low frequency (~0.1-1 Hz) vibrations on predominantly the horizontal components are associated with increases in discharge. This is likely due to higher discharges tilting the seismometer either through resonance of the stream channel or direct coupling of the sensor with the water table. High frequency (~10-20 Hz) vibrations probably correlate with bedload transport, as has been observed in other fluvial systems. Additional data collection and analysis on the Upper Colorado River in 2016 will further test the relationship between seismic noise and discharge. Future research on both rivers would benefit from continuous collection of bedload transport to more fully interpret the sediment transport component of the seismic energy.

**Presentations and Educational Opportunities**

One oral and one poster presentation were given at professional meetings as a result of this research. Plans for a manuscript are ongoing, and will include analysis of Colorado River data from 2015 and 2016.

Seven undergraduates, two MS students, and two PhD students from Geosciences, and one graduate student from ESS were involved in the field work phase and data collection in 2015 (Figure 6). A summer session of NR220 Natural Resources Ecology and Measurements with 50 students visited the South Fork site, as did the WR417 Watershed Measurements class during fall 2015. During 2016, two undergraduates, two MS students, and two PhD students from Geosciences were involved in equipment installation and data collection in 2016. Additionally, in fall 2016, the WR417 class will take a field trip to the South Fork site.

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Figure 1. Location of seismographs and infrasound equipment on the Upper Colorado River (UCR) and the South Fork Cache la Poudre River (SF). River flow is to the south on the Upper Colorado River and to the north on the South Fork. Images from GoogleEarth.

Figure 2. Image of the South Fork Cache la Poudre River showing locations of three seismographs in 2015. Flow is from left to right, and discharge was gaged on the foot bridge shown. Photograph by Rick Aster.

Figure 3. Acceleration spectrograms for the three components of SF01 (location shown in Figure 1) with discharge plotted as black line. Low frequency signals are strongly excited on the horizontal components during high discharge (lower portions of panel), likely due to the seismometer tilting, outlined in black ovals.

Figure 4. A) Acceleration H/V spectrogram for SF01 in A) with discharge shown in black line. B) High Frequency velocity H/V ratios versus discharge over time.

Figure 5. Discharge over summer 2015 from continuous measurement using a pressure transducer (black line) compared to synthetic discharge (red line) calculated from integrated velocity seismic noise power between 0.3-10 s and smoothed with a 1-hour moving average.

Figure 6. A) South Fork Cache la Poudre River with Geoscience students installing a compound seismographic -infrasound station with instrument box and solar panel. Photo by David Dust; B) Seismometer installation along the South Fork near the right bank. Photo by Rob Anthony; C) Students loaded with equipment ready for the hike into the Upper Colorado River to install equipment. Photo by Rick Aster; D) Seismometer installation at the Colorado River field site. Photo by Rick Aster; E) Students loaded with equipment after the May 2016 Colorado River installation with instrument boxes in background. Photo by Christina Anthony.