Poster #16

Advances and New Challenges in Investigating Seismic Site Response

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Behind the Curtain: Developing Methods and Toolkits Supporting Practical Assessment of the Nisqually River Within Mount Rainier National Park

I. Introduction & Motivation

Impacts from a changing climate are affecting the hydrology and geomorphology of rivers around the world. Upland watersheds are proving especially prone to impacts. Mountainous rivers are experiencing significant shifts in precipitation patterns and the storage of snow and ice in source areas, resulting in stark changes to hydrologic variability, sediment transport, and fluvial morphodynamics (Huss et al, 2017; Immerzeel et al, 2020). Difficulties resulting from the already energetic nature of these rivers are accelerated by climate change impacts, causing mountain rivers to become even less predictable with time.

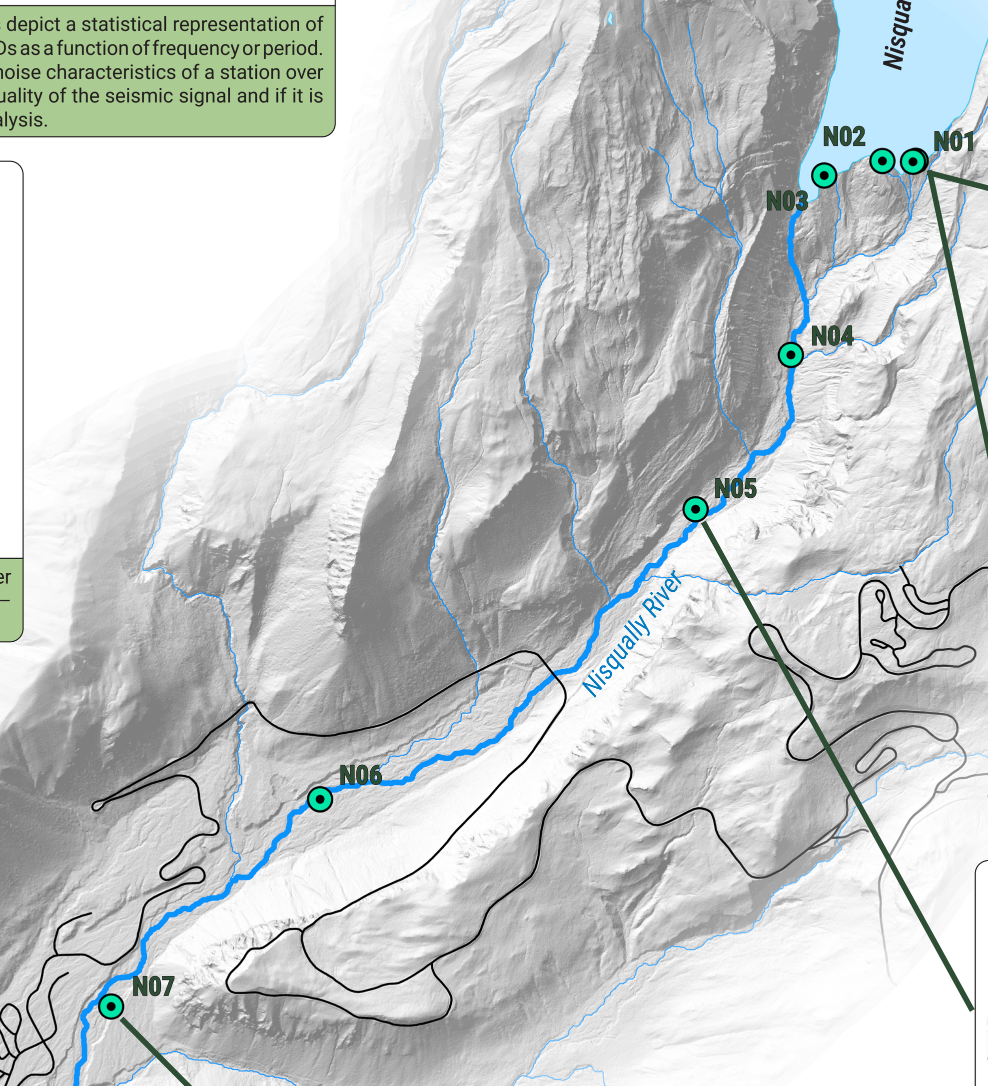
Most standard hydrology monitoring methods are based on rivers with a slope of <0.001 m/m, and the advancement of knowledge relevant to steeper rivers with more energy has followed slowly in response (Jarrett, 1990; Wohl, 2010). As a result, resource managers and hydrologists working with rivers in mountainous settings already typically lack the ability to accurately describe these rivers. With risk to equipment and personnel worsening over time due to increased river variability, practitioners often opt to simply move monitoring to distant downstream gaging sites and forfeit direct observations. To begin adequately dealing with steep mountainous rivers and protect assets at risk in these settings, improvements to current methods are required.

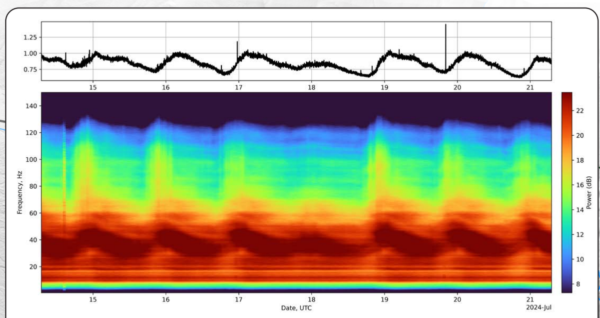
Significant advancements have been made in the field of environmental seismology for the measurement of discharge and bedload sediment transport, a complex but uniquely descriptive, low-risk, and low-impact emerging method for mountain hydrologists (Tsai et al., 2012; Gimbert et al., 2014; Dietze, 2018; Bakker et al., 2020). Such methods show potential to significantly improve the ability of professionals to monitor steep mountain rivers, and do so within constraints held by conservation agencies.

II. Goals & Objectives

We seek to create a GitHub repository which:

1. Relies strictly on open-source code libraries, and is itself open-source (R, Python, GitHub).
2. Contains a full suite of processing elements:
   a. Data processing and visualization.
   b. Discharge/bedload models.
   c. Active-source testing of seismic data.
3. Fits the widest possible range of environments.
4. Capable of being modular to combine different models, calibrations, and visualizations as needed.





Spectra N16: Spectrogram and RSAM of node N16, our most downstream node within the National Park boundary.

III. Background & Setting

Mount Rainier and other units within the National Park Service contain especially dramatic upland watersheds with tightly coupled fluvial-hillslope processes. With widely distributed low-resilience infrastructure (Beason et al., 2011), significant increases to precipitation intensities (Abbe et al., 2008), and glacial recession rates greater than 0.1 m/day (Allstadt et al., 2015), the Nisqually River within Mount Rainier National Park (MORA) exemplifies a nexus of modern land management issues driven by climate stressors of the US Pacific Northwest. The site provides an opportunity to observe mountain hydrology in a relatively pristine watershed primarily controlled by natural processes rather than human influences, yet also in a context of risk management for low-resilience infrastructure to maintain public access.

IV. Seismic Screening & Visualization

With 7.27 Tb of seismic data and complementary infrasound data over 3 years, and across 16 different field locations, the experiment requires substantial data management. Tools to inspect, screen, and visualize data are necessary to studying specific site characteristics. Using ObsPy, we screen the data at each site and on dates of interest for viable and representative data through a variety of tools, including:

- Real-Time Seismic Amplitude Measurement (RSAM) plots.
- Spectrograms.
- Probabilistic Power Spectral Density (PPSD) plots (Figure 1).
- Temporal Power Spectral Density (PSD) plots (Figure 2).
- Calibration testing (Figures 3 & 4):
  - Raw waveforms
  - Spectrograms

These tools allow for preliminary observation, providing us with insight into the general geomorphic and weather patterns of the watershed. This also means comparing across sites is practical.

With more melt from higher temperatures in the afternoon and less melt in the cooler hours, we can see evidence of diurnal variation in the spectral signatures at every site. These signatures also tell us about the local weather patterns, such as precipitation periods, which tends to wash out more explicit bedload and discharge signals (Spectra N01b & N09). We also see evidence of the river's dependence on solar incidence, observing less seismic power and thus lower flow when there is more cloud cover, even when temperatures are consistent.

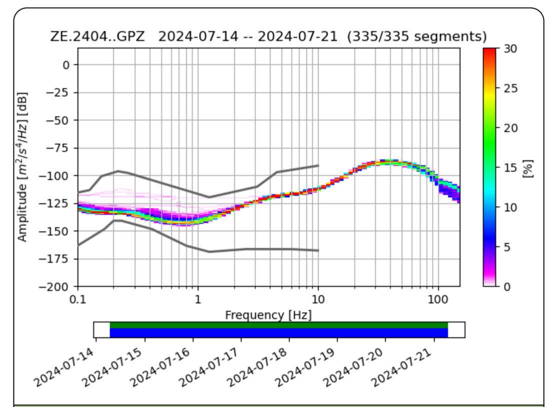


Figure 1: PPSD plots depict a statistical representation of the distribution of PSDs as a function of frequency or period. Useful in evaluating noise characteristics of a station over time to assess the quality of the seismic signal and if it is useful for further analysis.

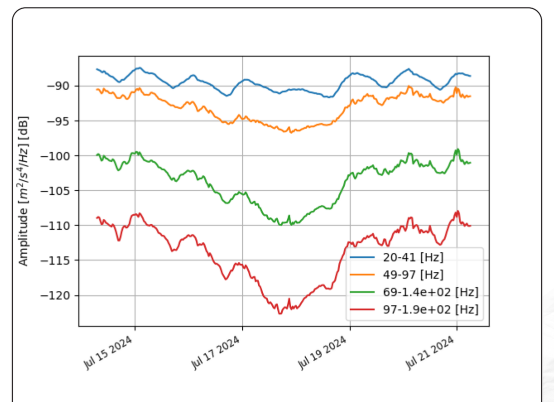
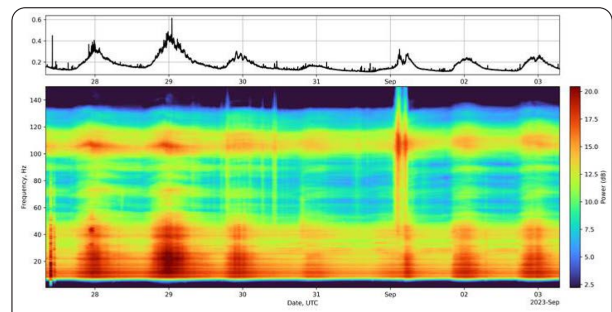
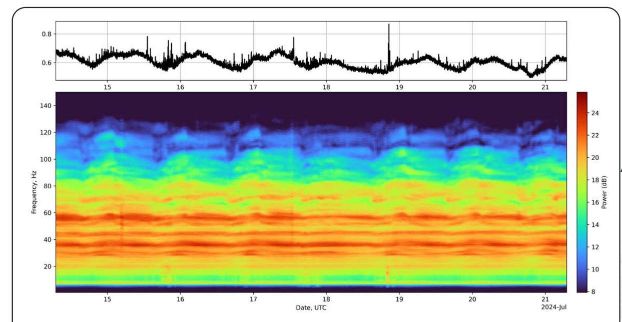


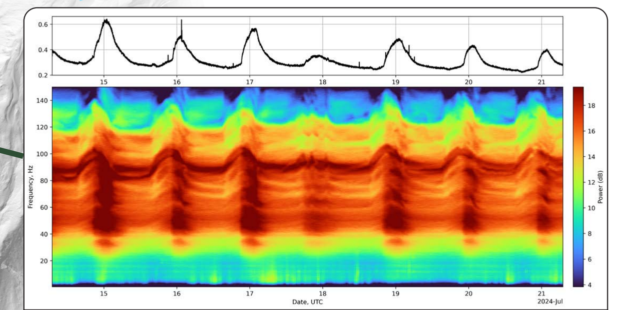
Figure 2: Temporal PSD plots depict the PSD signal over time at specific frequency bands of interest. Note the 20–41 Hz range here is the river-dominant signal.



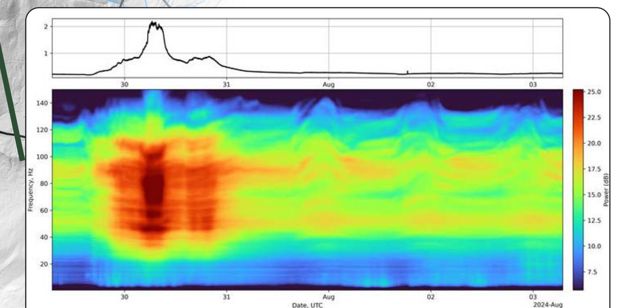
Spectra N09: Spectrogram and RSAM of node N09. The stronger signal early September 1, 2023, indicates precipitation. Also note the low frequency band ~(5, 40) Hz due to Qs and the higher frequency band ~(100, 120) Hz due to discharge.



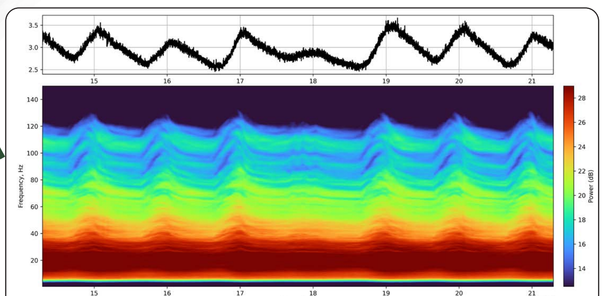
Spectra N13: Spectrogram and RSAM of node N13.



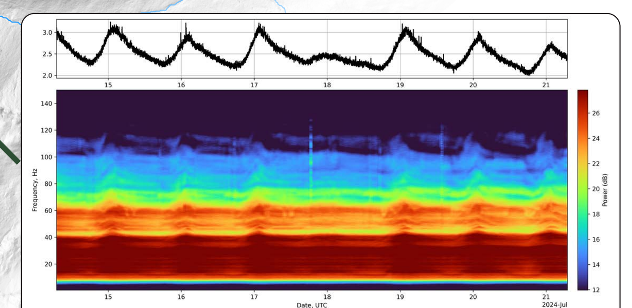
Spectra N01a: Spectrogram and RSAM of glacier node N01 during a period of consistent weather.



Spectra N01b: Spectrogram and RSAM of node N01. The Q and Q_s signals are washed out during a heavy precipitation event between August 30–31, 2024.



Spectra N05: Spectrogram and RSAM of node N05, just upstream of the Nisqually Glacier Bridge. The distinctive low frequency band represents the signal due to bedload and the more faint high frequency band points towards a signal due to discharge.



Spectra N07: Spectrogram and RSAM of node N07.

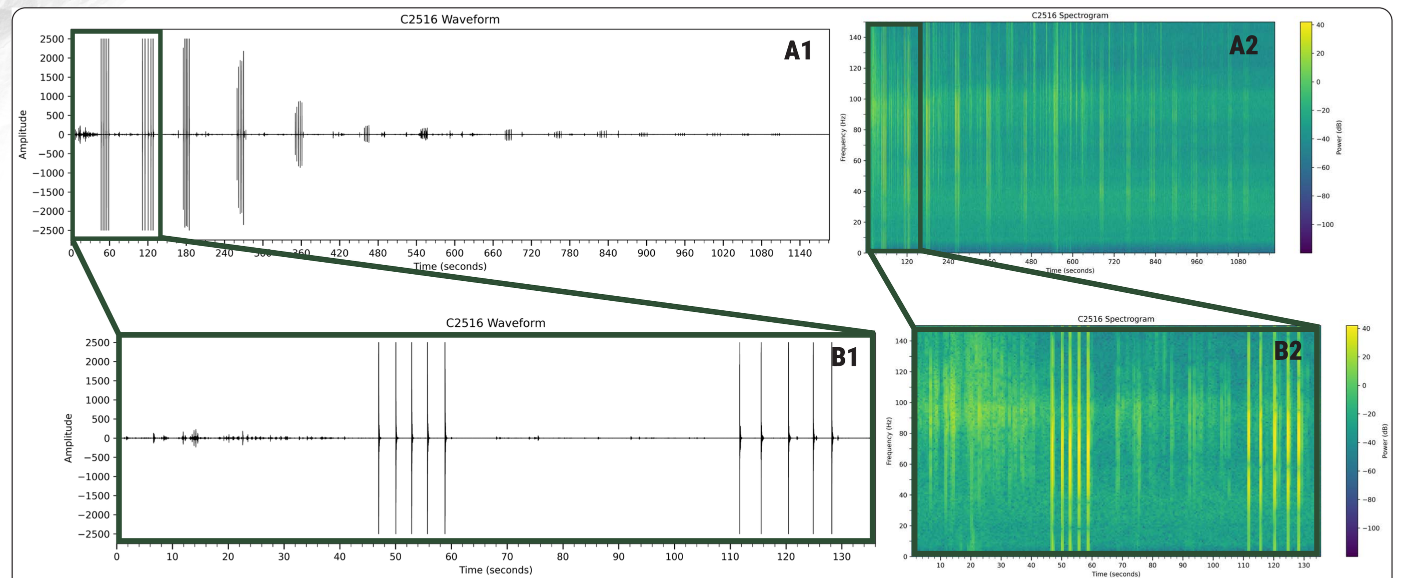


Figure 3: Raw waveform showing data from the full active-source test as observed by the calibration node C2516, 30 m from the primary node N16. **A1:** A set of five 5.4 kg sledgehammer impacts were performed in 2 m increments from the calibration node along a transect. The signals' attenuation to distance is very evident. **A2:** Spectrogram of the data in Figure 3-A1. **B1:** The first two sets of impacts at 2 and 4 m from the calibration node C2516 (28 and 26 m from the primary node N16). **B2:** Spectrogram of the two sets of impact data in Figure 3-B1.

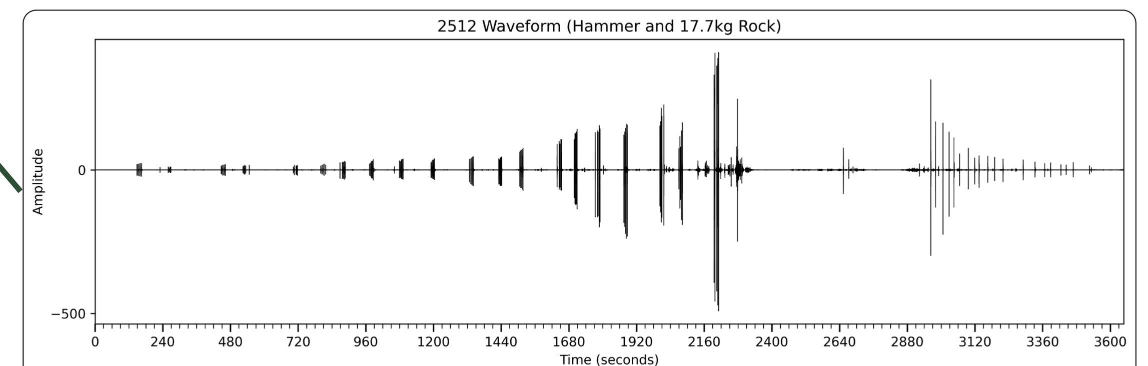


Figure 4: Active-source testing at site 12 with a 48 m calibration transect from the primary node N12. The waveform between (0, 2350) seconds is from performing sets of 5 sledgehammer impacts every 2 m along the transect, while lower amplitude data collected after is from 17.7 kg rock impacts dropped along the same 2 m increments.

V. Active-Source Testing

To best constrain the models to our data in such a complex setting, we performed active-source testing to constrain Green's function parameters. At each site, we set up a second node a known distance away from our existing node and performed a series of drop-tests to generate known impacts. We used a 5.44 kg sledgehammer on a steel plate in 2 m increments (Figure 5). In four cases, we also used an 11.6 kg and a 17.7 kg rock. By measuring the impact arrival times to the sensors, we can calibrate for site-specific ground properties that further quantify models, including:

- Rayleigh wave velocities.
- Ground quality factors.
- Green's displacement amplitude coefficients.

Figure 5: Taylor Kenyon performing the active-source sledgehammer tests at N08.

VI. Discharge & Bedload Analysis

The primary objective of this study is to quantify river discharge (Q) and bedload flux (Q_s) using continuous seismic and infrasound monitoring.

Seismic sensors show potential as non-contact equipment for river monitoring, allowing us to capture both the turbulence associated with water flow and the impacts from moving sediment. Together these signals allow us to explore how variations in water flow and sediment transport are expressed in the spectral content of the measured signals.

To relate sensor signals to Q and Q_s, we employ the *eseis* R toolkit (Dietze, 2018), which includes forward modeling functions: *model_bedload.R* predicting energy contributions from moving sediment, and *model_turbulence.R* simulating the contribution of water flow to the seismic signal (Figure 6). Using these models with defined site parameters generates a reference catalogue of synthetic spectra, which is then compared to observed spectra. The inversion routine *fmi_inversion.R* then fits the reference spectra to the measured signals, determining the flux combinations that most accurately represent the discharge and bedload contributions. Previous studies suggest it is important to invert estimates for both discharge and bedload together, as they iteratively inform each other to improve accuracy (Lagarde et al., 2021).

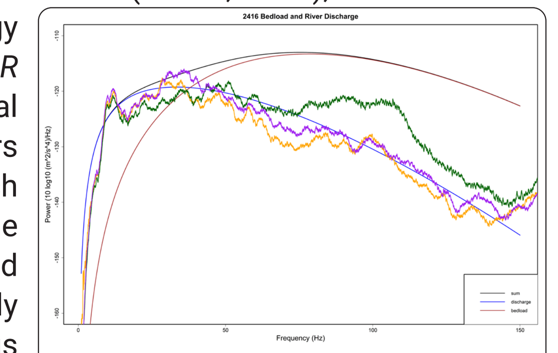


Figure 6: Node N16 PSDs computed at different times of day compared to rough model predictions for Q, Qs. The orange curve is the PSD at local time 0500, purple is 2000, and green is 1400. The models will be constrained by site-specific characteristics.

Very little data relevant to the steep rivers of Mount Rainier are available for fluvial seismology studies, so the Mount Rainier Geology team decided to collect our own. Sites were chosen to capture changing river characteristics as we move uphill from the Park boundary, noting differences in width, depth, slope, and grain size. Additional care was taken to select sites where discharge and bedload signals are more regular, reducing error and easing analysis. These sites are expected to reflect more favorable source-to-sensor geometry and local river conditions for improved model constraints (Spectra N05 & N09).

VII. Next Steps

The repository is built to eventually include additional coded methods supporting streamflow analysis. Methods constraining mountain rivers in seismic models may include:

- Sodium Dilution Gauging (NaCl).
- Large-Scale-Particle-Image-Velocimetry (LSPIV).
- Granular data of river geometry from remote sensing.
- Bedload tracer studies.

Using continuous, non-contact monitoring paired with active-source testing, we bridge the gap between field observations and model predictions—delivering the first quantitative measurements of discharge and bedload in Mount Rainier's rivers in 127 years. These studies are driven by conservation philosophies of the National Park Service, wherein we seek to understand and protect our rivers to the greatest extent possible, for this and future generations.

GitHub

Acknowledgements

Science takes a team, and the Mount Rainier Imminent Threats Program has been fortunate to have what feels like one of the best in recent years.

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