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Acoustics as a tool for detecting and inferring streamflow

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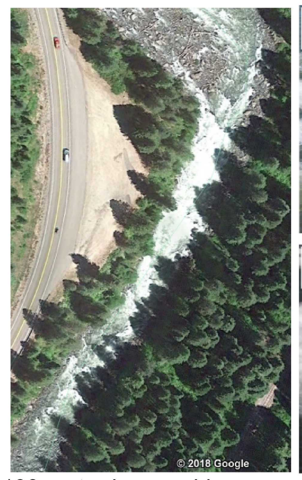
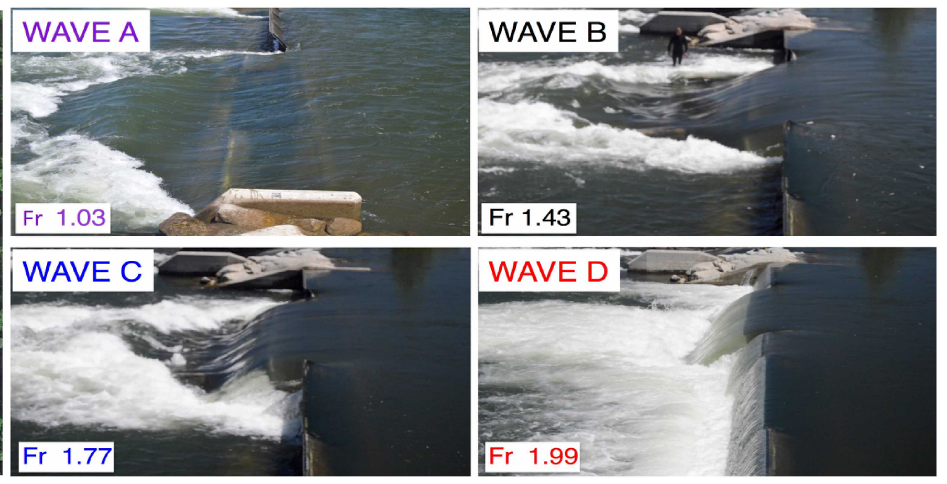
Field Sites

Chaos Rapid, N. Fork Payette, Idaho, USA



100-meter-long rapid consisting of many small drops. Flow is dam-regulated.

Boise Whitewater Park, Boise River, Idaho, USA



Discrete 1.5-meter drop whose geometry can be adjusted to change the wave's Froude number. Flow is dam-regulated.

Big Falls, S. Fork Payette, Idaho, USA

Series of 3 small waterfalls with a combined 12-meter drop. River is free-flowing, so discharge is controlled by seasonal snow-melt.

Diversion Dam, Boise River, Idaho, USA

Run-of-the-river dam; incoming flow is regulated by Lucky Peak Dam and partitioned among an irrigation canal, power plant, and spillway (20-meter drop over the top of the dam). Only the spillway generates sound.

Lucky Peak Dam, Boise River, Idaho, USA

Impounds Lucky Peak Reservoir; regulates flow downstream for flood control and irrigation. Outgoing flow is partitioned between a power plant and the spillway (pictured). Only the spillway generates infrasound; spillway head varies from 23-69 meters according to reservoir level.

Cascada San Rafael, Rio Coca, Sucumbios, Ecuador

Natural waterfall 150-meter waterfall. Flow is affected mainly by rainfall pulses and is often low due to upstream diversion. No gage.

Why use fluvial acoustics in planetary science?

Easy method of measuring streamflow remotely

Major high-gradient streams are significant sources of low-frequency sound and infrasound, which can propagate long distances without attenuation. Recording at a safe distance avoids potential flooding hazards to sensors, interference with stream processes, and the difficulty of installing in a flowing stream. Acoustic arrays can monitor multiple features simultaneously.

Integrates hydrologic information over catchment

Because streams are fed by large catchment areas, stream monitoring enables efficient monitoring of precipitation and melt-off over large spatial extents.

Significant noise source for other studies

Turbulent streams produce continuous noise that varies over time. This noise can can affect other studies by masking acoustic signals of interest (e.g., seisms or bolides), or can serve as signals in atmospheric studies.

Characteristics of stream turbulence sounds

Small river rapids appear to have broad spectra

Greatest spectral density in near-infrasound/low-audible bands (fig. 1, 3), but audible sound and ultrasound can still be significant.

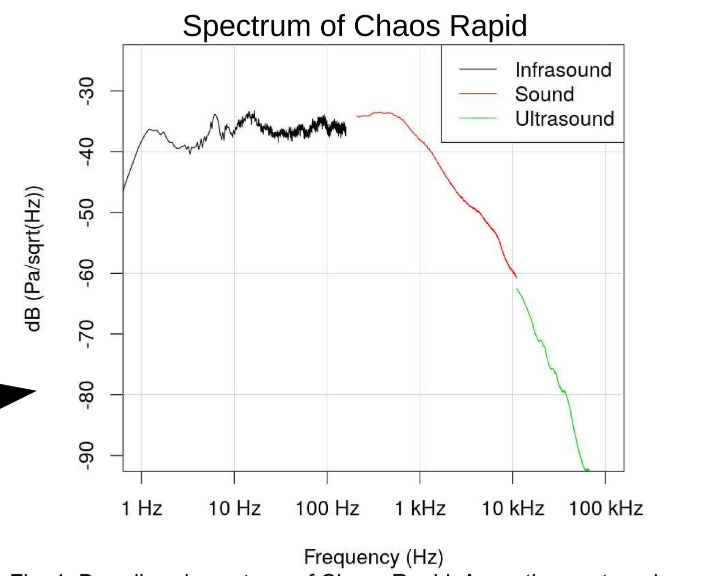


Fig. 1: Broadband spectrum of Chaos Rapid. Acoustic spectrum is approximately flat in the infrasound and low-frequency audible range and drops at higher frequencies, but significant high-frequency audible and ultrasonic energy is still present.

River sounds reflects the time scales of catchment processes

Snow-dominated watersheds see loudness cycles of weeks, rain-dominated watersheds see loudness cycles of hours or days, and regulated river loudness can change abruptly. Shorter loudness cycles may also emerge from surface water processes like seiches. In these sites, discharge tends to affect sound amplitude strongly and frequency content weakly (Fig. 2, 5, 6; Schmandt et al., 2013). People and wildlife near rivers must adapt to loudness changes at many scales.

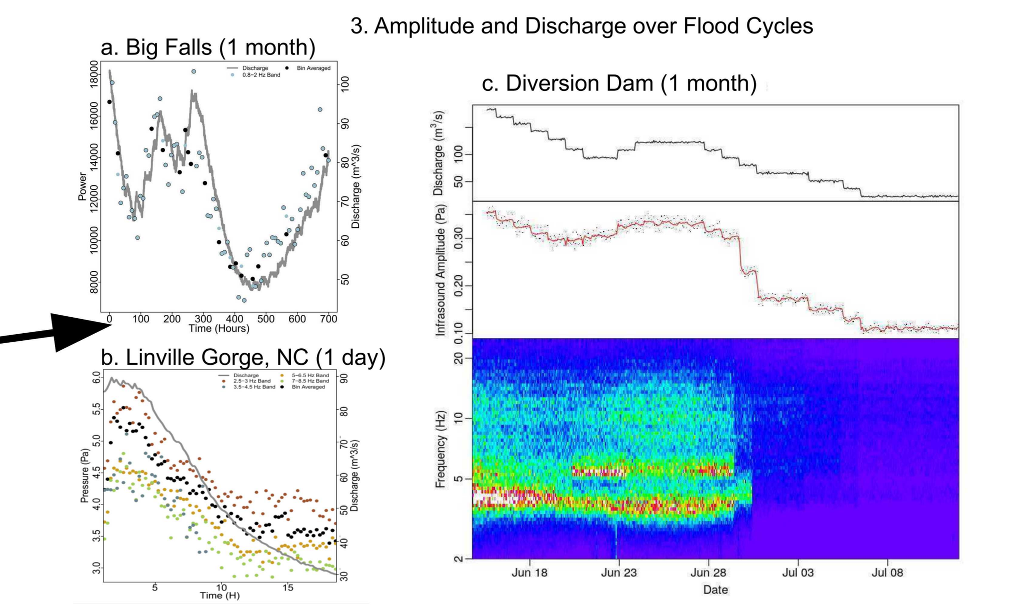


Fig. 2: Correspondence of acoustic amplitude to discharge in seasonal flood cycle (a), flash flood (b), and regulated dam spill-over (c), showing strong temporal variation in river sounds. The whitewater feature in Linville Gorge (not pictured) is a 1-meter wide constriction in the Linville river.

Major waterfalls appear to have acoustic power concentrated in infrasound,

sometimes including strong spectral peaks (fig. 4, 5). Infrasound can propagate long distances and would be a convenient means of monitoring in both a geophysical and planetary context.

Potential study sites

Titan

Despite frigid temperatures and exotic chemistry, Saturn's largest moon Titan is surprisingly Earth-like in its hydrology. Methane occurs as solid, liquid, and gas on Titan, has a cycle of evaporation, condensation, and precipitation, and has formed fluvial geomorphic features including major liquid-filled canyons (Poggiali et al., 2016). Acoustic recording with low-temperature sensors would be possible either on Titan's surface via lander (at a specific site of interest), or in its dense atmosphere via balloon (which would have low wind noise and superior spatial coverage).

Property	Earth	Titan	Significance
Temperature	~300 K	~100 K	Earth and Titan both have hydrological cycles that can lead to significant, unsteady surface flow
Liquid Composition	H_2O	Hydrocarbons	
Rock Composition	Silicates	H_2O	Substrates of Earth and Titan can be incised into confined channels and eroded into transportable fragments (e.g., gravel-sized).
Liquid density	1000 kg/m^3	420 kg/m^3	Water on Earth and methane on Titan are inviscid, dense liquids, prone to turbulent flow and able to erode and transport sediment.
Liquid viscosity	10^{-5} Pa.s	10^{-4} Pa.s	
Surface atmospheric pressure	100 kPa	145 kPa	Earth and Titan have similarly dense, high-pressure, mainly diatomic atmospheres. They should interact similarly with turbulent liquids and carry strong low-frequency sound for long distances.
Main atmospheric constituents	N_2 (78%), O_2 (21%)	N_2 (97%), CH_4 (3%)	

Mars

Liquid water appears to be present near the Martian surface in certain settings, and geomorphic features show that fluvial activity was widespread in the past (Orosei et al., 2018).

Earth

Fluvial sounds on Earth are widespread and are caused by both turbulence (Ronan et al., 2017) and sediment transport (Schmandt et al., 2013). They can interfere with geophysical monitoring (Johnson et al., 2006), affect wildlife positively and negatively (e.g., Barber et al., 2010), and may have physiological and health effects on humans (Goines and Hagler, 2007). Acoustics can be useful in monitoring streamflow, geomorphic changes, and sediment transport in streams.

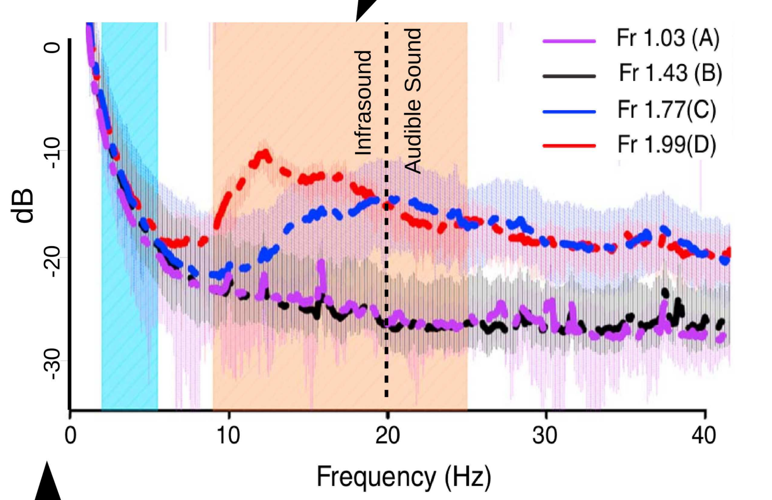


Fig. 3: Acoustic spectrum from Boise Whitewater Park in four configurations (see photo) with constant discharge. A critical Froude number (1.43 < Fr < 1.77) must be exceeded to produce significant infrasound; this range includes the threshold Fr = 1.7 where an "undular jump" transitions to a more vigorous "weak jump". Low frequencies below 5 Hz are ambient wind noise; infrasound spectrum is broad and not strongly peaked.

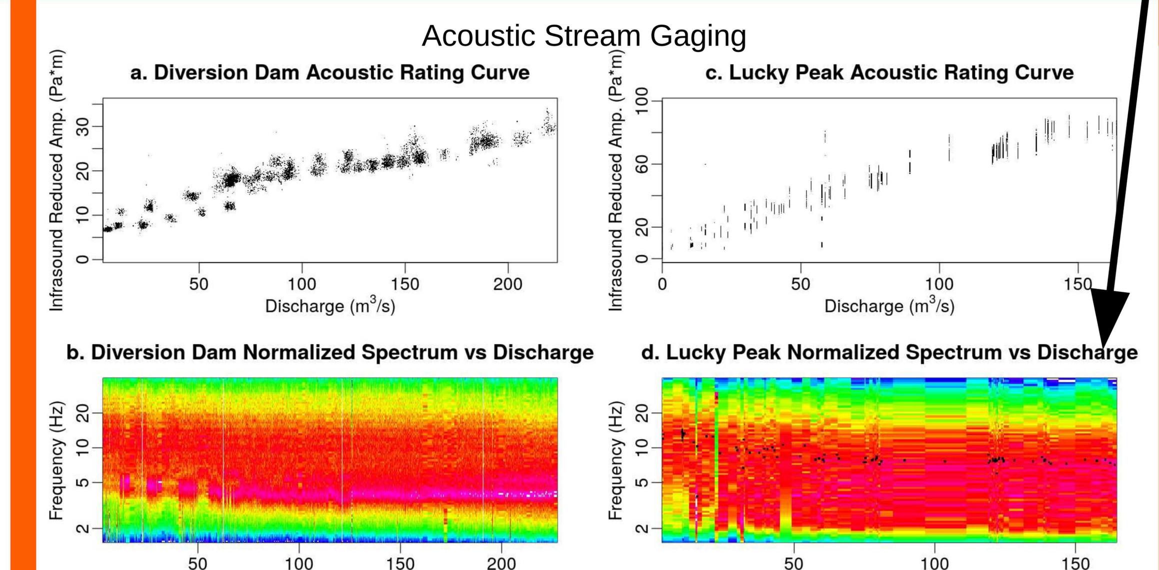


Fig. 4: Discharge-to-infrasound relationship at Boise River Diversion Dam (a-b) and Lucky Peak Dam (c-d). The discharge-amplitude relationship is clear in both cases; the greater variability in amplitude at Diversion Dam may be due to inconsistent use of different dam geometries to regulate flow. Spectral dependence on discharge is subtle, especially at higher flows. Both dams' spectra drop off over 20 Hz, but Diversion Dam has a clear peak around 4 Hz while Lucky Peak has a flatter spectrum.

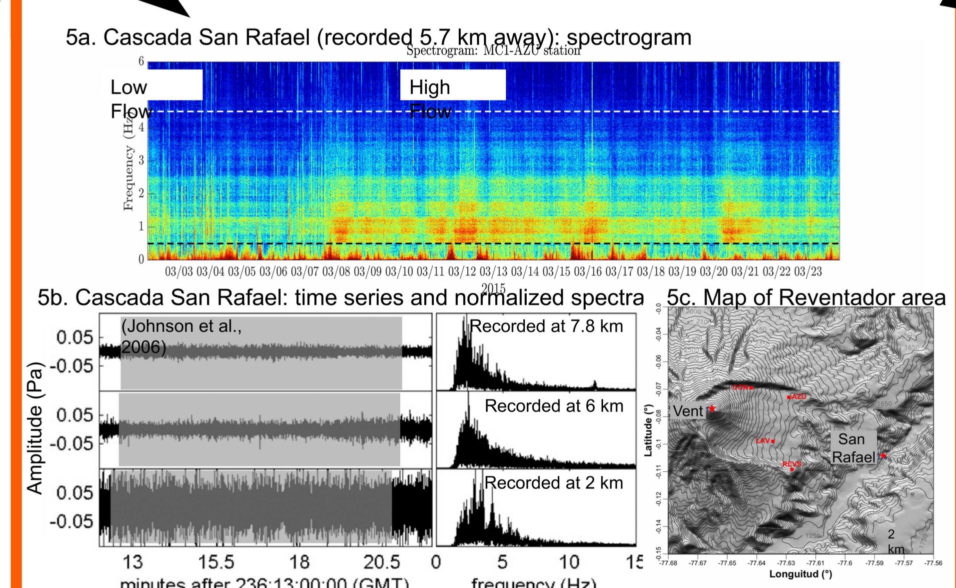


Fig. 5. Acoustic recordings from a 150-meter waterfall. a: The 0.5-4.5 Hz band is dominated by continuous waterfall infrasound whose amplitude (but not frequency content) varies with time, indicating high-flow events. b: Acoustic time series are steady, and spectra have peaks around 3 Hz. c: Proximity to the active volcano El Reventador makes the waterfall a continuous source of noise in volcano monitoring data.

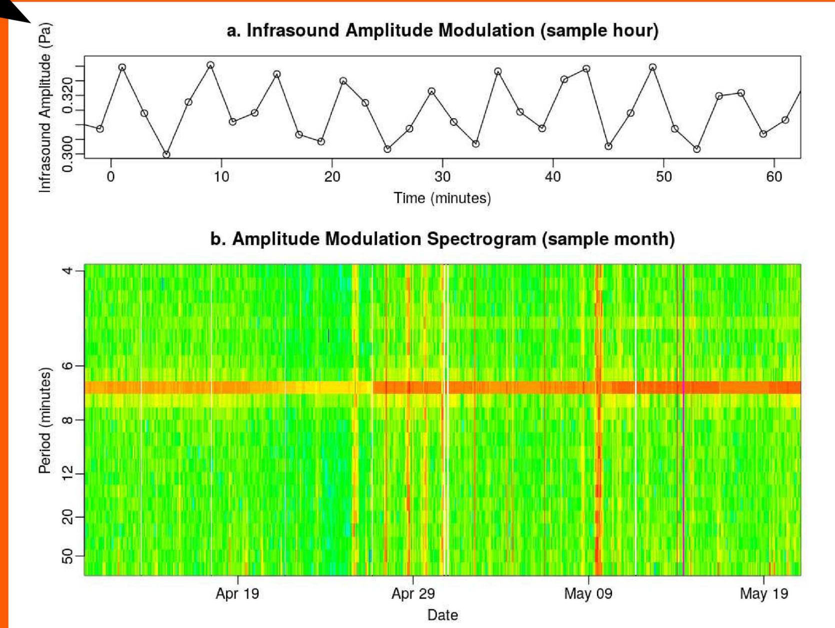


Fig. 6: Consistent, periodic fluctuations in acoustic amplitude. a: amplitude at Diversion Dam varies by 10% in 7-minute cycles. b: Amplitude modulation cycles are strongly peaked and continue for at least one month. We conjecture that this signal originates as a seiche in a lake upstream of the dam.

Physics of sound generation in stream turbulence

Rapid Morphology: Froude Number (Fr)

Most momentum transfer in streamflow happens via gravity waves (buoyancy waves), which move at a characteristic speed depending on gravity and water depth.

$$c_{gravity} = \sqrt{gD}$$

When the stream's velocity exceeds the local speed of gravity waves, the flow is called supercritical and a hydraulic jump (similar to a shock wave) forms. Hydraulic jumps are quantitatively described by the ratio of flow velocity to wave speed (called the Froude number, Fr); jumps with high Fr are more abrupt, violent, and convert more hydraulic power than waves with low Fr (fig. 3).

$$Fr = \frac{v}{\sqrt{gD}}$$

Fr	Jump Description
0-1	Subcritical
1-1.7	Undular Jump
1.7-2.5	Weak Jump
2.5-4.5	Oscillating Jump
4.5-9.0	Steady Jump
>9.0	Strong Jump

Ronan et al., 2013 found that a threshold Fr > 1.7 (corresponding to a morphological change from an "undular jump" to "weak jump" is needed to produce significant acoustic emissions (fig. 3).

Discharge

Discharge is the main variable property of most whitewater features. Depending on the setting, it can undergo dramatic variations over time scales ranging from seconds (dam-regulated rivers) to hours (flash floods) to weeks (seasonal snowmelt). Whitewater sounds typically change simultaneously with discharge (fig. 2)

Measuring discharge is important in many applications. Given a high-Fr whitewater feature, a site for an acoustic sensor, and accurate discharge data for calibration, we can construct an empirical "acoustic rating curve" for estimating discharge given the acoustic amplitude over a relevant frequency band (fig. 4a,c).

Hydraulic Power

Water that falls or flows downhill begins with substantial gravitational potential energy that is dissipated in hydraulic jumps, being converted into thermal, seismic, and acoustic energy. The total power converted by a hydraulic jump depends on discharge, gravity, and jump height:

$$P_{hydro} = \rho \phi g h$$

The total sound power emanating from the jump can be estimated given an acoustic recording at a known distance, and depends on pressure amplitude, distance, and the air density and sound speed:

$$P_{acoustic} = \frac{2\pi r^2 p^2}{\rho_{air} c_{air}}$$

Estimates of the conversion ratio from hydraulic to acoustic energy are approximately 10^{-6} at many stages at two spillways (fig. 7). We conjecture that for sufficiently high hydraulic jumps like waterfalls, this conversion ratio is approximately constant; more observations are needed to confirm or refute this conjecture. Using this relationship, we can estimate a discharge of 122 m^3/s for the 150-meter Cascada San Rafael (0.05 Pa RMS at 2 km; fig. 5b).

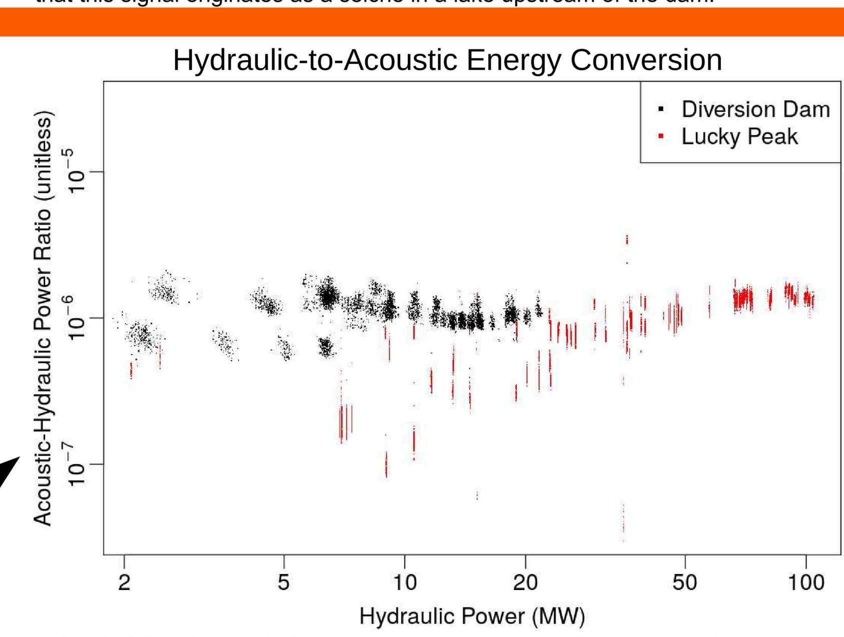


Fig. 7: Ratio of acoustic to hydraulic power as a function of hydraulic power for two spillways. We suggest that a conversion ratio of 10^{-6} may apply generally to features with very high Froude numbers like these waterfalls.

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