Open Space & Mountain Parks – City of Boulder

Acoustic monitoring report: 2022

ON THE COVER
Whiterocks001 Study Site, City of Boulder Photo

Open Space & Mountain Parks – City of Boulder

Acoustic monitoring report: 2021

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The National Park Service, Natural Resource Stewardship and Science office in Fort Collins, Colorado, publishes a range of reports that address natural resource topics. These reports are of interest and applicability to a broad audience in the National Park Service and others in natural resource management, including scientists, conservation and environmental constituencies, and the public.

The Natural Resource Technical Report Series is used to disseminate results of scientific studies in the physical, biological, and social sciences for both the advancement of science and the achievement of the National Park Service mission. The series provides contributors with a forum for displaying comprehensive data that are often deleted from journals because of page limitations.

All manuscripts in the series receive the appropriate level of peer review to ensure that the information is scientifically credible, technically accurate, appropriately written for the intended audience, and designed and published in a professional manner.

Data in this report were collected using methods based on established, peer-reviewed protocols and were analyzed and interpreted within the guidelines of the protocols.

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Executive Summary

This report presents the summary results of acoustical data gathered at two front country locations within the City of Boulder's Open Space & Mountain Parks system. Data were collected at these sites during the fall of 2021.

In this deployment, two Song Meter Mini recorders were placed in the field in September 2021. They were programmed to collect continuous acoustical data for one month. *It should be noted that recorders were programmed to record at a sampling rate of 24,000 Hz and with a high-pass filter turned on. Our typical analyses do not include high-pass filters and require a minimum sampling rate of 44,100 Hz. Because of this, reported dB values are approximately 3-10dB lower than what occurred at the sampling stations due to calculations including 0 dB values for the three lowest and three highest 1/3 octave bands.* Other equipment included a Hobo cup anemometer to collect wind speed and direction to be used to refine data analysis. In this document, "sound pressure level" refers to broadband (12.5 Hz - 20 kHz), A-weighted, 1-second time averaged sound level ($L_{Aeq, 1s}$), and hereafter referred to as "sound level." Sound levels are measured on a logarithmic scale relative to the reference sound pressure for atmospheric sources, 20 µPa. The logarithmic scale is a useful way to express the wide range of sound pressures perceived by the human ear. Sound levels are reported in decibels (dB). A-weighting is applied to sound levels to account for the response of the human ear (Harris, 1998). To approximate human hearing sensitivity, A-weighting discounts sounds below 1 kHz and above 6 kHz. For reference, Table 1 provides examples of sound levels measured in parks compared to sound levels of common sound sources.

Table 1. Sound level examples

Park Sound Sources	Common Sound Sources	Sound Level dB*
Volcano crater (HALE)	Human breathing at 3m	10
Leaves rustling (CANY)	Whispering	20
Crickets at 5m (ZION)	Residential area at night	40
Conversation at 5m (WHMI)	Busy restaurant	60
Cruiser motorcycle at 15m (BLRI)	Curbside of busy street	80
Thunder (ARCH)	Jackhammer at 2 m	100
Military jet at 100m AGL (YUCH)	Train horn at 1 m	120

* dB re 20 µPa A-weighted broadband (12.5 Hz—20 kHz), sound level measured over varied measurement durations and at the distances indicated.

Overall, measured existing ambient sound levels (L_{A50}; see glossary below for definitions of key terms) at site Aspen001 during the fall were 31.0 and 25.3 dB during the day and night respectively. At site Whiterocks001 during the fall, measured levels were 41.5 and 38.1 dB during the day and

night respectively. Table 2 reports the percent of time that measured levels at the monitoring locations were above four key sound level values. The first value, 35 dB ($L_{Aeq, 1s}$), addresses the health effects of sleep interruption. Recent studies suggest that sound events as low as 35 dB can have adverse effects on blood pressure in sleeping humans (Haralabidis et al. 2008). This level, 35 dB, is also the desired background sound level in classrooms (ANSI S12.60-2002). The second value addresses the World Health Organization's recommendations that noise levels inside bedrooms remain below 45 dB ($L_{Aeq, 1s}$) (Berglund et al. 1999). The third value, 52 dB ($L_{Aeq, 1s}$), is based on the EPA's speech interference level for speaking in a raised voice to an audience at 10 meters (EPA 1974). This value addresses the effects of sound on interpretive presentations in parks. The final value, 60 dB ($L_{Aeq, 1s}$), provides a basis for estimating speech interference on normal voice communications at 1 meter. Visitors viewing scenic areas in the park would likely be conducting such conversations.

Sound levels are often measured over narrow frequency bands (typically in one-third octave bands between 12.5 Hz - 20 kHz) because these smaller bands closely represent how humans distinguish between frequencies of sound. In this study, we examine how often sound levels exceeded key values in two frequency *ranges*. The top value in each split-cell of Table 2 uses the full frequency range (12.5 Hz - 20 kHz) collected, whereas the bottom value focuses on frequencies affected by low frequency noise sources (20-1,250 Hz). This Natural Sounds (NS) modification to A-weighting (referred to as ANS weighting, ANSI S3/SC1.100, 2014) eliminates high-frequency sound (leaf rustle, equipment noise, and biologic sounds) allowing for more accurate comparisons of low-frequency ambient sound levels across different land use types (e.g. urban, protected areas; ANSI S3/SC1.100, 2014). This frequency weighting scheme improves ambient sound level measurements in quiet environments. For instance, in the full frequency range, the 35 dB ($L_{Aeq, 1s}$) level was exceeded 9.2 % of the time during the day during the fall at Aspen001 and 1.4 % of the time at night, but in the 20-1,250 Hz range, the 35 dB functional sound level value was exceeded 37.5 % of the time during the day and 6.8 % of the time at night, indicating the contribution of low frequency noise sources. Speech interruption occurs (between two people 1 meter apart) at 60 dB ($L_{Aeq, 1s}$) and this level never exceeded 1 % except at Whiterocks001, where it was exceeded 1.3 % of the time when examining values within the 20-1,250 Hz range. As is noted in Table 2 below, these values would most likely be greater if filters were not mistakenly engaged on the acoustic recording devices.

Table 2. Time above metrics for the acoustical monitoring sites at Aspen001 and Whiterocks001 during the fall of 2021. Note that values in the 20-1,250 range are larger than the 12.5-20,000 range because the recordings units had a high-pass filter engaged and the sampling rate was set below the necessary minimum value of 44,100 Hz. Overall % time above levels reported here are lower than they would be due to these recorder settings.

Site ID	Frequency (Hz)	Time above sound level (% of daytime hours, 07:00 to 19:00)				Time above sound level (% of nighttime hours, 19:00 to 07:00)			
		35 dB*	45 dB*	52 dB*	60 dB*	35 dB*	45 dB*	52 dB*	60 dB*
Aspen001	12.5-20,000	9.2	0.4	0.0	0.0	1.4	0.1	0.0	0.0
	20-1,250	37.5	9.4	2.6	0.3	6.8	2.7	0.8	0.1
Whiterocks001	12.5-20,000	23.2	1.7	0.3	0.0	1.8	0.1	0.0	0.0
	20-1,250	95.0	34.2	9.9	1.3	81.4	7.9	0.7	0.1

* dB $L_{Aeq,\ 1s}$ re 20 µPa

After data collection was complete, a trained technician calculated how often noise[1] sources were audible. See Methods section for protocol details, equipment specifications, and metrics calculations. Sound source analysis revealed that noise is audible about between 49.9 and 97.9 % of the time across study sites when averaged across a 24 hour period (Table 3). The most common sources of noise during the study period were aircraft such as jets and propeller planes, and vehicles. Natural sources such as wind, rain, thunder, birds, and insects were also commonly audible. Natural ambient sound levels (L_{Anat}) during the fall ranged from 21.6 dB during the day and 9.8 dB at night at Aspen001 and 24.9 dB during the day and 21.5 dB at night at Whiterocks001.

Table 3. Mean time audible for human-caused noise, propeller planes, and commercial jets, existing and natural ambient sound levels (dB re 20 µPa, A-weighted broadband,12.5 Hz—20 kHz) at Aspen001 and Whiterocks001 during the fall (where day is 7:00 – 19:00 and night is 19:00 – 7:00).

Site ID	Season	Mean time audible for noise (% of 24 hour time period)			Median Existing Ambient (L_{A50}) in dB		Median Natural Ambient (L_{Anat}) in dB	
		All Noise	Prop Planes	Commercial Jets	Day	Night	Day	Night
Aspen001	Fall	49.9	6.9	23.6	25.2	10.4	21.6	9.8
Whiterocks001	Fall	97.9	27.4	9.5	31.0	25.3	24.9	21.5

[1]For the purposes of this document, we will refer to “noise” as any human-caused sound that masks or degrades natural sounds

Acknowledgments

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Glossary of Acoustic Terms

Term	Definition
A-weighting	A-weighting is applied to sound levels in order to account for the sensitivity of the human ear (Harris, 1998). To approximate human hearing sensitivity, A-weighting discounts sounds below 1 kHz and above 6 kHz.
Acoustic Environment	A combination of all the physical sound resources within a given area. This includes natural sounds and cultural sounds, and non-natural human-caused sounds. The acoustic environment of a park can be divided into two main categories: intrinsic and extrinsic.
Acoustic Resources	Includes both natural sounds like wind, water, & wildlife and cultural and historic sounds like tribal ceremonies, quiet reverence, and battle reenactments.
Amplitude	The relative strength of a sound wave, described in decibels (dB). Amplitude is related to what we commonly call loudness or volume.
ANS Weighting	The Natural Sounds (NS) modification to A-weighting eliminates high-frequency sound (leaf rustle, equipment noise, and biologic sounds) allowing for more accurate comparisons of low-frequency ambient sound levels across different land use types (e.g. urban, protected areas; ANSI S3/SC1.100, 2014). This frequency weighting scheme improves ambient sound level measurements in quiet environments.
Audibility	The ability of animals with normal hearing, including humans, to hear a given sound. It can vary depending upon the frequency content and amplitude of sound and by hearing ability of individual animals.
Decibel (dB)	A unit of sound energy. Sound levels are measured on a logarithmic scale relative to the reference sound pressure for atmospheric sources, 20 μPa. The logarithmic scale is a useful way to express the wide range of sound pressures perceived by the human ear. Sound levels are reported as decibels (dB). Every 10 dB increase represents a tenfold increase in energy. Therefore, a 20 dB increase represents a hundredfold increase in energy.
Existing ambient sound level (L_{A50})	sound level ($L_{Aeq, 1s}$) exceeded 50% of the time (50^{th} percentile) for a specified duration. This level is referred to as the existing ambient sound level and the preferred metric for chronic conditions, as it is insensitive to infrequent loud events.
Frequency	Related to the pitch of a sound, and defined as the number of times per second that the wave of sound repeats itself and is expressed in terms of hertz (Hz). Sound levels are often adjusted ("weighted") to match the hearing abilities of a given animal. In other words, different species of animals and humans are capable or hearing (or not hearing) at different frequencies. Humans with normal hearing can hear sounds between 20 Hz and 20,000 Hz, and as low as 0 dB at 1,000 Hz. Bats, on the other hand, can hear sounds between 20 Hz and 200,000 Hz.
Percentile sound levels (L_{A10}, L_{A50}, L_{A90})	Metrics used to describe A-weighted sound pressure levels (L), in decibels, exceeded 10, 50, and 90 percent of the time, respectively. Put another way, half the time the measured levels of sound are greater than the L_{A50} value, while 90 percent of the time the measured levels are higher than the L_{A90} value, and 10 percent of the time measured levels are higher than the L_{A10} value.

Day-Night average sound levels (L_{dn})	Day-Night Average Sound Level. Average equivalent sound level over a 24-hour period, with a 10-dB penalty added for sound levels between 10 p.m. and 7 a.m.
Energy Equivalent Sound Level (L_{Aeq})	The sound energy level averaged over the measurement period. Generally, refers to A-weighted 1-second time averaged sound levels measured between 12.5 Hz - 20 kHz. This is a standard measurement collected using NSNSD acoustic monitoring protocol for sound level meters. Sound levels measured over 1 second intervals are used to calculate summary statistics, specifically percent of the time a sound level of interest is exceeded.
Natural Ambient Sound Level (L_{Anat})	The natural sound conditions in parks, which would exist in the absence of any human-caused noise sources. L_{Anat} is the preferred metric to represent baseline or reference conditions.
Noise Free Interval (NFI)	The length of the continuous period of time during which no human-caused sounds are audible.
Time Above	Within a defined time period, the percent of the time sound levels ($L_{Aeq, 1s}$) are above a specified sound level ($L_{Aeq, 1s}$). Commonly used levels are 35, 45, 52 dB ($L_{Aeq, 1s}$).
Time Audible	The amount of time that various sound sources are audible to humans with normal hearing, commonly expressed in percent of day, or percent of daytime hours and nighttime hours. A sound may be above natural ambient sound pressure levels, but still not audible. Similarly, some sounds that are below the natural ambient can be audible. Time Audible is useful because of its simplicity. It is a measure that correlates well with visitor complaints of excessive noise and annoyance. Most noise sources are audible to humans at lower levels than virtually all wildlife species. Therefore, time audible is a protective proxy for wildlife. These data can be collected either by a trained observer (on-site listening) or by making high-quality digital recordings for later playback (off-site listening).
Sound Exposure Level (SEL)	The total sound energy of the actual sound during a specific time period. SEL is usually expressed using a time period of one second.
Sound Pressure	Minute change in atmospheric pressure due to passage of sound that can be detected by microphones.
Sound vs. Noise	Sound and noise are often used interchangeably to describe an acoustic source. A common definition of noise is unwanted sound or sounds that interfere with a signal of interest (Harris 1998; Templeton 1997). However, noise is not a purely subjective designation. Any sound that serves no function is noise. Most sounds produced by human transportation and other machinery are unintended and serve no function, therefore are noise regardless of the attitudes of the listener. While there are unintended sounds in nature, like the footfalls of an animal, these sounds provide vital cues for some receivers and are therefore considered sounds to the receiver, yet noise from the perception of the producer.
Soundscape	The human perception of physical sound resources.

Introduction

A 1998 survey of the American public revealed that 72 percent of respondents thought that providing opportunities to experience natural quiet and the sounds of nature was a very important reason for having national parks, while another 23 percent thought that it was somewhat important (Haas & Wakefield 1998). In another survey specific to park visitors, 91 percent of respondents considered enjoyment of natural quiet and the sounds of nature as compelling reasons for visiting national parks (McDonald et al. 1995). Acoustical monitoring provides a scientific basis for assessing the status of acoustic resources, identifying trends in resource conditions, quantifying impacts from other actions, assessing consistency with park management objectives and standards, and informing management decisions regarding desired future conditions.

National Park Service Natural Sounds and Night Skies Division

The Natural Sounds and Night Skies Division (NSNSD) helps parks manage sounds and soundscapes in a way that protects park resources and the visitor experience. The NSNSD addresses acoustical issues raised by Congress, NPS Management Policies, and NPS Director's Orders. The NSNSD works to protect, maintain, or restore acoustical environments throughout the National Park System. Its goal is to provide coordination, guidance, and a consistent approach to soundscape protection with respect to park resources and visitor use. The program also provides technical assistance to parks in the form of acoustical monitoring, data processing, park planning support, and comparative analyses of acoustical environments.

Soundscape Planning Authorities

The National Park Service Organic Act of 1916 states that the purpose of national parks is "… to conserve the scenery and the natural and historic objects and the wildlife therein and to provide for the enjoyment of the same in such manner and by such means as will leave them unimpaired for the enjoyment of future generations." In addition to the NPS Organic Act, the Redwoods Act of 1978 affirmed that, "the protection, management, and administration of these areas shall be conducted in light of the high value and integrity of the National Park System and shall not be exercised in derogation of the values and purposes for which these various areas have been established, except as may have been or shall be directly and specifically provided by Congress."

Direction for management of natural soundscapes2 is represented in 2006 Management Policy 4.9:

The Service will restore to the natural condition wherever possible those park soundscapes that have become degraded by unnatural sounds (noise), and will protect natural soundscapes from unacceptable impacts. Using appropriate management planning, superintendents will identify what levels and types of unnatural sound constitute acceptable impacts on park natural soundscapes. The frequencies, magnitudes, and durations of acceptable levels of unnatural sound will vary throughout a

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[2] The 2006 Management Policy 4.9 and related documents refer to "soundscapes" instead of "acoustic resources." When quoting from this authority, it is advisable to note that the term often refers to resources rather than visitor perceptions.

park, being generally greater in developed areas. In and adjacent to parks, the Service will monitor human activities that generate noise that adversely affects park soundscapes [acoustic resources], including noise caused by mechanical or electronic devices. The Service will take action to prevent or minimize all noise that through frequency, magnitude, or duration adversely affects the natural soundscape [acoustic resource] or other park resources or values, or that exceeds levels that have been identified through monitoring as being acceptable to or appropriate for visitor uses at the sites being monitored (NPS 2006a).

It should be noted that "the natural ambient sound level—that is, the environment of sound that exists in the absence of human-caused noise—is the baseline condition, and the standard against which current conditions in a soundscape [acoustic resource] will be measured and evaluated" (NPS 2006b). However, the desired acoustical condition may also depend upon the resources and the values of the park. For instance, "culturally appropriate sounds are important elements of the national park experience in many parks" (NPS 2006b). In this case, "the Service will preserve soundscape resources and values of the parks to the greatest extent possible to protect opportunities for appropriate transmission of cultural and historic sounds that are fundamental components of the purposes and values for which the parks were established" (NPS 2006b).

Further guidance is provided in 2006 Management Policies 4.1.4 Partnerships, 4.1.5 Restoration of Natural Systems, 8.2 Visitor Use, 8.2.2 Recreational Activities, 8.2.3 Use of Motorized Equipment, and 8.4 Overflights and Aviation Uses (NPS 2006).

Directors Order 47, Preservation of the Acoustic Environment and Noise Management (2015) builds on the principles set out in Management Policies, but goes on to direct how and when to consider acoustic resources in park management. Through this order, parks are guided to manage noise by: identifying noise sources, minimizing noise from park operations, considering the acoustic environment in park planning documents, and promoting park sounds and noise management through communication, education, and outreach.

National Parks Air Tour Management Act (NPATMA) was passed on April 5, 2000 to regulate commercial air tour operations for each unit of the National Park System, or abutting tribal land, where such operations occur or are proposed. The Act required the Federal Aviation Administration (FAA), in cooperation with the NPS, to develop an Air Tour Management Plan (ATMP) for each unit of the National Park System to provide acceptable and effective measures to mitigate or prevent the significant adverse impacts, if any, of commercial air tour operations upon natural and cultural resources and visitor experiences. In 2012, NPATMA was amended to allow the FAA and NPS to enter into voluntary agreements with a commercial air tour operator as an alternative to an ATMP.

Study Area

This report covers results from an acoustic inventory conducted in 2021 at Aspen001 and Whiterocks001. These sites are front country sites and City of Boulder Open Space & Mountain Parks is interested in the acoustical condition of the soundscape at these sites, especially the impact of overflights, but also other sources of noise. Figure 1 shows the location of acoustic inventory sites in map format.

Table 4. Metadata for each season of acoustical monitoring.

Site	Site Name	Dates Deployed	Vegetation	Elevation (m)	Latitude	Longitude
Aspen001 Fall	Aspen	9/15/2021-10/16/2021	Ponderosa Pine Forest	2135	39.96216	-105.31527
Whiterocks001 Fall	Whiterocks	9/15/2021-10/16/2021	Riparian and Grassland	1564	40.05102	-105.16842

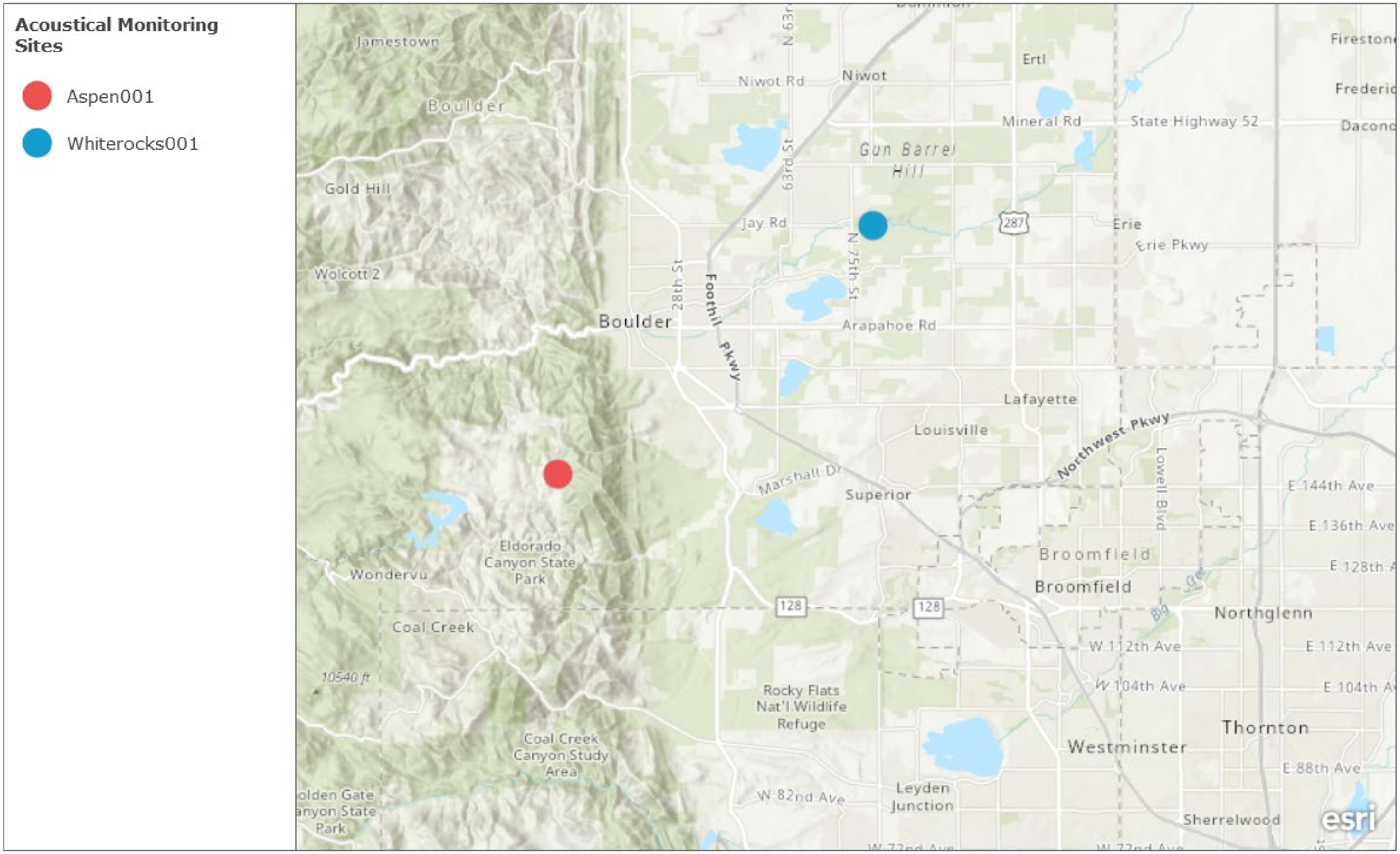

Figure 1. Location of monitoring sites Aspen001 and Whiterocks001.

Methods

Automatic Monitoring

A Wildlife Acoustics Song Meter Mini was deployed at the monitoring sites. These units were attached to metal/wooden poles placed at least 1m above ground level and recorded continuous audio from the deployment date to retrieval date. *It should be noted that recorders were programmed to record at a sampling rate of 24,000 Hz and with a high-pass filter turned on. Our typical analyses do not include high-pass filters and require a minimum sampling rate of 44,100 Hz. Because of this, reported dB values are approximately 3-10dB lower than what occurred at the sampling stations due to calculations including 0 dB values for the three lowest and three highest 1/3 octave bands.* After recordings were collected, audio files were converted to text files with sound pressure levels measured every 1s for each of the 33 1/3 octave bands. This was done using custom script written in R statistical computing software.

Hobo cup anemometers were deployed at least 0.5m above the recording units and gathered continuous wind speed and direction data to be used during analysis.

The sampling stations consisted of:

- Song Meter Mini acoustical recorder
- Hobo Cup Anemometer

The sampling stations collected:

- Continuous digital audio recordings
- Continuous meteorological data for wind speed and direction

Monitoring Period

The monitoring period lasted approximately 31 days at Aspen001 and 31 days at Whiterocks001. NSNSD has determined that a 25 day monitoring period during a season allows the data to capture seasonal differences that occur at each site within a reasonable margin of error (NPS 2005).

Calculation of Metrics

The status of the acoustical environment can be characterized by sound level (L_{A50}, L_{Anat}, L_{A90}, L_{A10}, L_{Aeq}) and frequency content, and event durations (through off-site listening). NPS uses descriptive figures and metrics to interpret these characteristics.

Two fundamental descriptors are existing ambient (L_{A50}) and natural ambient (L_{Anat}) sound levels. These are both examples of percentile levels, where each L_x value refers to the sound level that is exceeded x% of the time. The L_{A50} represents the median sound level, and is drawn from a full dataset (removing data with wind speed > 5m/s to eliminate error from microphone distortion). The L_{A50} is the preferred metric to represent prevailing acoustic conditions. The natural ambient (L_{Anat}) is an estimate of what the sound levels for a site would be if all human-caused noise sources were removed. L_{Anat} is the preferred metric to represent baseline or reference conditions.

For a given hour (or other specified time period), L_{Anat} is calculated to be the sound level exceeded x percent of the time, where x is defined by equation (1):

$$x = \frac{100 - P_H}{2} + P_H, \qquad (1)$$

P_H is the percentage of samples containing noise for the hour. For example, if human caused sounds are present 30 % of the hour, x = 65, and the L_{Anat} is equal to the L_{65}, or the level exceeded 65 % of the time. To summarize and display these data, the median of the hourly L_{Anat} values for the daytime hours (0700-1900) and the median of the hourly L_{Anat} values for the nighttime (1900-0700) are displayed in Figures 2-5 in the results section.

Off-Site Listening

Off-site listening is normally done by listening to an audio recording and simultaneously visually analyzing a spectrogram. Auditory analysis was used to calculate the audibility of sound sources at the monitoring locations. Trained technicians at the Colorado State University Listening Lab listened to a subset of .mp3 audio samples (10 seconds every two minutes from eight days of audio) to identify durations of audible sound sources. The total percent time noise was audible was then used to calculate the natural ambient sound level (L_{Anat}) for each hour (see Equation 1 above for more information). Bose Quiet Comfort Noise Canceling headphones were used for off-site audio playback to minimize limitations imposed by the office acoustical environment. For the complete results of this thorough audibility analysis, see Tables 6-7.

Results

Frequency content

To determine the effect that noise has on the acoustical environment, it is useful to examine percentile metrics across a frequency range. High frequency sounds (such as a cricket chirping) and low frequency sounds (such as flowing water) often occur simultaneously, so the frequency spectrum is split into 33 smaller ranges, each encompassing one-third of an octave. These smaller bands closely represent how humans distinguish between frequencies of sound. For each one-third octave band, sound level ($L_{eq,\ 1s}$) was recorded once per second for the duration of the monitoring periods. The percentile sound levels for 33 one-third octave band frequencies over the day and night periods are shown in Figures 2-5.

Examining the sound energy in each one-third octave band (combined with digital audio recordings) allows acoustic technicians to determine what types of sounds are contributing to the overall sound levels at a site. The grayed area of Figures 2-3 represents sound levels outside of the typical range of human hearing. The percentile levels (L_x) are also shown for each one-third octave band. They represent the sound levels exceeded x percent of the measurement period. For example, L_{90} is the sound level that has been exceeded 90% of the time, and only the quietest 10% of the samples can be found below this point. On the other hand, the L_{10} is the sound level that has been exceeded 10% of the time, and 90% of the measurements are quieter than the L_{10}. The bold portion of the column represents the difference between L_{50} and L_{nat}. The height of this bold portion is a measure of the contribution of anthropogenic noise to the existing sound levels at this site. The size of this portion of the column is directly related to the percent time that human caused sounds are audible. When bold portions of the column do not appear the natural and existing sound levels were either very close to each other, or were equal. The typical frequency levels for transportation, conversation, and songbirds are presented on the figure as examples for interpretation of the data. These ranges are estimates and are not vehicle-, species-, or habitat-specific.

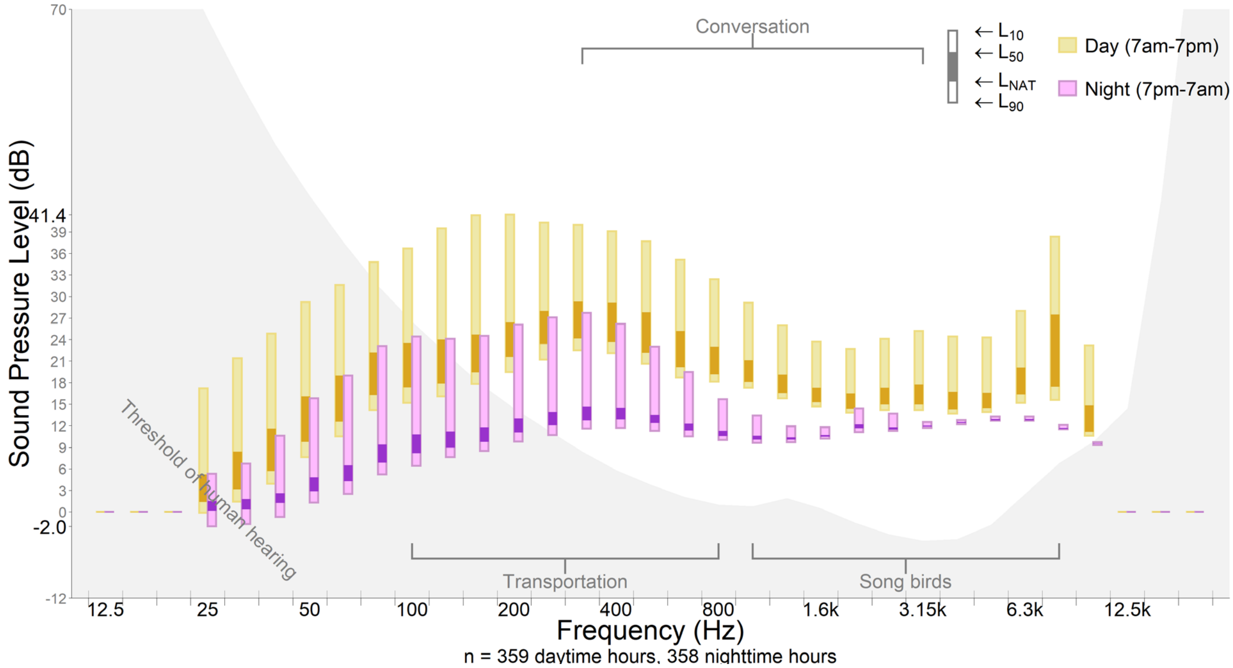

Figure 2. Day and night percentile sound pressure levels for 33 one-third octave bands at Aspen001 during the fall. The highest and lowest 1/3 octave bands have no data due to a high-pass filter and a sampling rate set below the minimum frequency of 44,100 Hz. These are depicted with dashed horizontal lines in graph above. Note the brackets indicating the typical frequencies containing sounds associated with transportation and biological sounds like songbirds, and the shaded area which depicts areas outside the threshold of human hearing.

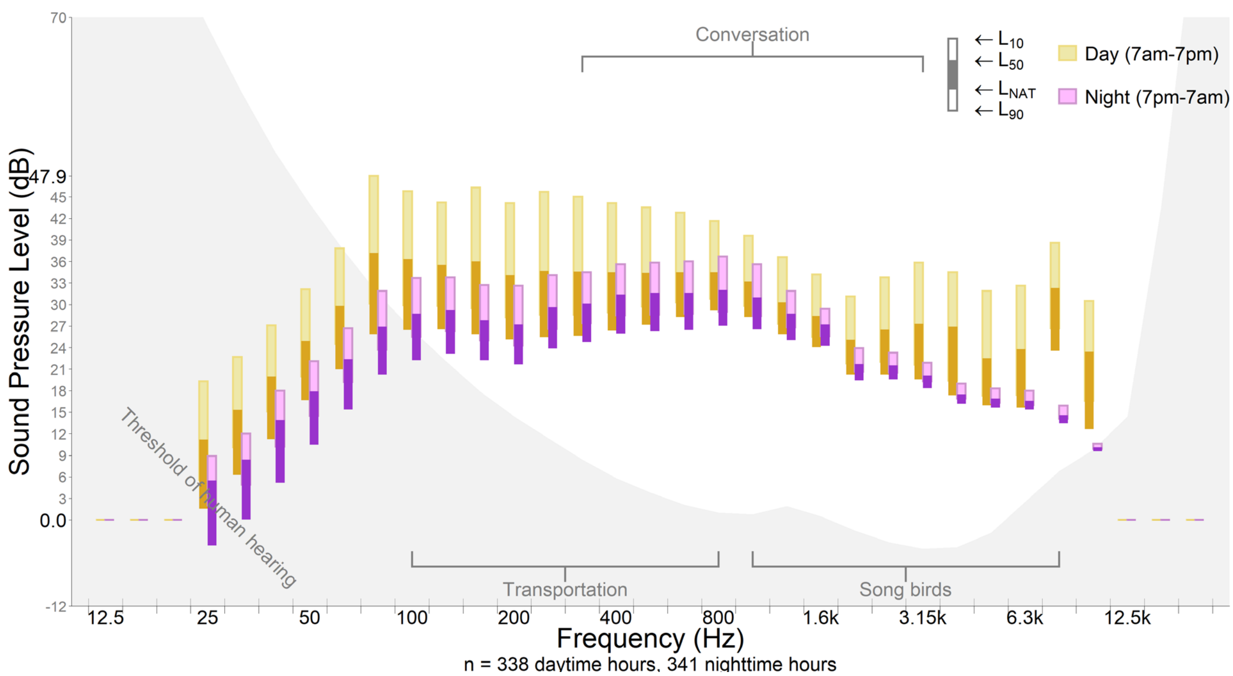

Figure 3. Day and night percentile sound pressure levels for 33 one-third octave bands at Whiterocks001 during the fall. The highest and lowest 1/3 octave bands have no data due to a high-pass filter and a sampling rate set below the minimum frequency of 44,100 Hz. These are depicted with dashed horizontal lines in graph above. Note the brackets indicating the typical frequencies containing sounds associated with transportation and biological sounds like songbirds, and the shaded area which depicts areas outside the threshold of human hearing.

Sound level: Time Above

To understand how acoustic conditions in the park might affect visitors, measured sound levels are compared to established sound levels. Specifically, Table 5 reports the percent of time that measured sound levels ($L_{Aeq,1s}$) were above four key functional values during the monitoring periods (daytime and nighttime). The top value in each split-cell uses the full frequency range, whereas the bottom values report the percent of time ANS-weighted sound levels (20-1,250 Hz) are above functional values. Most motorized human-caused noise is confined to the truncated, lower-frequency range, while many natural sounds, including insects and birds, are higher in pitch. ANS weighting eliminates high-frequency sound (leaf rustle, equipment noise, and biologic sounds) allowing for more accurate comparisons of low-frequency ambient sound levels across different land use types (e.g. urban, protected areas; ANSI S3/SC1.100, 2014). This frequency weighting scheme improves ambient sound level measurements in quiet environments.

The first functional value in Table 5 is 35 dB ($L_{Aeq,1s}$), which is designed to address the health effects of sleep interruption. Studies suggest that sound events as low as 35 dB can have adverse effects on blood pressure in sleeping humans (Haralabidis et al. 2008). This is also the desired background sound level in classrooms (ANSI S12.60-2002). The second sound level value, 45 dB ($L_{Aeq,1s}$), addresses the World Health Organization's recommendations that noise levels inside bedrooms remain below 45 dB ($L_{Aeq,1s}$) (Berglund et al. 1999). The third sound level value, 52 dB ($L_{Aeq,1s}$), is based on the EPA's speech interference threshold for speaking in a raised voice to an audience at 10 meters (EPA 1974). This threshold addresses the effects of sound on interpretive presentations in parks. The final value, 60 dB ($L_{Aeq,1s}$), provides a basis for estimating impacts on normal voice communications at 1 meter. Visitors viewing scenic areas in the park would likely be conducting such conversations.

Table 5. Time above metrics for the two monitoring sites during the fall of 2021. Note that values in the 20-1,250 range are larger than the 12.5-20,000 range because the recordings units had a high-pass filter engaged and the sampling rate was below the minimum frequency of 44,100 Hz. Overall % time above levels are lower than they actually are due to these recorder settings.

Site ID	Frequency (Hz)	Time above sound level (% of daytime hours, 07:00 to 19:00)				Time above sound level (% of nighttime hours, 19:00 to 07:00)			
		35 dB*	**45 dB***	**52 dB***	**60 dB***	**35 dB***	**45 dB***	**52 dB***	**60 dB***
Aspen001	12.5-20,000	9.2	0.4	0.0	0.0	1.4	0.1	0.0	0.0
	20-1,250	37.5	9.4	2.5	0.3	6.8	2.7	0.8	0.0
Whiterocks001	12.5-20,000	23.2	1.7	0.3	0.0	1.8	0.1	0.0	0.0

Site ID	Frequency (Hz)	Time above sound level (% of daytime hours, 07:00 to 19:00)				Time above sound level (% of nighttime hours, 19:00 to 07:00)			
		35 dB*	45 dB*	52 dB*	60 dB*	35 dB*	45 dB*	52 dB*	60 dB*
	20-1,250	95.0	34.2	9.9	1.3	81.4	7.9	0.7	0.1

* dB $L_{Aeq, 1s}$ re 20 μPa

Sound Level: Percentile Levels

To understand the range of acoustic conditions at the park, percentile sound levels are reported (Figures 4-5). In these figures, the A-weighted percentile sound levels (L_{A90}, L_{Anat}, L_{A50}, and L_{A10}) for Aspen001 and Whiterocks001 are shown across the seasons. The hourly percentile sound levels are calculated from the broadband (12.5 Hz - 20 kHz) A-weighted, 1-second time averaged sound levels ($L_{Aeq, 1s}$) within each hour of the day. For instance, in Figure 4, the L_{A50} (median) sound level for Aspen001 during the 10:00 hour is ~31.0 dB. On the other hand, the sound level exceeded 10% of the time (L_{A10}) for the same hour at this site is ~37.0 dB, meaning 90% of the measurement period is quieter. In other words, 90% of the measurements are quieter. Hours where the L_{A50} and the L_{Anat} differ the most are usually hours where humans are most active and thus have the most human-caused noise (in this case, typically 6:00 – 20:00).

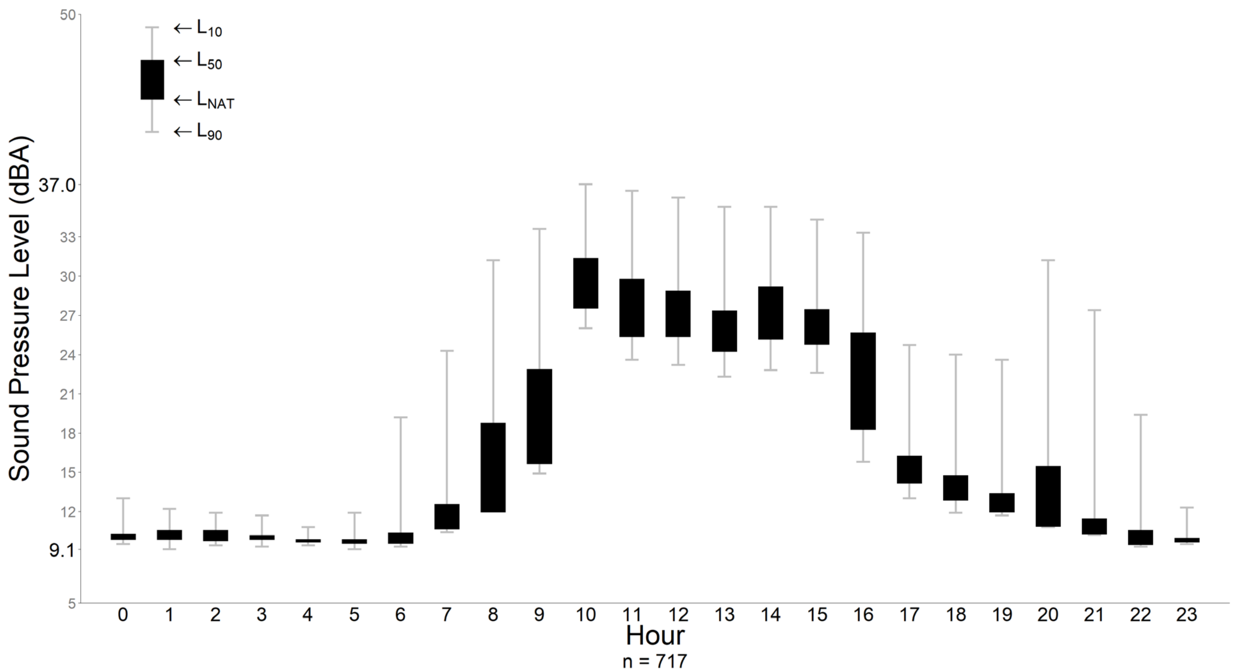

Figure 4. Median percentile sound levels ($L_{Aeq,\ 1s}$), in dB re 20 μPa (Standard sound pressure reference level), at Aspen001 during the fall.

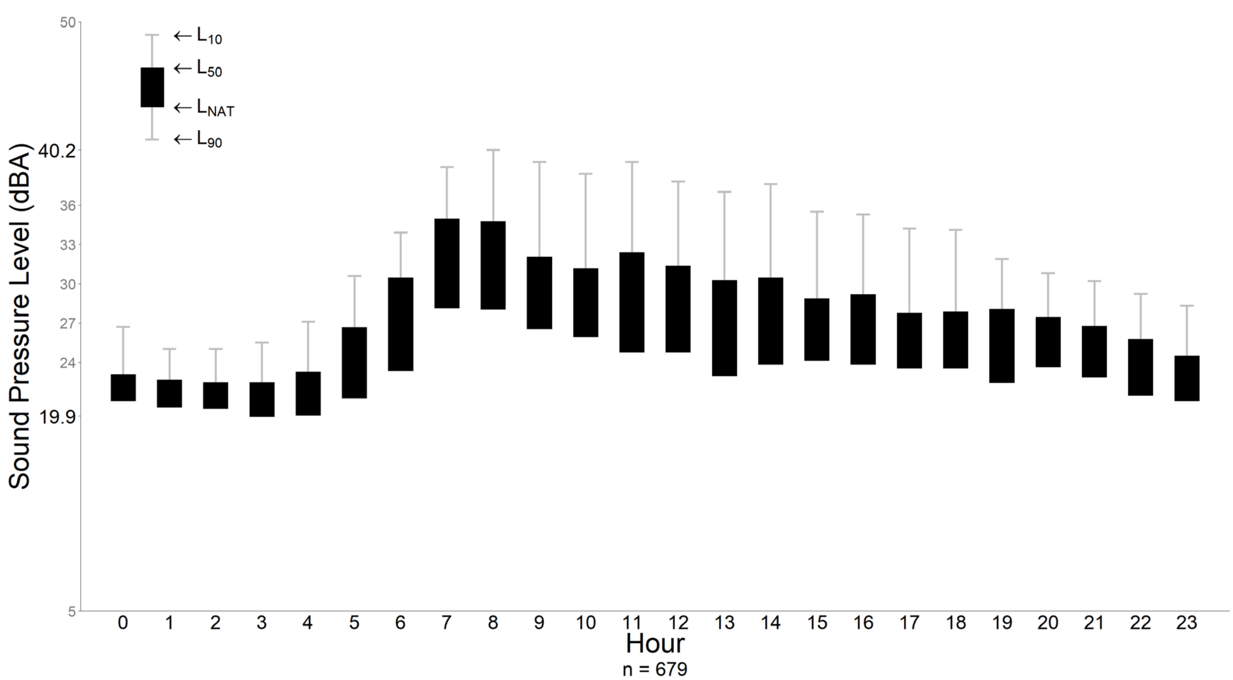

Figure 5. Median percentile sound levels ($L_{Aeq,\ 1s}$), in dB re 20 μPa (Standard sound pressure reference level), at Whiterocks001 during the fall.

Event duration

Through off-site listening analysis, event duration for all audible sounds is calculated. Tables 6-7 list audible natural sounds and noise sources at Aspen001 and Whiterocks001 during the fall. Mean hourly audibility was calculated over eight days of analysis. See Appendix A for more information on analysis procedures. Figures 6-7 display hourly audibility for all non-natural sources, as compared to audibility of two specific noise sources of interest: commercial jets and propeller planes.

Table 6. Mean hourly time audible (%) for each sound source at Aspen001 during the fall, n=8 days. Noise sources are highlighted in gray.

Sound Source	00h	01h	02h	03h	04h	05h	06h	07h	08h	09h	10h	11h	12h	13h	14h	15h	16h	17h	18h	19h	20h	21h	22h	23h
Aircraft	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.3	0.3	0.3	0.0	0.0	0.3	0.3	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
Jet	3.7	4.7	4.3	3.0	8.0	2.7	21.3	20.7	41.7	33.7	30.0	26.7	37.0	21.3	29.3	15.0	37.3	28.0	35.0	44.7	47.3	43.7	36.0	13.7
Prop Plane	1.7	1.3	0.0	1.0	1.3	0.3	1.3	20.7	11.0	20.7	11.3	14.3	8.0	13.7	12.3	13.3	9.7	9.3	8.7	4.0	2.7	0.3	0.7	1.7
Helicopter	0.0	0.0	0.0	0.0	0.0	0.0	0.0	2.0	10.3	9.7	11.3	8.0	7.0	4.3	5.0	11.3	6.3	2.0	1.3	0.3	0.0	0.7	0.0	0.0
Vehicle	3.3	2.7	1.0	1.7	0.0	3.3	5.3	1.7	0.3	1.3	0.7	0.3	1.0	0.0	1.7	1.3	0.7	0.3	1.7	0.7	0.3	1.0	1.0	5.3
Automobile	1.7	2.0	0.7	1.3	0.7	5.3	3.0	3.0	0.3	1.0	0.0	0.3	0.0	1.0	0.0	0.0	0.0	0.3	3.3	2.3	2.0	1.3	2.7	5.0
Train Rumble	3.7	2.7	10.7	8.7	3.3	1.0	7.7	7.0	14.3	2.0	5.7	2.3	1.0	2.0	0.0	7.0	0.3	0.3	0.7	8.0	11.0	5.7	11.3	9.7
Train Whistle	1.0	0.0	1.0	0.0	0.0	0.0	0.0	0.3	1.3	1.7	1.3	0.3	0.0	0.3	0.0	0.0	0.0	0.0	0.0	1.0	0.7	1.0	0.0	0.7
Grounds Care	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.3	0.0	1.7	1.0	2.0	1.0	2.3	0.0	0.3	0.0	0.0	0.0	0.0	0.0	0.0
Voices	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.7	0.0	0.7	0.3	1.3	0.0	0.0	0.7	1.3	0.0	0.0	0.0	1.7	0.0	0.3	0.0	0.0
Dog	0.0	0.3	0.0	0.0	0.0	0.3	0.3	0.7	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.3	0.7	0.7	0.0	0.0	0.0	0.0	0.0
Construction	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.3	0.0	0.0	0.3	0.0	0.0	0.3	0.0	0.0	0.0	0.0	0.0	0.0	0.0
Non-natural Other	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	1.7	3.0	0.0	0.0	0.0	0.0
Non-natural Unkwn.	15.0	6.7	6.7	6.3	6.3	7.0	8.3	5.0	8.3	6.7	9.7	9.3	3.7	7.0	7.0	7.7	4.3	9.0	6.7	5.0	7.0	7.7	7.7	10.0
Wind	5.0	5.3	5.3	3.3	4.0	4.7	3.0	3.3	2.0	13.7	25.0	36.7	41.7	41.7	35.0	38.7	28.0	18.3	7.0	5.7	3.3	2.7	0.7	3.7
Rain	28.3	30.0	30.0	30.7	30.0	31.3	29.0	20.0	23.0	6.7	1.3	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.3	0.0	0.0	0.0	0.0	0.3
Thunder	2.0	1.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
Mammal	0.0	0.0	0.0	1.0	0.0	0.0	12.3	8.3	8.3	4.0	1.0	0.3	2.7	1.7	0.0	0.3	1.7	5.3	1.7	0.7	2.7	0.3	0.0	0.0
Bird	31.0	25.3	28.0	30.0	32.3	32.7	59.0	94.7	95.7	90.0	85.7	70.3	68.0	71.0	67.3	53.0	62.0	61.3	66.3	38.0	28.3	30.0	32.7	30.7
Insect	23.3	21.0	22.3	20.0	20.3	21.3	25.7	24.7	18.3	61.7	79.3	76.0	78.3	74.0	75.0	74.0	65.3	57.0	50.3	54.0	46.7	33.0	31.7	27.7
Animal	1.3	7.0	2.0	1.0	2.3	2.0	1.0	4.7	0.7	5.3	2.0	1.7	1.7	2.0	0.7	2.3	1.7	7.3	3.0	0.7	0.3	2.0	1.3	2.0
Wind-induced Nat.	10.3	10.3	12.3	9.7	11.7	14.7	15.3	11.3	10.0	19.3	31.3	36.7	47.7	52.7	52.3	48.7	42.3	35.0	23.7	21.7	20.0	18.3	18.3	19.3
Natural Unkwn.	3.3	3.7	4.0	4.7	3.3	2.0	5.7	6.0	4.7	2.0	3.3	3.3	4.3	1.0	1.0	2.3	2.7	6.0	5.3	3.3	2.0	3.7	2.7	3.3
Artifact	0.0	0.0	0.3	0.0	0.0	0.0	0.0	0.0	0.0	0.7	0.7	1.3	2.7	3.0	3.0	2.7	1.0	0.0	0.0	0.0	0.7	1.0	0.7	0.0
Wind Distortion	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.3	0.3	0.0	1.0	2.7	1.3	1.3	1.0	1.0	0.0	0.0	1.0	1.0	0.3	0.0	0.0
Precipitation on Mic	0.0	0.0	0.3	8.3	4.3	0.7	2.0	0.0	0.0	0.0	0.3	0.0	0.3	0.3	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
Unknown	0.0	1.3	0.3	0.3	0.3	0.3	0.3	0.0	0.0	0.3	0.3	0.0	0.0	0.0	0.0	0.0	0.0	1.3	0.0	0.0	0.0	0.0	0.0	0.0

*Non-natural unknown sources are human-associated noise events, but their exact identity can't be determined.
**Wind-induced natural sources are sound sources such as the movement of grasses, leaves, and branches initiated by wind.
***Natural unknown sources are not human-associated sound events, but their exact identify can't be determined.
****Artifacts are sounds that occur only because of the presence of the microphones in the field.

Table 7. Mean hourly time audible (%) for each sound source at Whiterocks001 during the fall, n=8 days. Noise sources are highlighted in gray.

Sound Source	00h	01h	02h	03h	04h	05h	06h	07h	08h	09h	10h	11h	12h	13h	14h	15h	16h	17h	18h	19h	20h	21h	22h	23h
Aircraft	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.3	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
Jet	2.3	2.3	2.0	2.0	1.3	1.3	4.3	1.7	12.0	12.7	12.3	17.3	20.3	11.7	24.3	13.0	19.0	7.3	16.0	20.3	7.7	12.3	9.0	3.7
Propeller Plane	1.7	0.3	0.3	0.0	2.0	2.3	7.3	14.3	36.3	56.7	63.3	67.7	61.7	68.0	66.3	56.3	49.0	46.3	36.7	13.7	19.7	8.7	4.0	2.3
Helicopter	1.7	0.0	0.0	0.7	0.0	0.0	0.0	2.0	0.0	1.3	1.0	0.3	1.3	0.3	1.0	0.3	0.3	1.0	0.3	0.0	0.7	1.0	0.7	1.0
Vehicle	85.0	93.0	92.7	97.3	95.3	96.7	98.0	97.0	79.0	62.0	51.3	28.3	26.0	28.7	27.7	35.3	41.7	64.7	74.0	84.0	87.3	91.3	97.7	97.7
Alarm, Horn	0.3	0.3	0.0	0.3	0.0	0.3	4.0	0.0	2.7	0.3	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.3	0.0	0.0	0.0	0.0	0.0
Train	0.0	0.0	0.0	0.0	0.0	0.0	0.3	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.3	0.0	0.0	0.0	0.0	0.0
Train Rumble	0.0	5.7	1.0	1.3	5.0	2.7	0.0	4.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	1.0	0.0	0.0	5.7
Train Whistle	0.7	1.3	0.3	0.3	1.3	0.0	0.0	1.0	0.0	0.0	0.0	0.0	0.0	0.0	0.3	0.0	0.3	0.3	0.3	0.0	0.7	0.0	0.0	0.0
People	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.3	0.0	0.0	0.0	0.0	0.0	0.0	0.3	0.3	0.0	0.0	0.0	0.0	0.0	0.0	0.0
Voices	0.3	0.0	0.0	0.0	0.0	0.0	0.0	0.0	1.0	0.7	1.7	1.0	0.0	1.3	0.0	0.3	0.3	0.3	0.0	0.0	0.0	0.0	0.0	0.0
Walking	0.0	0.0	0.0	0.0	0.0	0.0	0.3	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.3	4.7	0.0	0.0	0.0	0.0	0.0	0.0	0.0
Domestic Animal	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	1.0	0.0	0.0
Dog	9.7	10.3	11.7	10.0	9.3	7.0	9.3	6.0	7.0	1.0	0.3	0.3	0.3	0.3	0.7	0.7	1.0	3.7	10.3	17.7	14.0	5.3	12.0	9.0
Cow	0.0	1.3	0.0	0.0	0.0	0.0	2.0	0.7	5.7	19.3	1.3	0.3	0.0	0.0	0.0	0.0	0.0	0.0	0.3	2.0	0.0	2.3	2.0	0.3
Non-natural Unkwn.	2.3	5.0	5.0	2.0	2.0	0.7	3.7	0.3	1.0	1.3	1.7	2.0	3.0	3.7	2.7	2.7	3.0	2.3	0.7	2.3	2.3	1.7	0.3	0.7
Wind	1.7	0.7	5.7	1.3	0.0	1.7	1.0	0.0	0.0	0.3	7.3	11.3	13.3	14.3	10.0	8.0	5.3	2.3	0.3	0.3	2.0	2.3	1.7	0.0
Rain	8.7	10.0	5.3	18.0	20.3	10.0	0.3	0.0	0.0	0.0	0.0	0.0	0.3	0.0	0.0	0.3	0.0	0.3	0.0	1.7	0.0	0.3	0.0	0.3
Flowing Water	22.0	11.0	7.0	6.3	6.0	3.0	2.0	0.0	0.0	0.7	0.7	1.0	4.0	3.3	3.7	1.3	2.0	3.0	0.0	2.3	1.7	1.3	4.3	3.0
Thunder	1.0	0.0	0.3	0.3	0.0	0.3	0.0	0.0	0.0	0.0	0.0	0.0	0.3	0.7	0.3	1.0	0.3	0.0	0.0	0.0	0.0	0.0	0.0	0.0
Mammal	8.3	6.3	2.0	3.3	1.7	2.3	2.3	1.7	4.3	8.3	2.3	2.3	3.7	17.7	19.3	18.0	23.7	17.3	13.0	9.3	9.7	19.7	16.3	20.0
Coyote	2.0	2.0	1.3	3.0	1.0	0.0	1.3	0.0	0.7	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	1.0	1.3	1.3	1.7	1.0
Bird	30.3	29.7	23.3	26.0	27.0	33.7	66.0	100.0	97.3	89.3	72.7	61.3	64.3	50.0	55.3	43.7	57.7	70.0	80.3	21.7	17.7	23.0	17.0	23.3
Insect	25.0	15.7	11.7	6.3	1.7	1.3	0.0	1.7	50.3	77.0	79.7	83.3	94.7	89.3	97.7	98.7	86.0	71.3	66.3	73.3	61.3	55.3	45.3	46.7
Animal	2.3	3.0	3.0	4.3	1.7	1.3	0.3	0.0	0.0	0.0	1.0	0.7	1.3	0.7	0.3	1.7	0.7	0.3	1.7	2.0	1.7	1.0	1.3	2.0
Wind-induced Nat.	9.3	10.0	18.3	8.0	1.3	11.0	15.7	0.0	3.7	17.7	39.7	52.3	48.7	50.7	49.3	41.0	45.7	30.7	9.3	8.7	10.0	6.0	1.3	1.3
Natural Unknown	0.3	1.3	2.3	0.3	1.3	0.3	0.7	0.0	2.0	0.3	2.0	0.7	1.7	0.7	1.7	2.0	0.3	0.7	0.3	1.0	0.0	1.3	0.7	0.7
Artifact	0.0	0.3	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.3	1.0	1.3	0.3	0.7	0.3	1.3	0.0	0.0	0.0	0.0	0.0	0.0	0.0
Precipitation on Mic	0.0	0.0	0.0	2.3	1.3	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
Unknown	0.3	1.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.3	0.0	0.0	0.0	0.3	0.0	0.0	0.0	0.0

*Non-natural unknown sources are human-associated noise events, but their exact identity can't be determined.
**Wind-induced natural sources are sound sources such as the movement of grasses, leaves, and branches initiated by wind.
***Natural unknown sources are not human-associated sound events, but their exact identify can't be determined.
****Artifacts are sounds that occur only because of the presence of the microphones in the field.

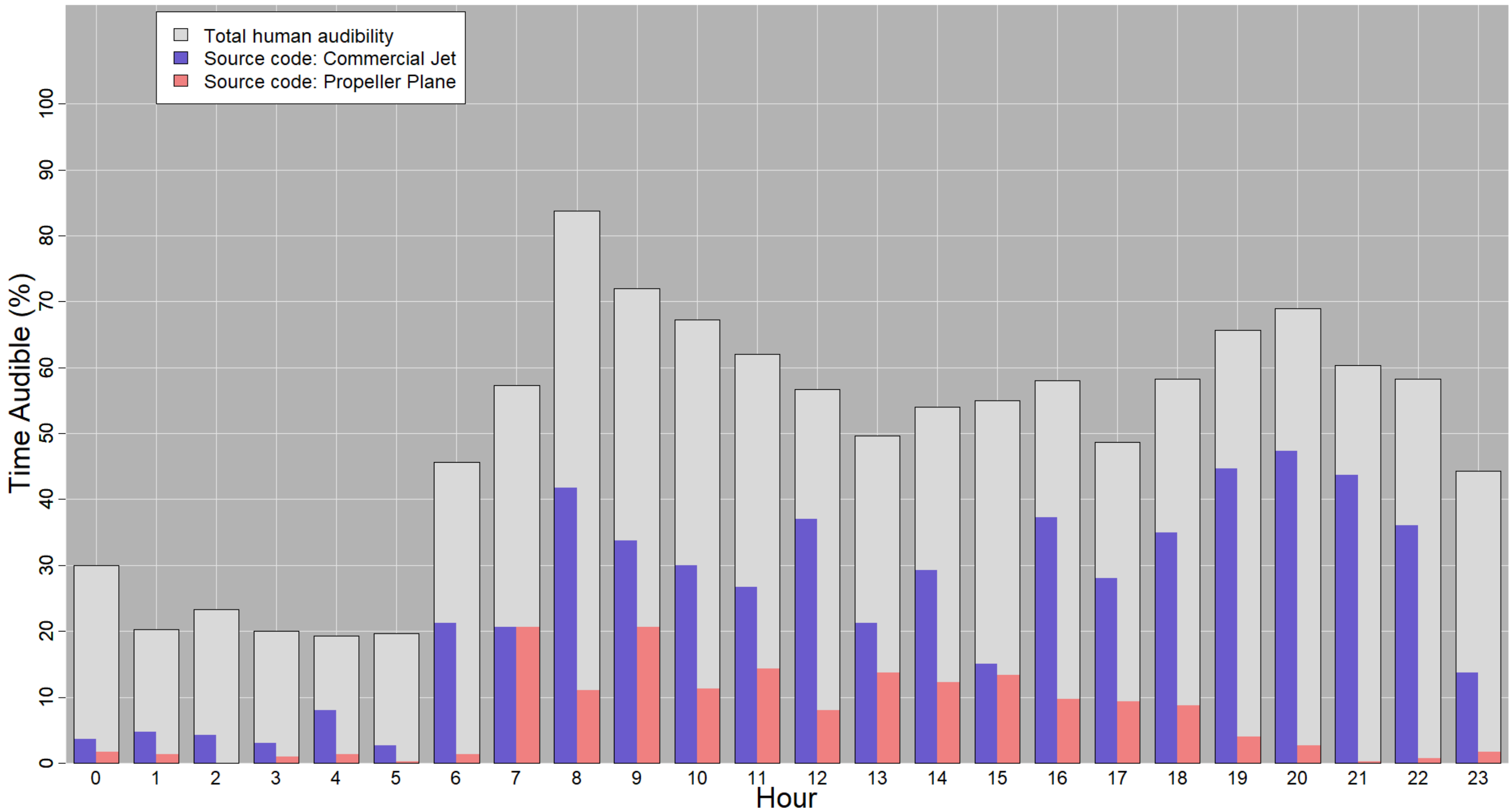

Figure 6. Hourly time audibility for commercial jets, propeller planes, and all noise sources at Aspen001 during the fall.

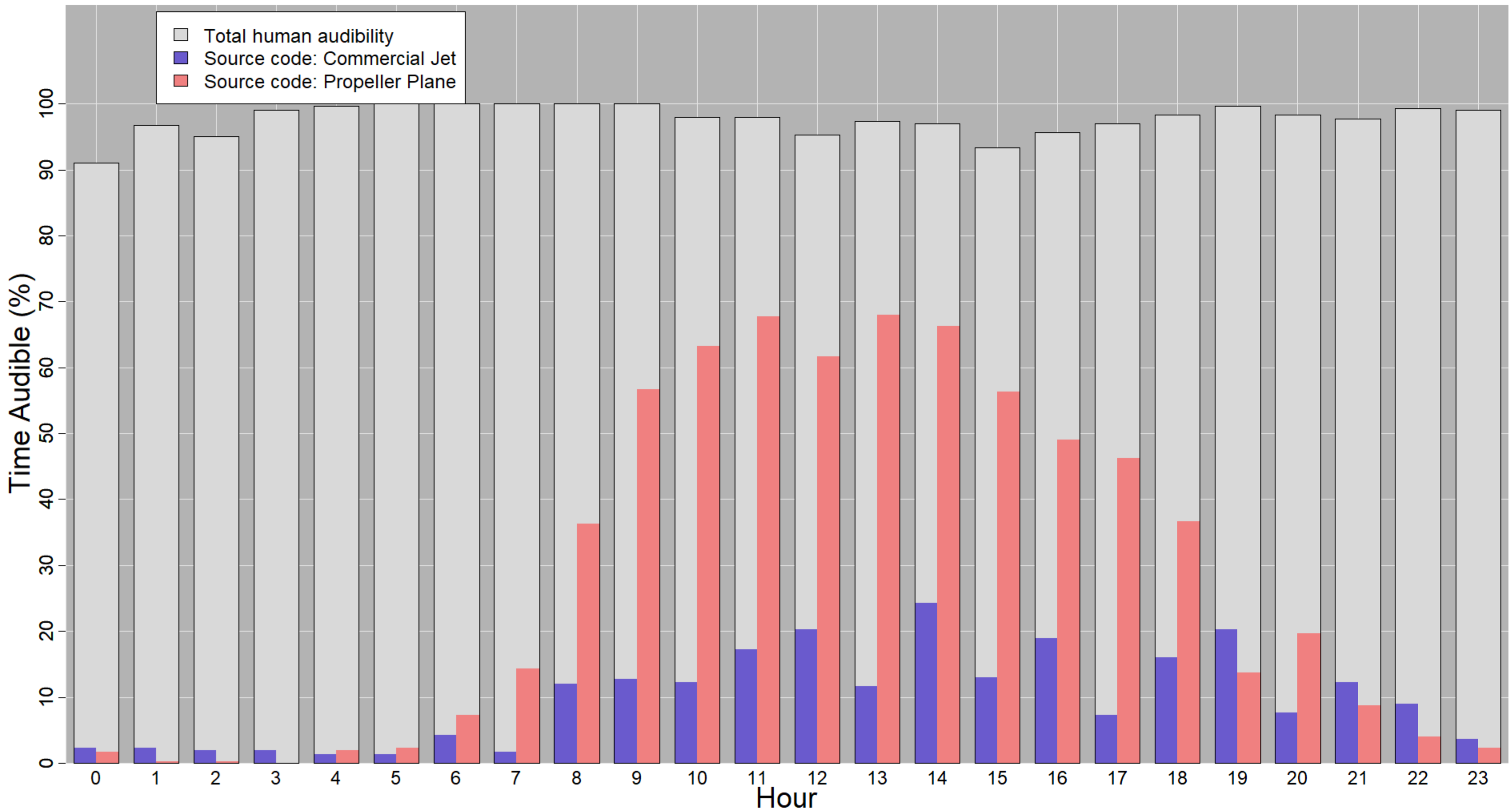

Figure 7. Hourly time audibility for commercial jets, propeller planes, and all noise sources at Whiterocks001 during the fall.

Conclusions

Acoustic monitoring allows parks to gain insight into levels of extrinsic noise and biological activity. The results can help estimate the effects of noise on park visitors and wildlife alike. The study was successful in determining the acoustical conditions at two front country locations within the City of Boulder's Open Spaces & Mountain Parks during the fall of 2021.

Results from Aspen001 and Whiterocks001 included measures of existing ambient sound levels, calculations of sound source audibility through off-site listening, and estimates of natural ambient levels. Sound source analysis revealed that noise is audible between 49.9 % and 97.9 % of the time at the study sites when averaged across all hours of the day and across seasons. The most common noise sources heard varied between sites. At Aspen001, overflights and trains were the most common noise sources and were heard 34.2 % and 5.5 % of the time respectively. Overflight noise was particularly dominant, with commercial jets comprising most of the noise (Figure 6). At Whiterocks1, overflights and vehicles were the most common noise sources and were heard 36.4 % and 72.2 % of the time respectively. Vehicles were most prominent during the overnight and early morning hours, while propeller plans were most common during the daylight period (Figure 7). While noise sources often overlap at both sites, they are likely simultaneously audible to an observer as frequency composition never fully overlap. For instance, propeller planes and vehicles frequently occur at the same time at Whiterocks001, but both are likely to be heard due to their differential frequency content and loudness.

In general, the median existing ambient sound level (L_{a50}) between daytime and nighttime periods differed quite a bit at Aspen001, but are much more similar at Whiterocks001 (Figures 4 & 5, and Table 3). This is likely due to the proximity of the Whiterocks001 site to major roads and the constant presence of vehicle noise from motors and tires on pavement.

Natural sources such as birds, mammals, insects, rain/flowing water were commonly audible at both sites across seasons. Birds were especially prominent at both sites, including during the daytime, and at night where Great Horned Owl (*Bubo virgianus*), Northern Pygmy Owl (*Glaucidium gnoma*), and Northern Saw-whet Owl (*Aegolius acadicus*) were detected. Mammals were also heard throughout the daytime and nighttime periods at both sites with the following species being detected at one or both sites: coyote (*Canus latrans*), red squirrel (*Sciurus vulgaris*), black bear (*Ursus americanus*), mountain lion (*Puma concolor*), and unidentified ungulate species. Finally, an insect chorus could be heard at night and various dipteran and hymenopteran species heard during the daytime at both sites.

Existing ambient sound levels (encompassing natural and noise sources) during the fall were measured to be 25.2 dB (L_{A50}) during the day and 10.2 dB (L_{A50}) at night at Aspen001 and 31.0 dB (L_{A50}) during the day and 25.3 dB (L_{A50}) at night at Whiterocks001.

For a broader context for the acoustic conditions at Aspen001 and Whiterocks001, a comprehensive 1982 study of noise levels in residential areas found that nearly 87 % of US residents were exposed to day-night sound levels (L_{dn}) over 55 dB, and an additional 53 % were exposed to L_{dn} over 60 dB (EPA 1982). Note that noise levels have increased nationally with population growth since the EPA study (Suter 1991; Barber et al. 2010). Additionally, a nationwide study modeling daytime sound levels indicated that only 23 % of the continental United States was predicted to have an existing ambient sound level above 40 dB ($L_{A50,\ 12\ hr}$), and only 1 % of the continental U.S. was predicted to have an existing daytime ambient sound level above 50 dB ($L_{A50,\ existing}$) (Mennitt 2013). Consider, though, that daily sound levels reported in this report for Aspen001 and Whiterocks001 can be influenced by both natural and non-natural sources.

To minimize exposure to noise pollution at these sites, visitors might time their visits to periods of low noise pollution as indicated in Figures 4 & 5. Additionally, the City of Boulder Open Spaces and Mountain Parks might consider working with local airports to work on establishing noise budgets or timing and frequency of propeller aircraft overflights over these open spaces. Similar noise budgets have been established in Grand Canyon, Hawaii Volcanoes, Yellowstone National Parks. The City of Boulder Open Spaces and Mountain Parks might reach out to NSNSD for more guidance on this issue.

Based on the results of this study, visitors and wildlife at the Whiterocks001 site are unlikely to experience a significant noise-free interval, as the presence of noise is consistent throughout the daytime and nighttime hours (Figures 9, Table 7). However, visitors and wildlife at the Aspen001 site have significantly less exposure to noise, especially during the late night and early morning hours (2300 – 500). Noise has the potential to affect a visitor's experience in parks by causing annoyance (Rapoza et al. 2015), reducing the perceived scenic beauty (Weinzimmer et al. 2014), or simply by limiting opportunities for solitude. Increased sound levels may also have wide ranging effects on wildlife such as reduced predatory success (Mason 2015), changes in vocal communication, or increased vigilance by keystone species (Shannon et al. 2014). In a review of literature addressing the effects of noise on wildlife published between 1990 and 2013, wildlife responses to noise were observed beginning at about 40 dB ($L_{Aeq,\ x}$).[3] Of the papers reviewed, 20% showed impacts to terrestrial wildlife at or below noise levels of 50 dB ($L_{Aeq,\ 1s}$) (Shannon et al. 2015).

The information presented in this report will be used to inform park managers and planners when they make management decisions, but it will also serve as a permanent record of what these sites sounded like during the fall of 2021. It should be noted that results of this study are limited to these specific sites during the fall season, and care should be taken when extrapolating results from this study to different sites at different times of the year. Additionally, it's important to acknowledge the limitations that the high-pass filter and sampling rate impose on the interpretation of these results.

[3] This metric is a composite of multiple metrics with varying time averaging metrics.

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Appendix A: Office Listening

Office listening is a way to characterize the length and type of noise events occurring at a monitored site. The NSNSD protocol calls for 8 days of analysis per monitoring period. The Acoustical Monitoring Toolbox splits the audio files in to 10 second clips every two minutes per one day. This results in 16 hours' worth of data being analyzed per site. Each sound is assigned a number which is then put into the Listening Center program each time the listener hears the sound. These numbers are eventually used to calculate the LA_{nat} for the site.

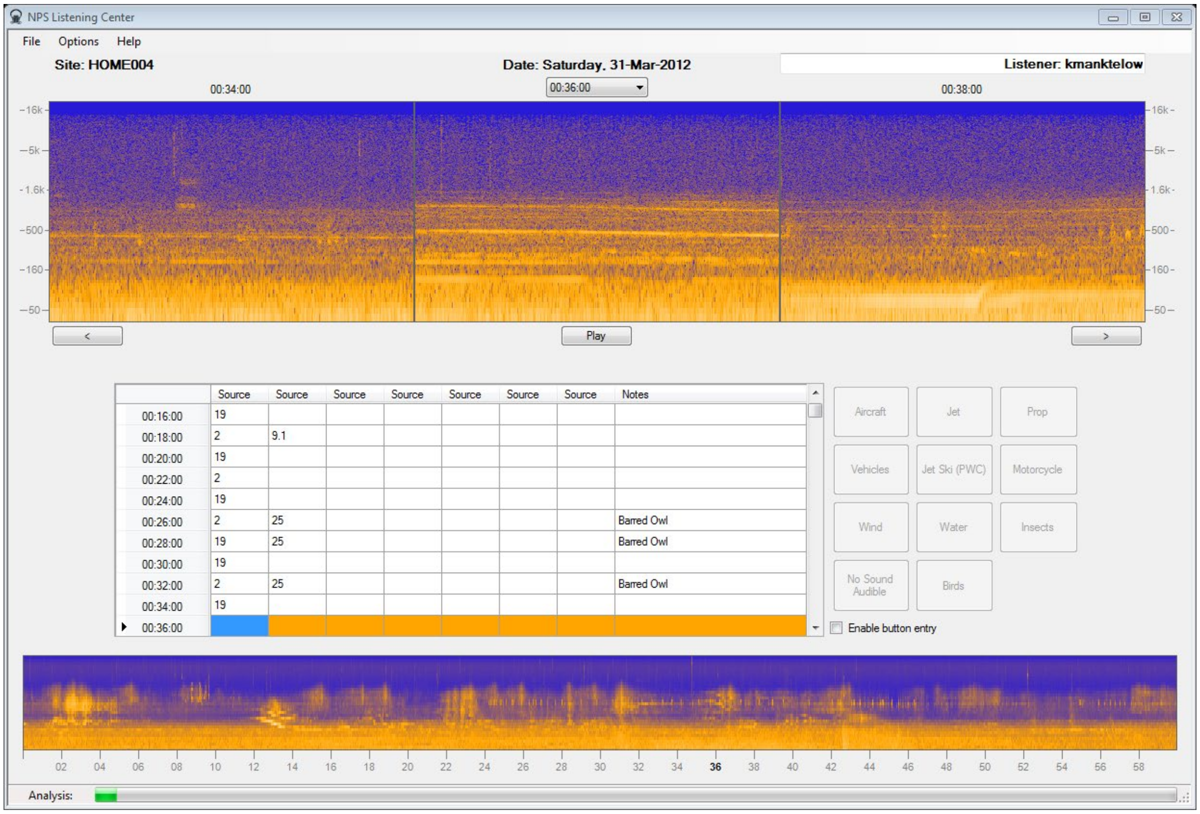

Figure 2. Screen shot of Listening Center. Three ten second samples are displayed side by side. Audible sound sources and annotations are recorded in the spreadsheet cells below.