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

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Key Points:

- For the first time, we examine combined effects of discharge and wave morphology on sound.
- Significant sound is only produced above discharge rates exceeding ~35 m^3/s.
- Wave morphology has potential to create powerful or insignificant sound, but interannual geomorphic changes may also be significant.

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 m^3/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.

Plain Language Summary

Previous research has explored the potential of using sound to measure stream discharge and evaluate stream hazards. Discharge and wave types were examined at an artificial wave feature known as Boise Whitewater Park: Phase 1 (BWPP1), which changes formation to adapt to daily changes in recreation and seasonal changes in irrigation. Through this study, we found that significant sound is only observed over a certain threshold and that the formation of the wave affects sound consistently during the year but changes between years, potentially due to outside effects on the overall stream. Future work should aim to better understand wave 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 combined, complex effects of stream traits on sound.

1. Introduction

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

1.1. Hydraulics of Breaking Waves in Streams

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

$$Fr = v / \sqrt{gh} \qquad (1)$$

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

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

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 hydraulic jumps (Ronan et. al., 2017). At geomorphic features like weirs (Leutheusser and Birk, 1991) or downward steps in the streambed (Padova et. al., 2017), hydraulic jumps are more 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 depth, to wave jumps and wave trains at intermediate tailwater depth, to B-jumps at low tailwater 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. al., 2017, fig. 1b), and the wave setting labeled “Wave/Hole” (Fig. 1D) resembles the “minimum B-jump” condition (Padova et. al., 2017, fig. 1e).

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

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 the US mostly monitor high-order streams (low-order streams are severely under-monitored) and their number is generally declining (Hannah et. al., 2011). Gauges can be far sparser in other countries, with little or no reliable observations of streamflow (Fekete and Vorosmarty, 2007). Additionally, a common issue found during flooding periods (where recorded data is often the 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 deprives monitoring agencies of critical data during flood emergencies (Gochis et. al., 2015). By comparison, infrasound has been identified as a potentially cheaper, non-invasive, and less flood-prone supplement or alternative to continuously monitor river stage. Low-cost infrastructure would allow gaps in hydrometric stations to be filled, and the out-of-stream placement of infrasound sensors would allow better protection for equipment.

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

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 monitoring.

2. Methods

2.1. Site Description

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 focuses on the upstream location, commonly referred to as “Phase 1.” At Phase 1 (BWPP1), water is allowed to flow through the dam in three openings: a small, non-adjustable spillway on river left partly obstructed by rip-rap, the main, central adjustable wave, and an opening operated as safe passage for boats on river right. For the purpose of measuring sound, this study assumes that the central wave is the dominant infrasound source, as both the left and right openings lack large waves. Flashboards and Wave Shapers (Fig. 1, cyan and red features respectively) located 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 appealing waves for recreation and maintain required irrigation diversions despite seasonal changes in discharge and interannual changes in riverbed morphology due to sediment erosion and deposition (City of Boise, n.d.).

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

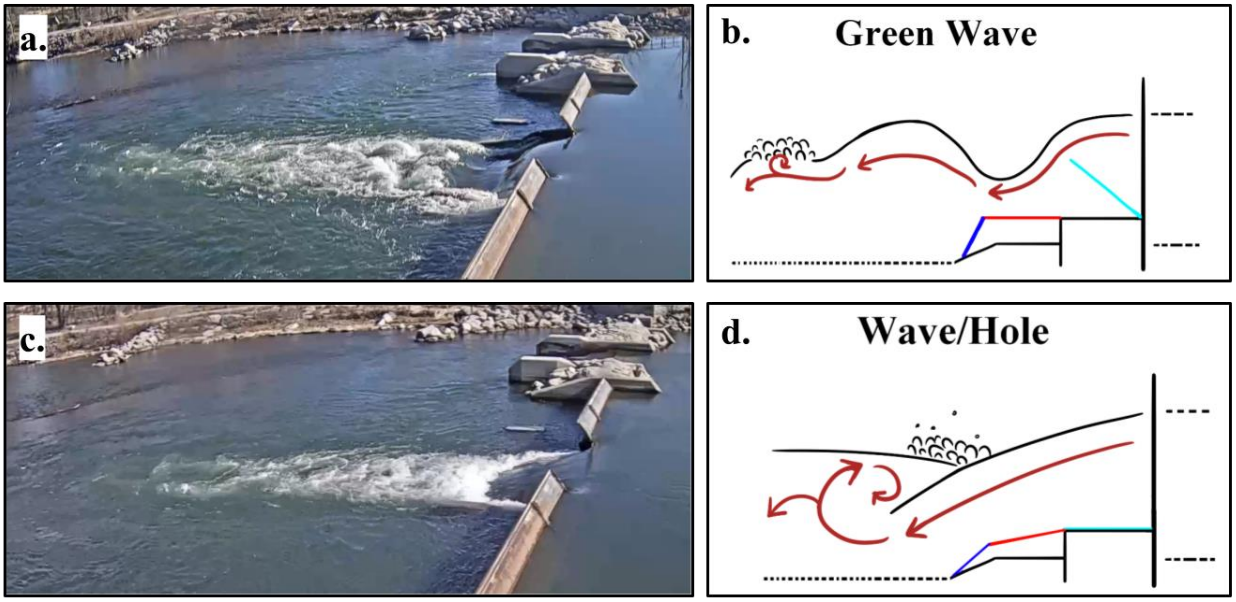

Figure 1: Images and cross-section drawings of Green Wave [A and B] and Wave/Hole [C and D] configurations.

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

2.2. Field Methods and Data Analysis

We installed instruments to monitor low-frequency sound (Anderson et al., 2016) along the left bank of the Boise River during the 2016, 2021, and 2022 flow seasons. Sensors were located ~46m downstream. During the 2022 flow season, photos were taken of the site through webcams provided by the park. Discharge data for all three years were retrieved from USGS gauge #13206000 (USGS, 2016) located 5.26 km downstream; discharge at this site was 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 (excluding flood conditions, which are not interpreted), discharge was not sufficient to transport sediment.

Maximizing signal fidelity is essential when studying low-power continuous signals, and we took various actions in the field and in analysis to achieve this. Sensors were concealed under leaves along a wooded section of the river bank, which protected sensors from noise due to 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 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 transients.

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.

3.1 Infrasound Over the 2021 and 2022 Flow Seasons

Figure 2 shows stream discharge, infrasound power, and infrasound frequency during 2021 and 2022. 2021 discharge ranges from ~10 to 50 m^3/s, while 2022 discharge rates range from ~10 to 80 m^3/s. In 2021, large peaks in infrasound power occur simultaneously with the year's highest discharges (~50-55 m^3/s). By contrast, in 2022, the highest values of infrasound power occur after the flow drops from a peak of 80 m^3/s to a plateau around 40 m^3/s. Outside of these high flow periods, changes in infrasound power (ranging from 2 to 4 * 10^{-4} Pa^2) do not coincide with changes in discharge or wave configuration; these fluctuations are likely noise.

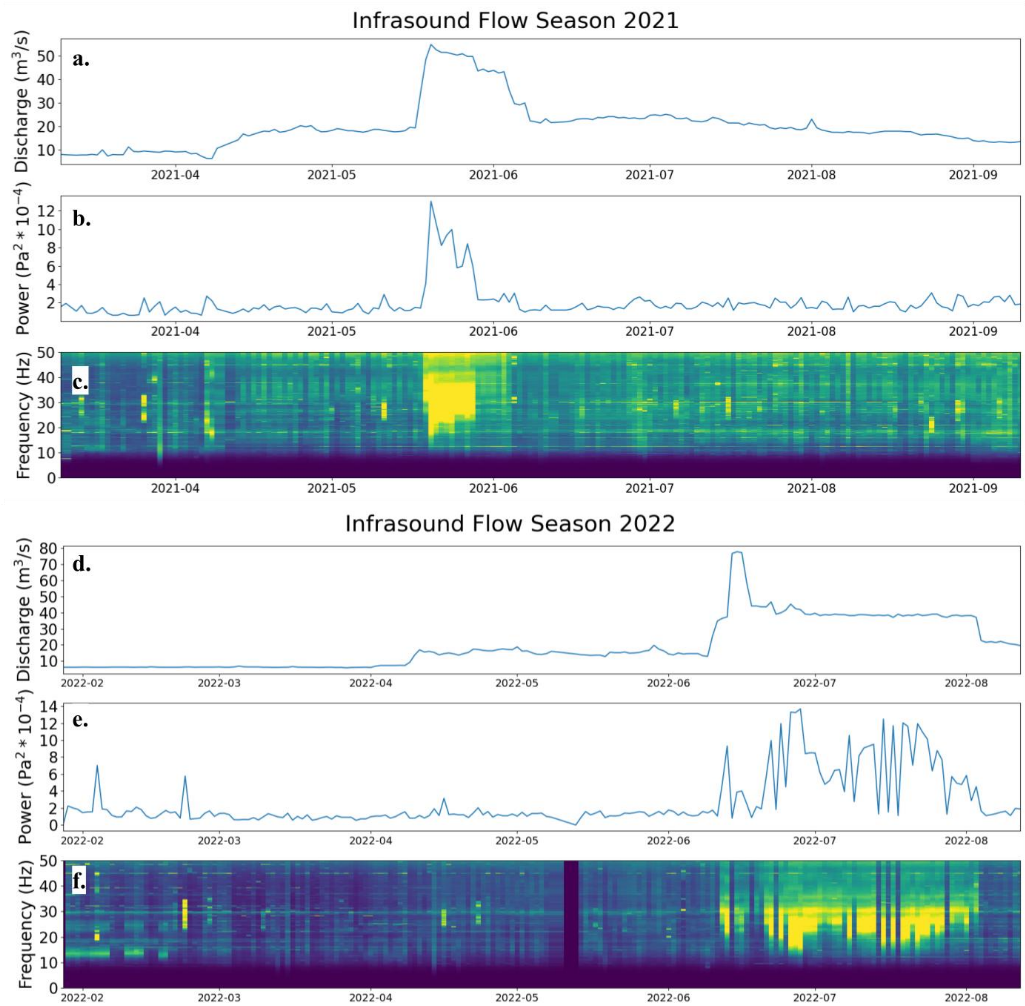

Figure 2. Discharge [A, D], Power [B, E], and Frequency [C, F] of stream and infrasound data recorded from March-September 2021 and January-August 2022. Periods of infrasound power in February and early March 2022 (February 18th through March 6th) are related to construction near the dam.

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

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 m^3/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 m^3/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 m^3/s (Fig. 4J-K). However, the opposite pattern was observed in 2022, where Green Waves displayed a higher acoustic power than Wave/Hole configurations. On the other hand, no dependence of acoustic power on wave configuration was observed during May 11-23, 2016 (when discharge varied from 45 to 80 m^3/s) (Fig. 3A-B) and in all 2021 data (with a maximum discharge of 55 m^3/s) (Fig. 3D-E).

Images taken throughout June and July 2022 also display a similar lack of dependence. 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 m^3/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 (~35-40 m^3/s).

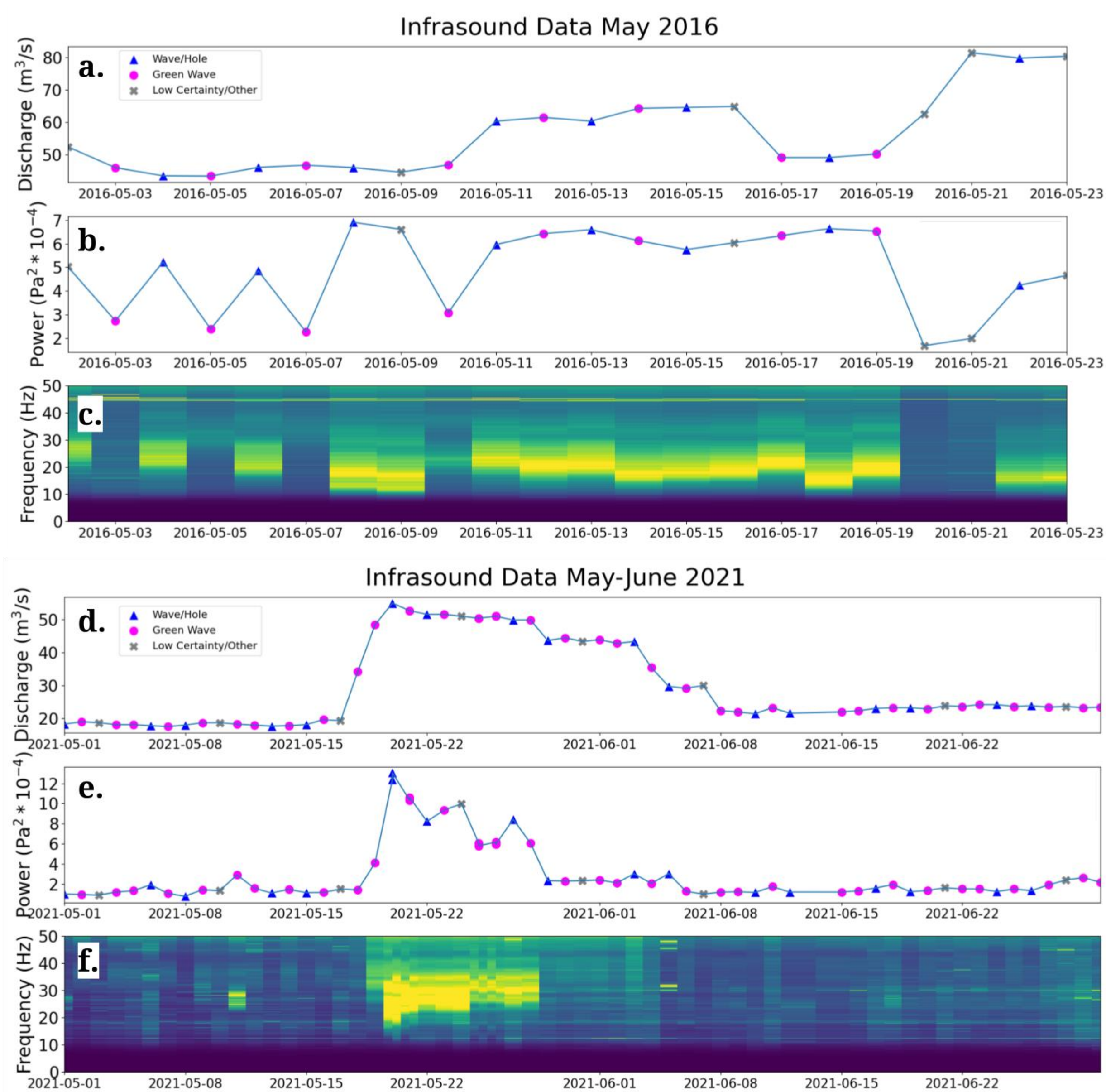

Figure 3. Discharge [A and D], Power [B and E], and Frequency [C and F] of stream and infrasound data recorded in June 2021 and May 2016.

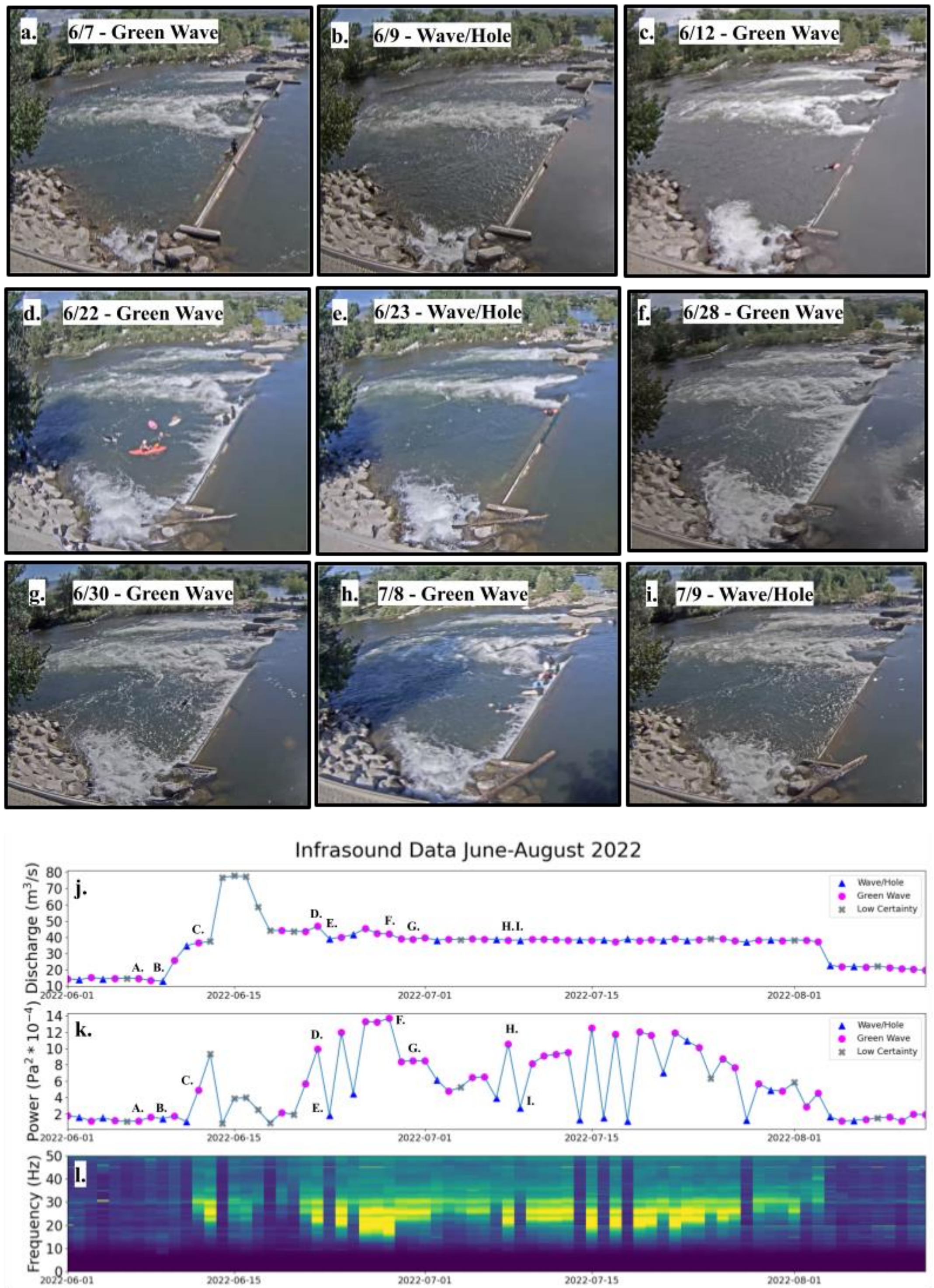

Figure 4. Images [A-I] and Discharge [J], Power [K], and Spectrogram [L] of stream and infrasound data during 2022. A-B shows Green Wave and Wave/Hole configurations occurring during a period of low discharge (~15 m^3/s), while C shows a Green Wave configuration occurring at a higher discharge (~35 m^3/s). D-E and H-I show medium sound power Green Wave configuration and low power Wave/Hole occurring at a similar discharge (~35-40 m^3/s), and F-G

show days where infrasound power decreases despite unchanging discharge and no visible change to wave configuration (~40 m^3/s).

4 Discussion

4.1. Dependence of Infrasound on Discharge

The observed sound-to-discharge relationship is nonlinear, non-monotone, and often affected by wave configuration. Significant infrasound power only occurs at discharge rates above 35 m^3/s; sound below this threshold is attributed to noise. Background noise can often be attributed to atmospheric turbulence and human activity–mainly heating, ventilation, and air conditioning from nearby buildings. We attribute spikes in infrasound frequency near 10 Hz to construction machinery working near the dam, and high power at a wide range of frequencies to stormy weather. These noise types are familiar in infrasound studies and not surprising to see at BWPP1.

The 35 m^3/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 ~35 m^3/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, Green Wave and Wave/Hole configurations at Boise Whitewater Park can change sound in a way that is predictable within a given year but not have characteristic sounds that persist over multiple years. This is shown during the first week of May 2016 (May 3rd to 10th) (Fig. 3A-B), 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 m^3/s (the threshold required for sound production) and 50 m^3/s (above which the normal dam configurations must be modified to ensure user safety). The unexpected reversal of the dependence of sound power on wave configuration between 2016 (in which Wave/Holes are louder), 2021 (in which the waves are indistinguishable), and 2022 (in which Green Waves are 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 changed incidentally by dam reconfiguration. Morphological differences in the dam and riverbed between 2016-2022, as well as changes in dam operator practices in how they adjust the dam to create appealing waves, may explain the year-to-year inconsistency.

When discharge reached levels of flood conditions (typically around ~60 m^3/s), BWPP1 widened the wave by opening more flashboards. Some flood configurations mimicked traits of 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 that for the highest periods of discharge within our study, the wave configuration was drastically altered from the usual schedule. Because of the inconsistency of these flood configurations, various acoustic effects may occur. Due to limited observations of high flow throughout the three years, we do not attempt to interpret higher flows.

4.3. The Origin of Whitewater Sounds and Future Work

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

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

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.

5 Conclusions

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

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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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