Whitewater Sound Dependence on Discharge and Wave Configuration at an Adjustable Wave Feature

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Abstract

Stream acoustics has been proposed as a means of monitoring discharge and wave hazards from outside the stream channel. To better understand the dependence of sound on discharge and wave characteristics, this study analyzes discharge and infrasound data from an artificial wave feature. This feature, known as Boise Whitewater Park: Phase 1 (BWPP1), is adjusted to accommodate daily changes in recreational use and seasonal changes in irrigation demand. Significant sound is only observed when discharge exceeds ~35 m3/s, and even above that threshold the sound-discharge relationship is non-linear and inconsistent. When sound is observed, it shows consistent dependence on wave type within a given year, but the direction of this dependence varies among the three years studied (2016, 2021, and 2022). These findings support previous research that establishes discharge and stream morphology as significant controls on stream acoustics and highlights the complex, combined effects of these variables.

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7	
8	Key Points:
9	• For the first time, we examine combined effects of discharge and wave morphology on
10	sound.
11	• Significant sound is only produced above discharge rates exceeding \sim 35 m ³ /s.
12	• Wave morphology has potential to create powerful or insignificant sound, but interannual
13	geomorphic changes may also be significant.

Abstract 14

Stream acoustics has been proposed as a means of monitoring discharge and wave 15 hazards from outside the stream channel. To better understand the dependence of sound on 16 discharge and wave characteristics, this study analyzes discharge and infrasound data from an 17 artificial wave feature. This feature, known as Boise Whitewater Park: Phase 1 (BWPP1), is 18 adjusted to accommodate daily changes in recreational use and seasonal changes in irrigation 19 demand. Significant sound is only observed when discharge exceeds \sim 35 m³/s, and even above 20 21 that threshold the sound-discharge relationship is non-linear and inconsistent. When sound is observed, it shows consistent dependence on wave type within a given year, but the direction of 22 this dependence varies among the three years studied (2016, 2021, and 2022). These findings 23 support previous research that establishes discharge and stream morphology as significant 24 controls on stream acoustics and highlights the complex, combined effects of these variables. 25

26 **Plain Language Summary**

Previous research has explored the potential of using sound to measure stream discharge 27 and evaluate stream hazards. Discharge and wave types were examined at an artificial wave 28 feature known as Boise Whitewater Park: Phase 1 (BWPP1), which changes formation to adapt 29 to daily changes in recreation and seasonal changes in irrigation. Through this study, we found 30 that significant sound is only observed over a certain threshold and that the formation of the 31 wave affects sound consistently during the year but changes between years, potentially due to 32 outside effects on the overall stream. Future work should aim to better understand wave 33 34 formation and specific wave traits that contribute to certain patterns of sound. Overall, this study supports the findings of previous research and applies them further by investigating the 35 combined, complex effects of stream traits on sound. 36

1. Introduction 37

38 Stream acoustics is the use of stream sounds for monitoring fluvial processes (Ex. sediment transport and stream turbulence). Past research has found that sound power and 39 spectrum depends on turbulent features' morphology (Ronan et. al., 2017) and discharge 40 (Schmandt et. al., 2013; Ronan et. al., 2017; Osbourne et. al., 2021). As more information is 41 discovered about stream acoustics, potential applications for out-of-channel stream discharge 42 gauges and the detection of drowning hazards can be further explored (Leutheusser et. al., 1991), 43 broadening the already growing list of acoustic monitoring used in earth and atmospheric 44 processes. Geophysical acoustic monitoring focuses on infrasound (sounds whose frequencies 45 are below 20 Hz, the human hearing limit) and low-frequency audible sounds (approximately 20-46 50 Hz). These sounds are frequently used to measure volcanic eruptions (Watson et. al., 2022), 47 snow and ice avalanches (Johnson et. al., 2021), debris flows (Hübl et. al., 2013), lahars (Bosa et. 48 al., 2021; Johnson et. al., 2015), pyroclastic flows (Lyons et. al., 2021), and nuclear explosions 49 (Che et. al., 2014). With further research, stream acoustics may be added to this list. 50

51 **1.1. Hydraulics of Breaking Waves in Streams**

The breaking of buoyancy waves in water, characterized by turbulence and air 52 entrainment that create the characteristic whitewater appearance, is widely recognized as a 53 source of seismoacoustic generation (Ronan et. al., 2017; Lyons et. al., 2021). In gravity-54 dominated processes like open-channel flow and buoyancy waves, an important descriptor of 55 flow characteristics is the dimensionless Froude number 56 57

$$Fr = v / \sqrt{gh} \tag{1}$$

where v is flow speed, g is the acceleration due to gravity $(9.8 \text{ m}^2/\text{s})$, and h is the depth of the flow.

In flowing channels, stationary breaking waves called hydraulic jumps form where water 60 transitions from supercritical flow (Fr > 1) to subcritical flow (Fr < 1). In uniform channels, 61 hydraulic jump morphology corresponds to a range of Froude numbers of the incoming 62 supercritical flow. For example, undular jump morphology is associated with a Froude number 63 from 1.0 to 1.7, while weak breaking hydraulic jump morphology is associated with Froude 64 numbers from 1.7 to 2.5 (Chow, 1959). Fr=1.7 represents a boundary between undular jumps 65 that turn to weak breaking hydraulic jumps, which creates a collapsing wave that transfers 66 kinetic energy to associated seismoacoustic fields (Ronan et. al., 2017). Hydraulic jumps 67 68 identified in high-speed lava flows have also been identified as a source of infrasound (Lyons et. al., 2021). 69

70 Seismoacoustic generation has also been linked to stream morphology, including features such as bed roughness, obstacles within the stream (Osborne et. al., 2021), and drops that form of 71 hydraulic jumps (Ronan et. al., 2017). At geomorphic features like weirs (Leutheusser and Birk, 72 1991) or downward steps in the streambed (Padova et. al., 2017), hydraulic jumps are more 73 74 complicated than in uniform channels and are categorized morphologically following different schemes. The categories used for steps, ranging from A-jumps that occur at very high tailwater 75 depth, to wave jumps and wave trains at intermediate tailwater depth, to B-jumps at low tailwater 76 77 depth, are most relevant to our study site. The wave setting at Boise Whitewater Park Phase 1 (BWPP1) labeled "Green Wave" (Fig. 1B) resembles the "wave jump" condition (Padova et. 78 al., 2017, fig. 1b), and the wave setting labeled "Wave/Hole" (Fig. 1D) resembles the "minimum 79 80 B-jump" condition (Padova et. al., 2017, fig. 1e).

81 **1.2. Benefits of Using Infrasound to Measure Stream Flow**

While the use of infrasound and low-frequency audible sound is fairly new in relation to 82 monitoring stream acoustics, it has been widely used for monitoring a variety of other surface 83 and flow processes. In particular, fluvial sound has been studied from lahars (Johnson et. al., 84 2015; Bosa et. al., 2021) and waterfalls (Johnson et. al., 2006). Low-frequency sound is 85 considered an appealing monitoring method for several reasons: it can be measured remotely, its 86 low data rate makes automated real-time analysis feasible and computationally inexpensive, it 87 doesn't require human supervision to operate and needs infrequent maintenance, and it is not 88 affected by loss of visibility (Ex. darkness, fog, etc). 89

90 Continuous stream monitoring is currently performed by in-stream gauges that measure river stage, from which discharge is estimated using an empirical rating curve. Stream gauges in 91 the US mostly monitor high-order streams (low-order streams are severely under-monitored) and 92 their number is generally declining (Hannah et. al., 2011). Gauges can be far sparser in other 93 countries, with little or no reliable observations of streamflow (Fekete and Vorosmarty, 2007). 94 Additionally, a common issue found during flooding periods (where recorded data is often the 95 96 most important) is that in-stream gauges along heavily flooded stream systems are often destroyed; this forces past research to reconstruct and estimate peak flows for these events and 97 deprives monitoring agencies of critical data during flood emergencies (Gochis et. al., 2015). By 98 99 comparison, infrasound has been identified as a potentially cheaper, non-invasive, and less floodprone supplement or alternative to continuously monitor river stage. Low-cost infrastructure 100 would allow gaps in hydrometric stations to be filled, and the out-of-stream placement of 101

102 infrasound sensors would allow better protection for equipment.

Additionally, infrasound monitoring would not only help fill gaps in discharge data, but 103 also could enable monitoring hazardous wave conditions. At certain combinations of discharge 104 and tailwater height, hydraulic jumps at weirs or drops in streams can partly submerge, forming a 105 rotating current with a strong upstream-directed surface current. Though their whitewater is 106 visually less impressive than non-submerged hydraulic jumps, these vortices are much more 107 dangerous because buoyant objects, recreators, and rescuers can become trapped in the turbulent 108 back-current that even strong swimmers cannot escape (Leutheusser et. al., 1991). An improved 109 understanding of how wave morphology affects infrasound production could enable automated 110 alerts to recreators and safety personnel when changing flow conditions create hazards like 111 submerged jumps, helping save lives of recreators and rescuers. 112 113 In this study, we investigate the relationship between sound, discharge, and wave

configuration at Boise Whitewater Park Phase 1 (BWPP1), an artificial, adjustable dam located
 in Boise, Idaho. BWPP1 is known for adjustments in configuration relating to daily, weekly, and
 seasonal changes in recreational and irrigation demand. Using infrasound recordings from 2016,
 2021, and 2022, the effects of discharge and dam configuration on the acoustic spectrum were
 analyzed on daily and seasonal scales in order to better understand the relationships between
 infrasound and stream features with the intent to further explore potential applications in stream

120 monitoring.

121 **2. Methods**

122 **2.1. Site Description**

123 Boise Whitewater Park is an adjustable dam located along the Boise River in Boise, Idaho. The park is divided into two phases: one upstream and one downstream. This study 124 focuses on the upstream location, commonly referred to as "Phase 1." At Phase 1 (BWPP1), 125 water is allowed to flow through the dam in three openings: a small, non-adjustable spillway on 126 river left partly obstructed by rip-rap, the main, central adjustable wave, and an opening operated 127 as safe passage for boats on river right. For the purpose of measuring sound, this study assumes 128 that the central wave is the dominant infrasound source, as both the left and right openings lack 129 large waves. Flashboards and Wave Shapers (Fig. 1, cyan and red features respectively) located 130 131 within the dam determine the shape of the wave, consisting of the angle of entry and speed of water allowed to pass. By adjusting flashboards and waveshapers, park operators aim to create 132 appealing waves for recreation and maintain required irrigation diversions despite seasonal 133 changes in discharge and interannual changes in riverbed morphology due to sediment erosion 134 and deposition (City of Boise, n.d.). 135

Boise Whitewater Park Phase 1 produces two types of wave configurations–Green Wave 136 and Wave/Hole (Fig. 1)--which differ in their retentiveness (tendency to obstruct floating 137 objects). Green Waves typically have smoother fronts with relatively little turbulence at the 138 surface (Asiaban et. al., 2021). Surfers prefer these less-retentive waves because surfboards 139 produce less friction and have an easier time moving against the current. Wave/Holes have 140 abrupt, recirculating fronts with turbulence at circulating points. Kayakers prefer these more-141 retentive waves because kayaks are more affected by stream velocity than surfboards, and the 142 upstream currents' recirculating waves help prevent them from being swept downstream. These 143 descriptions pertain to the initial wavefront at the hydraulic jump itself; any subsequent 144 downstream waves may not contain these features. BWPP1 alternates between these two 145 configurations for recreational use with schedules that vary throughout the flow season. During 146 periods of high flow ($> -60 \text{ m}^3/\text{s}$), additional flashboards are opened to allow higher volumes of 147

148 water to pass through, which overrides any prior wave configuration schedule. These specific

149 configurations are excluded from our analysis.

150



Figure 1: Images and cross-section drawings of Green Wave [A and B] and Wave/Hole [C and D] configurations.

151 Figure 1. Images and cross-section drawings of Green Wave [A and B] and Wave/Hole [C and 152 D] configurations. Flashboards (cyan) are adjusted by pneumatic bladders that range over a 153 variety of angles (including the ability to completely block flow through sections of the dam), 154 while hydraulic-controlled wave shapers (red) range only between 0 to 9 degrees. Green Waves 155 have smooth fronts and are formed by water spilling over elevated flashboards onto horizontal 156 waveshapers, while Wave/Hole are circulating waves with foamy, turbulent fronts formed by 157 water that is allowed to plunge into the downstream pool by horizontal flashboards and 158 downward-sloped waveshapers. The blue "trash gates" prevent debris accumulation under the 159 waveshapers and do not significantly affect flow patterns. 160

161

162 **2.2. Field Methods and Data Analysis**

We installed instruments to monitor low-frequency sound (Anderson et al., 2016) along 163 the left bank of the Boise River during the 2016, 2021, and 2022 flow seasons. Sensors were 164 located ~46m downstream. During the 2022 flow season, photos were taken of the site through 165 webcams provided by the park. Discharge data for all three years were retrieved from USGS 166 gauge #13206000 (USGS, 2016) located 5.26 km downstream; discharge at this site was 167 168 expected to be the same as BWPP1 except for an approximately one-hour delay and small flow differences from minor ungauged irrigation diversions and returns. During the periods studied 169 (excluding flood conditions, which are not interpreted), discharge was not sufficient to transport 170 sediment. 171 Maximizing signal fidelity is essential when studying low-power continuous signals, and 172

172 Waximizing signal indenty is essential when studying low-power continuous signals, and 173 we took various actions in the field and in analysis to achieve this. Sensors were concealed under 174 leaves along a wooded section of the river bank, which protected sensors from noise due to 175 atmospheric turbulence without impeding the infrasound. During analysis, hour-long windows

were selected during the early morning hours local time (9:00-10:00 UTC) to minimize

background noise from human activity and atmospheric turbulence. Stationary river and wave

conditions are expected at this time because park staff, irrigation officials, and upstream

reservoir managers do not normally make changes overnight. Additionally, inspection of all data

180 showed that infrasound frequencies below 10 Hz were never associated with flow conditions in

the park, and instead were dominated by transient atmospheric turbulence noise or, in quiet

conditions, by instrument self-noise. Therefore, after deconvolving the sensor's instrument
 response, we filtered all data above 10 Hz to remove noise without affecting signals of interest.

We calculated spectra using Welch's method, which, by dividing the hour-long recording period

into 10-second windows with 50% overlap and averaging all spectra, ensures that the resulting

spectrum is representative of the recording period and is not strongly influenced by occasional

187 transients.

188 **3 Results**

This study investigates stream discharge, infrasound power, and infrasound frequency. Figures in this paper are divided into three sections to demonstrate three different variables: A.) stream discharge from the nearest USGS gauge, B.) infrasound power, and C.) infrasound spectrogram. Infrasound power is the mean of squares of the filtered infrasound pressure signal,

a single value for each day's hour-long recording period. Spectrograms show how the power

during each recording period is distributed over frequency. Bright-colored horizontal bands in the spectrogram represent frequencies that consistently have high power over long periods of

time; narrow horizontal bands are often produced by building air conditioners and other large
 machines. Bright-colored vertical bands in the spectrogram indicate moments in time that have

significant power at a wide range of frequencies, most commonly due to storms.

199 **3.1 Infrasound Over the 2021 and 2022 Flow Seasons**

Figure 2 shows stream discharge, infrasound power, and infrasound frequency during 201 2021 and 2022. 2021 discharge ranges from ~10 to 50 m³/s, while 2022 discharge rates range 202 from ~10 to 80 m³/s. In 2021, large peaks in infrasound power occur simultaneously with the 203 year's highest discharges (~50-55 m³/s). By contrast, in 2022, the highest values of infrasound 204 power occur after the flow drops from a peak of 80 m³/s to a plateau around 40 m³/s. Outside of 205 these high flow periods, changes in infrasound power (ranging from 2 to 4 * 10⁻⁴ Pa²) do not 206 coincide with changes in discharge or wave configuration; these fluctuations are likely noise. 207



Figure 2. Discharge [A, D], Power [B, E], and Frequency [C, F] of stream and infrasound data
 recorded from March-September 2021 and January-August 2022. Periods of infrasound power in
 February and early March 2022 (February 18th through March 6th) are related to construction
 near the dam.

214 **3.2. Daily Changes During 2016, 2021, and 2022 Flow Season**

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We investigate day-to-day changes in infrasound over select periods including high flows during 2016, 2021, and 2022 to determine the effects of wave configuration. The selected periods include May 2016, May-June 2021 (Fig. 3), and June-August 2022 (Fig. 4, which also includes images for select days during that period). In 2016, 2021, and 2022, dominant frequencies were consistently between 15 to 35 Hz on days with significant infrasound, regardless of wave configuration or discharge; significant fluvial infrasound only occurs at discharges above 35 m³/s, regardless of the year.

In 2016, a distinct dependence of infrasound power on wave configuration was observed in the first week (May 3rd to 10th) when discharge was approximately 42 m³/s (Fig. 3A-B). During this week, Green Wave configuration days have much lower acoustic power than Wave/Hole configuration days. A similar difference in wave configurations was also observed in the third week of June 2022 (June 19th to 26th) and the second and third week of July 2022 (July 13th to 19th) when discharge was approximately 42-45 m³/s (Fig. 4J-K). However, the opposite



Images taken throughout June and July 2022 also display a similar lack of dependence.

- 233 Most days maintain similar, recognizable Green Wave and Wave/Hole configurations that
- continue to be observed throughout the flow season. Images shown in Figure 4 include a range of
- days from low to medium discharge (~15-40 m³/s). Certain days (Fig 4D-E and H-I) display
- patterns of medium sound power Green Wave configuration paired with a low power Wave/Hole configuration at the same, similar level of discharge (\sim 35-40 m³/s).
- 238



239 240 241

Figure 3. Discharge [A and D], Power [B and E], and Frequency [C and F] of stream and infrasound data recorded in June 2021 and May 2016.







Figure 4. Images [A-I] and Discharge [J], Power [K], and Spectrogram [L] of stream and

- 245 infrasound data during 2022. A-B shows Green Wave and Wave/Hole configurations occurring
- during a period of low discharge (~15 m^3/s), while C shows a Green Wave configuration
- occurring at a higher discharge (\sim 35 m³/s). D-E and H-I show medium sound power Green Wave
- configuration and low power Wave/Hole occurring at a similar discharge (\sim 35-40 m³/s), and F-G

show days where infrasound power decreases despite unchanging discharge and no visible

- 250 change to wave configuration (~40 m^3/s).
- 251

252 **4 Discussion**

4.1. Dependence of Infrasound on Discharge

The observed sound-to-discharge relationship is nonlinear, non-monotone, and often 254 affected by wave configuration. Significant infrasound power only occurs at discharge rates 255 above 35 m³/s; sound below this threshold is attributed to noise. Background noise can often be 256 attributed to atmospheric turbulence and human activity-mainly heating, ventilation, and air 257 conditioning from nearby buildings. We attribute spikes in infrasound frequency near 10 Hz to 258 construction machinery working near the dam, and high power at a wide range of frequencies to 259 stormy weather. These noise types are familiar in infrasound studies and not surprising to see at 260 BWPP1. 261

The 35 m³/s threshold for infrasound production was observed in all three years recorded, spanning a variety of discharge values. It is important to note that while significant sound only occurs above \sim 35 m³/s, days with the highest discharge were not necessarily days with the highest infrasound power.

4.2. Daily Changes and Wave Configuration

Based on our observations of daily changes during periods of significant infrasound, 267 Green Wave and Wave/Hole configurations at Boise Whitewater Park can change sound in a 268 way that is predictable within a given year but not have characteristic sounds that persist over 269 multiple years. This is shown during the first week of May 2016 (May 3rd to 10th) (Fig. 3A-B), 270 271 and June-July 2022 (June 19th to 26th; July 13th to 19th) (Fig. 4J-K), when wave configuration and sound had an observable pattern. Importantly, both periods occurred at discharge between 35 272 m^3/s (the threshold required for sound production) and 50 m^3/s (above which the normal dam 273 configurations must be modified to ensure user safety). The unexpected reversal of the 274 dependence of sound power on wave configuration between 2016 (in which Wave/Holes are 275 louder), 2021 (in which the waves are indistinguishable), and 2022 (in which Green Waves are 276 277 louder) shows that the flow characteristics that determine sound generation do not depend directly on the intended recreational use of the wave (i.e., its retentiveness), but are instead 278 changed incidentally by dam reconfiguration. Morphological differences in the dam and riverbed 279 between 2016-2022, as well as changes in dam operator practices in how they adjust the dam to 280 create appealing waves, may explain the year-to-year inconsistency. 281

When discharge reached levels of flood conditions (typically around $\sim 60 \text{ m}^3/\text{s}$), BWPP1 282 widened the wave by opening more flashboards. Some flood configurations mimicked traits of 283 284 typical Green Wave and Wave/Hole forms for a larger volume of water (evidenced by some images during this period, e.g. figure S4), while others formed a smooth non-wave. This means 285 that for the highest periods of discharge within our study, the wave configuration was drastically 286 altered from the usual schedule. Because of the inconsistency of these flood configurations, 287 various acoustic effects may occur. Due to limited observations of high flow throughout the three 288 years, we do not attempt to interpret higher flows. 289

4.3. The Origin of Whitewater Sounds and Future Work

291 Our work demonstrates that at favorable discharge levels, an adjustable whitewater 292 feature produces significant sound under certain configurations and insignificant sound under

different configurations. However, the enigmatic finding that the relationship between sound and 293 wave morphology can disappear (2021) or reverse between years (2016 vs 2022) highlights the 294 need to identify the specific wave process responsible for low-frequency sound production. 295 Clearly, the shape of the wave's front (the key characteristic manipulated by park staff for 296 recreational utility) is not the sole determinant of the sound; otherwise, the dependence of sound 297 on wave configuration would be consistent every year. We generally expect whitewater sounds 298 to originate in regions of the flow that are highly turbulent (where tractions exerted on the 299 atmosphere are strong) and/or foamy (where underwater sound transmits better to the atmosphere 300 due to the smaller contrast in acoustic impedance). Breaking waves-either the main front of a 301 wave (e.g., this study's Wave/Hole in 2016 and 2021), or secondary breakers downstream (e.g., 302 this study's Green Wave in 2021-2022)-may serve as sound sources whose loudness can change 303 dramatically in response to apparently minor changes in flow patterns. 304

Though less prominent and smaller in discharge than the main wave feature, we also 305 consider whether flow elsewhere along the dam could account for the observed low-frequency 306 sound. Apart from the main wave, significant whitewater features along the dam include the 307 rocky spillway on the river-left side, the bypass chute on the river-right side, and small waterfalls 308 over raised flashboards (fig. 4A-I). Flow through all of these features depends on the difference 309 between the upstream and downstream water levels, which we note is consistently higher for 310 Green Waves than for Wave/Hole configuration. In particular, during the period examined in 311 312 2022, the upstream water level only rises above raised flashboards when the dam is configured for a green wave (fig. 4). Though our sensors were closer to the left side of the dam than the right 313 side, the resulting detection bias on possible sound sources is small (power ratio vs the main 314 wave feature less than 1.5) compared to the sound power differences we observe in Figures 2-4 315 (power ratio between 2-7); therefore, sound produced along any part of the dam would have been 316 detectable. Therefore, we suggest that changes to the main wave may incidentally increase or 317 decrease flow in other parts of the dam whose morphology is more conducive to sound 318 production. Future work may elucidate morphological controls on whitewater sound production 319 using high-resolution acoustic or optical imaging to identify source regions, or by direct 320 manipulation of the dam to identify morphological changes that coincide with increasing sound 321 322 power. 323

Finally, we affirm the utility of adjustable waves in whitewater parks for studying effects of hydrodynamics and discharge on geophysical wave fields (first demonstrated by Ronan et. al., 2017). These increasingly common waves offer the unique ability to manipulate wave morphology at river scale and can perform useful roles in controlled short-term experiments, as well as long-term natural experiments when the wave is routinely adjusted similar to this study.

329 **5 Conclusions**

In order to better understand sound dependence on discharge and wave configuration, this 330 study examined infrasound from three years at an adjustable wave feature located in Boise 331 Whitewater Park. In comparison to past research that investigated discharge and wave 332 morphology separately, this study examines these variables jointly in their relationship with 333 sound. Discharge above a specific threshold was required for significant infrasound. 334 Relationships between sound and wave configuration were only present above this threshold, 335 where morphological changes in the wave could cause sound to become powerful or 336 insignificant. Changes in wave configuration and sound were consistent within the year but not 337

- between years, perhaps due to geomorphic changes in the stream outside of wave morphology.
- Because of their ability to control wave morphology on a river scale, collaboration with
- 340 whitewater parks offers opportunities for future work into the origin of whitewater sound.

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347 Data Availability Statement

Data presented here is archived and may be accessed from the Boise State University Infrasound Data Repository at https://scholarworks.boisestate.edu/infrasound_data/ and https://doi.org/10.18122/infrasound_data.11.boisestate.

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