



Shenandoah National Park

Acoustic Monitoring Report, 2016–2017

Natural Resource Report NPS/SHEN/NRR—2023/2572



ON THE COVER

Moormans River Overlook

NPS

Shenandoah National Park

Acoustic Monitoring Report, 2016–2017

Natural Resource Report NPS/SHEN/NRR—2021/2572

Grace Carpenter

National Park Service
Natural Sounds and Night Skies Division
1316 Cherokee Orchard Road
Gatlinburg, Tennessee 37738

October 2023

U.S. Department of the Interior
National Park Service
Natural Resource Stewardship and Science
Fort Collins, Colorado

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 Report Series is used to disseminate comprehensive information and analysis about natural resources and related topics concerning lands managed by the National Park Service. The series supports the advancement of science, informed decision-making, and the achievement of the National Park Service mission. The series also provides a forum for presenting more lengthy results that may not be accepted by publications with page limitations.

All manuscripts in the series receive the appropriate level of peer review to ensure that the information is scientifically credible and technically accurate.

Views, statements, findings, conclusions, recommendations, and data in this report do not necessarily reflect views and policies of the National Park Service, U.S. Department of the Interior. Mention of trade names or commercial products does not constitute endorsement or recommendation for use by the U.S. Government.

This report is available in digital format from https://www.nps.gov/subjects/sound/acousticmonitoring_reports.htm and the [Natural Resource Publications Management website](#). If you have difficulty accessing information in this publication, particularly if using assistive technology, please email irma@nps.gov.

Please cite this publication as:

Carpenter, G. 2023. Shenandoah National Park: Acoustic monitoring report, 2016–2017. Natural Resource Report NPS/SHEN/NRR—2023/2572. National Park Service, Fort Collins, Colorado. <https://doi.org/10.36967/2300465>

Contents

	Page
Figures.....	iv
Tables	vi
Executive Summary	viii
Acknowledgments.....	xiii
Glossary of Acoustic Terms	xiv
Introduction.....	1
National Park Service Natural Sounds and Night Skies Division	1
Soundscape Planning Authorities	1
Study Area.....	3
Methods.....	6
Automatic Monitoring	6
Monitoring Period	6
Calculation of Metrics	6
Off-Site Listening.....	7
Results.....	9
Frequency content	9
Sound level: Time Above	13
Sound Level: Percentile Levels	17
Event duration	21
Conclusions.....	38
Literature Cited	41
Appendix A: Office Listening.....	43

Figures

	Page
Figure 1. Study sites in Shenandoah National Park, USA 2016–2017.	5
Figure 2. Colorado State University student identifies sound sources using Acoustic Monitoring Toolbox (NPS) software.	8
Figure 3. Day and night percentile sound pressure levels for 33 one-third octave bands at SHEN001 in summer.	9
Figure 4. Day and night percentile sound pressure levels for 33 one-third octave bands at SHEN001 in winter.	10
Figure 5. Day and night percentile sound pressure levels for 33 one-third octave bands at SHEN002 in summer.	10
Figure 6. Day and night percentile sound pressure levels for 33 one-third octave bands at SHEN002 in winter.	11
Figure 7. Day and night percentile sound pressure levels for 33 one-third octave bands at SHEN003 in summer.	11
Figure 8. Day and night percentile sound pressure levels for 33 one-third octave bands at SHEN003 in winter.	12
Figure 9. Day and night percentile sound pressure levels for 33 one-third octave bands at SHEN004 in summer.	12
Figure 10. Day and night percentile sound pressure levels for 33 one-third octave bands at SHEN004 in winter.	13
Figure 11. Median percentile sound levels ($L_{Aeq, 1s}$), in dB re 20 μ Pa, at SHEN001 in summer.	17
Figure 12. Median percentile sound levels ($L_{Aeq, 1s}$), in dB re 20 μ Pa, at SHEN001 in winter.	18
Figure 13. Median percentile sound levels ($L_{Aeq, 1s}$), in dB re 20 μ Pa, at SHEN002 in summer.	18
Figure 14. Median percentile sound levels ($L_{Aeq, 1s}$), in dB re 20 μ Pa, at SHEN002 in winter.	19
Figure 15. Median percentile sound levels ($L_{Aeq, 1s}$), in dB re 20 μ Pa, at SHEN003 in summer.	19
Figure 16. Median percentile sound levels ($L_{Aeq, 1s}$), in dB re 20 μ Pa, at SHEN003 in winter.	20

Figures (continued)

	Page
Figure 17. Median percentile sound levels (LAeq, 1s), in dB re 20 μ Pa, at SHEN004 in summer.....	20
Figure 18. Median percentile sound levels (LAeq, 1s), in dB re 20 μ Pa, at SHEN004 in winter.....	21
Figure 19. Hourly time audible for aircraft and all noise sources at SHEN001 in summer.....	30
Figure 20. Hourly time audible for aircraft and all noise sources at SHEN001 in winter.	31
Figure 21. Hourly time audible for aircraft and all noise sources at SHEN002 in summer.....	32
Figure 22. Hourly time audible for aircraft and all noise sources at SHEN002 in winter.	33
Figure 23. Hourly time audible for aircraft and all noise sources at SHEN003 in summer.....	34
Figure 24. Hourly time audible for aircraft and all noise sources at SHEN003 in winter.	35
Figure 25. Hourly time audible for aircraft and all noise sources at SHEN004 in summer.....	36
Figure 26. Hourly time audible for aircraft and all noise sources at SHEN004 in winter.	37
Figure 27. Screen shot of Listening Center.....	44

Tables

	Page
Table 1. Sound level examples	viii
Table 2. Percent time above metrics for SHEN001, SHEN002, SHEN003, and SHEN004 during summer.	x
Table 3. Percent time above metrics for SHEN001, SHEN002, SHEN003, and SHEN004 during winter.	x
Table 4. Summary of summer noise sources and sound levels at four Shenandoah National Park study sites.....	xi
Table 5. Summary of winter noise sources and sound levels at four Shenandoah National Park study sites.	xii
Table 6. Metadata for each acoustical monitoring site at Shenandoah National Park.....	4
Table 7. Percent time above metrics for SHEN001, SHEN002, SHEN003, and SHEN004 during summer.	15
Table 8. Percent time above metrics for SHEN001, SHEN002, SHEN003, and SHEN004 during winter.....	15
Table 9. Mean hourly time audible (%) for each natural sound source at SHEN001 in summer, n=8 days.	22
Table 10. Mean hourly time audible (%) for each natural sound source at SHEN001 in winter, n=8 days.	22
Table 11. Mean hourly time audible (%) for each noise source at SHEN001 in summer, n=8 days.....	22
Table 12. Mean hourly time audible (%) for each noise source at SHEN001 in winter, n=8 days.....	23
Table 13. Mean hourly time audible (%) for each natural sound source at SHEN002 in summer, n=8 days.	23
Table 14. Mean hourly time audible (%) for each natural sound source at SHEN002 in winter, n=8 days.	24
Table 15. Mean hourly time audible (%) for each noise source at SHEN002 in summer, n=8 days.....	24
Table 16. Mean hourly time audible (%) for each noise source at SHEN002 in winter, n=8 days.....	25

Tables (continued)

	Page
Table 17. Mean hourly time audible (%) for each natural sound source at SHEN003 in summer, n=8 days.	25
Table 18. Mean hourly time audible (%) for each natural sound source at SHEN003 in winter, n=2 days.	26
Table 19. Mean hourly time audible (%) for each noise source at SHEN003 in summer, n=8 days.	26
Table 20. Mean hourly time audible (%) for each noise source at SHEN003 in winter, n=2 days.	27
Table 21. Mean hourly time audible (%) for each natural sound source at SHEN004 in summer, n=8 days.	27
Table 22. Mean hourly time audible (%) for each natural sound source at SHEN004 in winter, n=8 days.	28
Table 23. Mean hourly time audible (%) for each noise source at SHEN004 in summer, n=8 days.	28
Table 24. Mean hourly time audible (%) for each noise source at SHEN004 in winter, n=8 days.	28

Executive Summary

This report presents acoustical data gathered by the Natural Sounds and Night Skies Division (NSNSD) at Shenandoah National Park (SHEN) in August–September of 2016 and January–March of 2017. Data were collected at four sites (Figure 1) to provide park managers with information about the acoustical environment, sources of noise¹, and the existing ambient sound levels within the park.

In these deployments, sound pressure level (SPL) was measured continuously every second by a calibrated sound level meter. Other equipment included an anemometer to collect wind speed and a digital audio recorder collecting continuous recordings to document sound sources. 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 μ Pa. 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 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 μ Pa A-weighted broadband (12.5 Hz–20 kHz), sound level measured over varied measurement durations and at the distances indicated.

Overall, existing ambient sound levels (LA_{50}) at sites within SHEN ranged from 31.1–44.4 dB during the day and 35.5–54.1 dB at night during the summer, and 29.8–38.0 dB during the day and 32.3–0.5 dB at night during the winter. Table 2 and 3 report 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

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

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 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 52 dB ($L_{Aeq, 1s}$) level was exceeded at SHEN001 4.25 % of the time during the day and 19.70 % of the time at night, but in the 20-1,250 Hz range, the 52 dB functional sound level value was very rarely exceeded in daytime or nighttime. Speech interruption (between two people 1 meter apart) occurs at 60 dB ($L_{Aeq, 1s}$) and this level was rarely exceeded at any of the sites.

After data collection was complete, trained technicians calculated how often noise sources were audible. See Methods section for protocol details, equipment specifications, and metrics calculations. Sound source analysis revealed that noise was audible about 62–85 % of the time during summer and 23–87 % of the time during winter at study sites when averaged across all hours of the day (Table 4-Table 5). The most common source of noise during this study period was aircraft and trains. Natural sources such as wind, rain, thunder, barred owls, songbirds, and insects were also commonly audible. Natural ambient sound levels (L_{Anat}) ranged between 25.7–40.9 dB during the day and 32.2–52.9 dB at night in summer and 27.7–34.0 dB during the day and 29.7–37.3 dB at night in winter. Increased natural ambient sound levels during the night were likely due to insect and bird activity in the evening hours (see Figure 3).

Table 2. Percent time above metrics for SHEN001, SHEN002, SHEN003, and SHEN004 during summer.

Site ID	Frequency Range	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 ^A	45 dB ^A	52 dB ^A	60 dB ^A	35 dB ^A	45 dB ^A	52 dB ^A	60 dB ^A
SHEN001	Full	12.5–20,000	97.49	48.51	4.25	0.10	99.99	70.13	19.70	0.00
	ANS Weighted ^B	20–1,250	4.16	0.67	0.15	0.00	1.07	0.07	0.01	0.00
SHEN002	Full	12.5–20,000	33.55	6.89	0.73	0.01	90.39	71.95	51.20	0.37
	ANS Weighted ^B	20–1,250	7.02	0.55	0.08	0.00	16.34	0.31	0.04	0.00
SHEN003	Full	12.5–20,000	35.14	1.86	0.26	0.02	58.82	11.70	0.54	0.00
	ANS Weighted ^B	20–1,250	10.86	0.77	0.15	0.01	34.64	0.54	0.03	0.00
SHEN004	Full	12.5–20,000	68.50	8.92	0.57	0.02	93.91	75.74	61.49	1.82
	ANS Weighted ^B	20–1,250	30.81	0.81	0.13	0.01	46.37	1.62	0.05	0.00

^A dB LAeq, 1s re 20 µPa

^B The percent of time ANS-weighted sound levels (20-1,250 Hz) are above functional values.

Table 3. Percent time above metrics for SHEN001, SHEN002, SHEN003, and SHEN004 during winter.

Site ID	Frequency Range	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 ^A	45 dB ^A	52 dB ^A	60 dB ^A	35 dB ^A	45 dB ^A	52 dB ^A	60 dB ^A
SHEN001	Full	12.5-20,000	58.29	13.48	0.61	0.01	31.85	2.71	0.17	0.00
	ANS Weighted ^B	20-1,250	56.26	9.60	0.28	0.01	27.45	2.13	0.05	0.00
SHEN002	Full	12.5-20,000	32.82	4.14	0.44	0.02	43.87	16.50	2.31	0.02
	ANS Weighted ^B	20-1,250	29.59	2.76	0.24	0.01	42.21	12.67	0.63	0.01
SHEN003	Full	12.5-20,000	65.45	19.26	1.54	0.05	78.31	34.00	8.53	0.07
	ANS Weighted ^B	20-1,250	57.12	8.35	0.39	0.04	73.85	33.52	4.32	0.04

^A dB LAeq, 1s re 20 µPa

^B The percent of time ANS-weighted sound levels (20-1,250 Hz) are above functional values.

Table 3 (continued). Percent time above metrics for SHEN001, SHEN002, SHEN003, and SHEN004 during winter.

Site ID	Frequency Range	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 ^A	45 dB ^A	52 dB ^A	60 dB ^A	35 dB ^A	45 dB ^A	52 dB ^A	60 dB ^A
SHEN004	Full	12.5-20,000	30.58	2.55	0.09	0.00	43.58	14.14	0.90	0.00
	ANS Weighted ^B	20-1,250	15.30	0.41	0.03	0.00	32.17	5.01	0.08	0.00

^A dB L_{Aeq, 1s} re 20 µPa

^B The percent of time ANS-weighted sound levels (20-1,250 Hz) are above functional values.

Table 4. Summary of summer noise sources and sound levels at four Shenandoah National Park study sites. Included for each site are a) mean percent time audible for all human-caused noise, including the top two known noise sources, and b.) existing (L_{A50}) and natural (L_{Anat}) ambient sound levels (dB re 20 µPa, A-weighted broadband, 12.5 Hz—20 kHz) during the day (0700-1900) and night (1900-0700). The difference between the natural and existing ambient sound levels indicates the deviation from the natural condition.

Site ID	a) Mean time audible for noise (% of 24-hour time period)				b) Median Existing Ambient (L _{A50}) in dB		Median Natural Ambient (L _{Anat}) in dB	
	All Noise	Aircraft	Train	Non-Natural Unknown	Day	Night	Day	Night
SHEN001	71.4	41.7	7.7	19.6	44.4	48.6	40.9	47.2
SHEN002	61.7	31.0	9.1	18.8	31.8	51.7	26.4	50.9
SHEN003	84.8	21.8	41.8	19.2	31.1	35.5	25.7	32.2
SHEN004	66.9	27.8	32.1	6.0	37.1	54.1	31.3	52.9

Table 5. Summary of winter noise sources and sound levels at four Shenandoah National Park study sites. Included for each site are a) mean percent time audible for all human-caused noise, including the top two known noise sources, and b.) existing (L_{A50}) and natural (L_{Anat}) ambient sound levels (dB re 20 μ Pa, A-weighted broadband, 12.5 Hz—20 kHz) during the day (0700-1900) and night (1900-0700). The difference between the natural and existing ambient sound levels indicates the deviation from the natural condition.

Site ID	a) Mean time audible for noise (% of 24-hour time period)				b) Median Existing Ambient (L_{A50}) in dB		Median Natural Ambient (L_{Anat}) in dB	
	All Noise	Aircraft	Train	Non-Natural Unknown	Day	Night	Day	Night
SHEN001	87.4	23.7	56.6	6.5	35.7	32.3	31.4	29.7
SHEN002	44.5	26.9	7.8	7.9	32.2	34.5	27.9	32.6
SHEN003	72.8	17.4	2.2	52.7	38.0	40.5	34.0	37.3
SHEN004	22.6	15.9	0.8	3.9	29.8	34.3	27.7	33.2

Acknowledgments

Acoustic data for this report were gathered by Scott McFarland.

Glossary of Acoustic Terms

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 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 μ Pa. 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 (LA50): Sound level (LAeq, 1s) exceeded 50% of the time (50th 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 of 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 (LA10, LA50, LA90): 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 LA50 value, while 90 percent of the time the measured levels are higher than the LA90 value, and 10 percent of the time measured levels are higher than the LA10 value.

Day-Night average sound levels (Ldn): 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 (LAeq): 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 (LAnat): The natural sound conditions in parks, which would exist in the absence of any human-caused noise sources. LAnat 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 (LAeq, 1s) are above a specified sound level (LAeq, 1s). Commonly used levels are 35, 45, 52 dB (LAeq, 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 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 wild life 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

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, Soundscape Preservation and Noise Management (2000) 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 2016 and 2017 at SHEN001, SHEN002, SHEN003, and SHEN004 (Table 6). SHEN001 was located at Madison Run administrative road, west of Browns Gap Road. SHEN002 was located near the popular hiking trail, Saddle Trail, on Old Rag Mountain. SHEN003 was located near the Appalachian Trail on Stony Man Mountain, and SHEN004 was located near the Appalachian Trail on Hogback Mountain (Figure 1.).

Table 6. Metadata for each acoustical monitoring site at Shenandoah National Park.

Site	Site Name	Vegetation	Summer Dates Deployed	Winter Dates Deployed	Elevation (m)	Latitude	Longitude (-)
SHEN001	Madison Run	Temperate Broadleaf/Mixed	8/15/2016– 9/28/2016	1/17/2017– 2/22/2017	585	N38.250094	W78.734825
SHEN002	Old Rag	Temperate Broadleaf/Mixed	8/16/2016– 9/23/2016	1/18/2017– 3/2/2017	920	N38.550833	W78.318747
SHEN003	Stony Man	Temperate Broadleaf/Mixed	8/17/2016– 9/14/2016	1/19/2017– 2/24/2017	1214	N38.597764	W78.372239
SHEN004	Hogback	Temperate Broadleaf/Mixed	8/18/2016– 9/22/2016	1/17/2017– 2/22/2017	1044	N38.761578	W78.272439



Shenandoah National Park

Acoustic Monitoring Sites

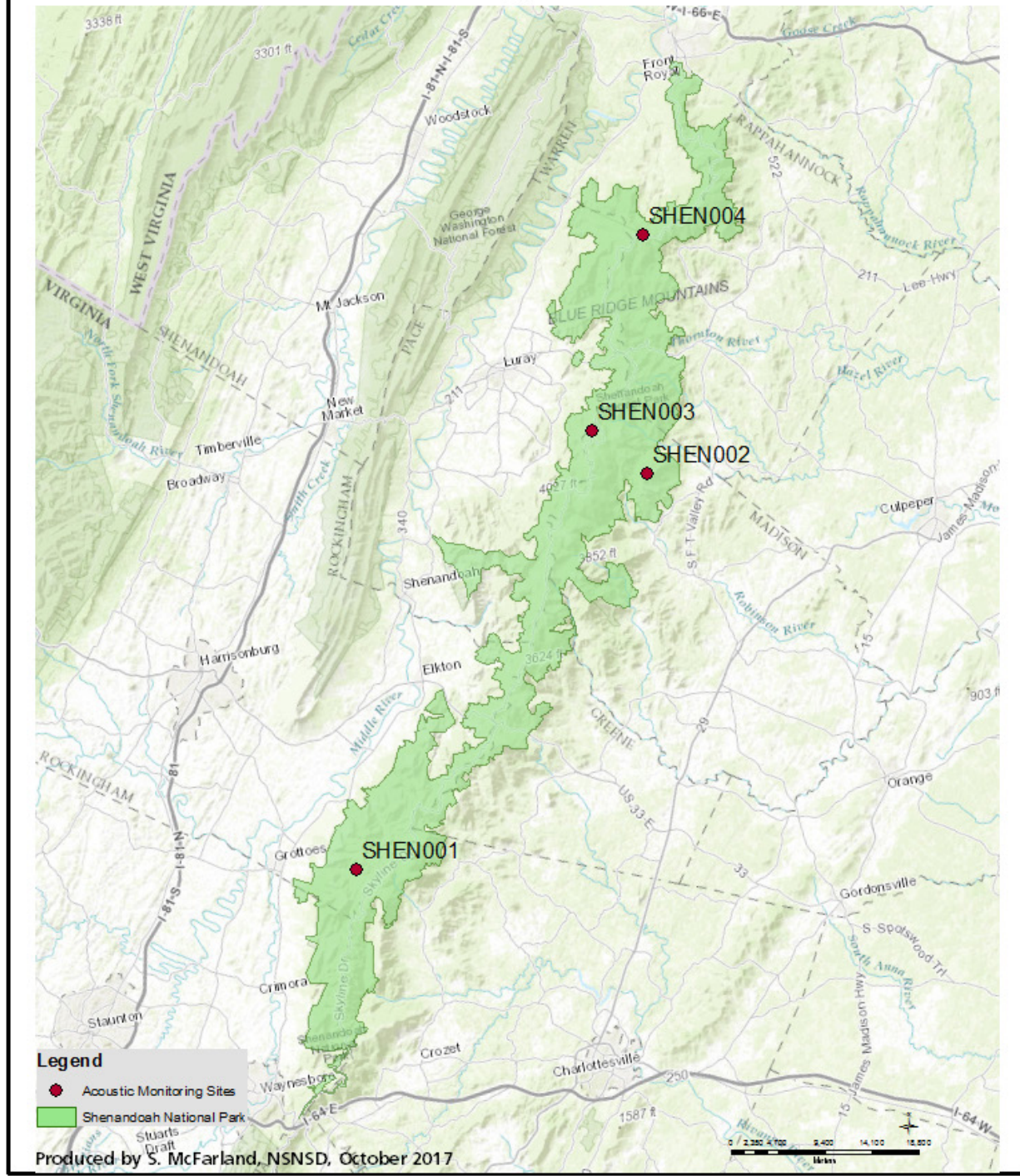


Figure 1. Study sites in Shenandoah National Park, USA 2016–2017.

Methods

Automatic Monitoring

A Larson Davis 831 sound level meter (SLM) was deployed at each monitoring site. The Larson Davis SLM is a hardware-based, real-time analyzer which constantly records sound pressure level (SPL) and one-third octave band data. This Larson Davis-based site met American National Standards Institute (ANSI) Type 1 standards. The sound level meter provided the information needed to calculate metrics described below in Calculation of Metrics.

Acoustical monitoring equipment is used by many industries to determine noise levels in different environments, both indoors and outdoors. NPS uses equipment that is similar to the equipment used by other industries but has developed a unique configuration that stands up to the potentially harsh environment encountered in national parks. The microphone with environmental shroud was set up on a tripod at 1.5 m above the ground, which approximates the average height of the human ear. The digital audio recorder recorded continuous audio through the entire monitoring period. An anemometer was attached to a tripod and placed approximately 10 feet from the microphone, to capture local wind conditions without recording possible sound from anemometer wind cup rotation.

The sampling station consisted of:

- Type 1 sound level meter
- Microphone with environmental shroud
- Preamplifier
- 12 V battery pack
- Anemometer (wind speed)
- Digital audio recorder

The sampling station collected:

- A-weighted 1 second time averaged sound level ($L_{Aeq, 1s}$) in dB re 20 μ Pa
- Continuous digital audio recordings
- One-third octave band data every second ranging from 12.5 Hz – 20,000 Hz
- Continuous meteorological data for wind speed

Monitoring Period

NSNSD has determined that 25-day monitoring periods during opposing seasons allow the data to capture seasonal differences that occur at each site within a reasonable margin of error (NPS 2005). The monitoring periods at SHEN lasted approximately 35 days.

Calculation of Metrics

The status of the acoustical environment can be characterized by sound level (L_{A50} , 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 $> 5\text{m/s}$ 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):

$$x = \frac{100 - P_H}{2} + P_H$$

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 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 (for more information on Listening Center software, see Appendix C). Auditory analysis was used to calculate the audibility of sound sources at the monitoring locations. Trained technicians at Colorado State University (Figure 2) listened to a subset of .mp3 audio samples (10 seconds every two minutes for eight days of audio) in order to identify durations of audible sound sources. Audio recording equipment failed early at the SHEN003 site during the winter, so only two days of audio were analyzed for that monitoring period. 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 in the Results chapter.



Figure 2. Colorado State University student identifies sound sources using Acoustic Monitoring Toolbox (NPS) software.

Results

Frequency content

In order 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 Figure 3–Figure 10.

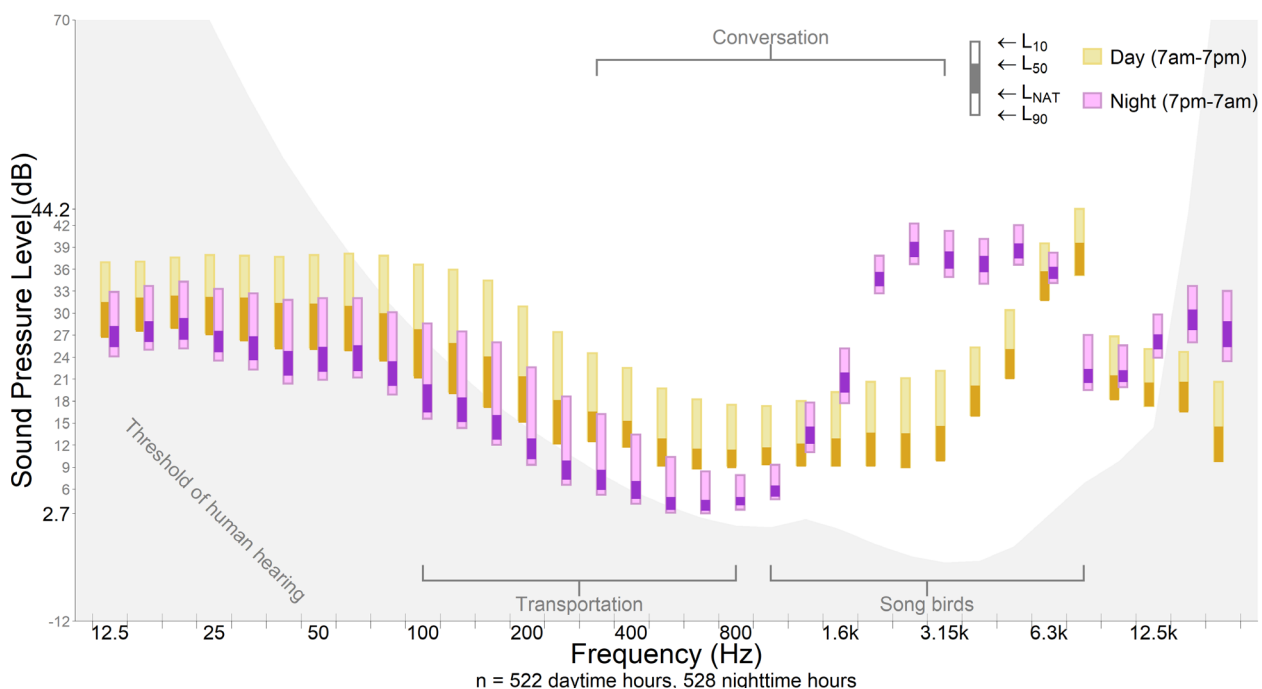


Figure 3. Day and night percentile sound pressure levels for 33 one-third octave bands at SHEN001 in summer.

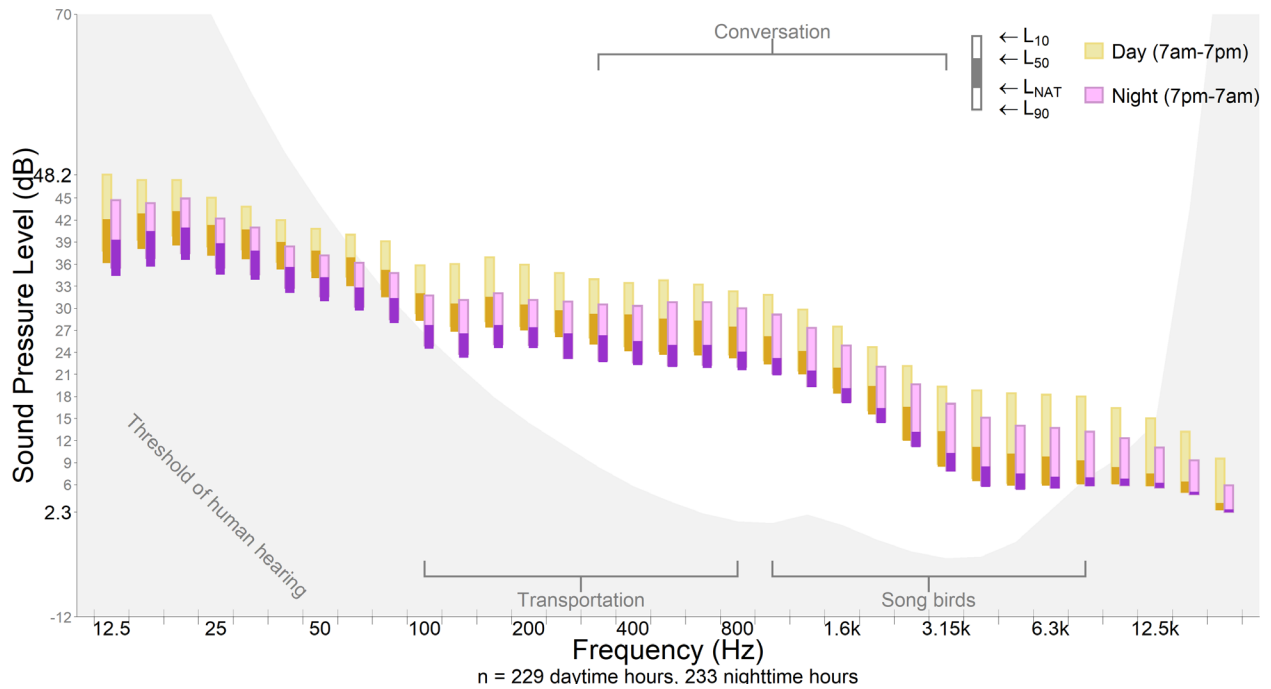


Figure 4. Day and night percentile sound pressure levels for 33 one-third octave bands at SHEN001 in winter. For each bar, the bold color indicates the range of existing (L_{A50} ; upper) and natural ($L_{A_{nat}}$; lower) sound pressure levels.

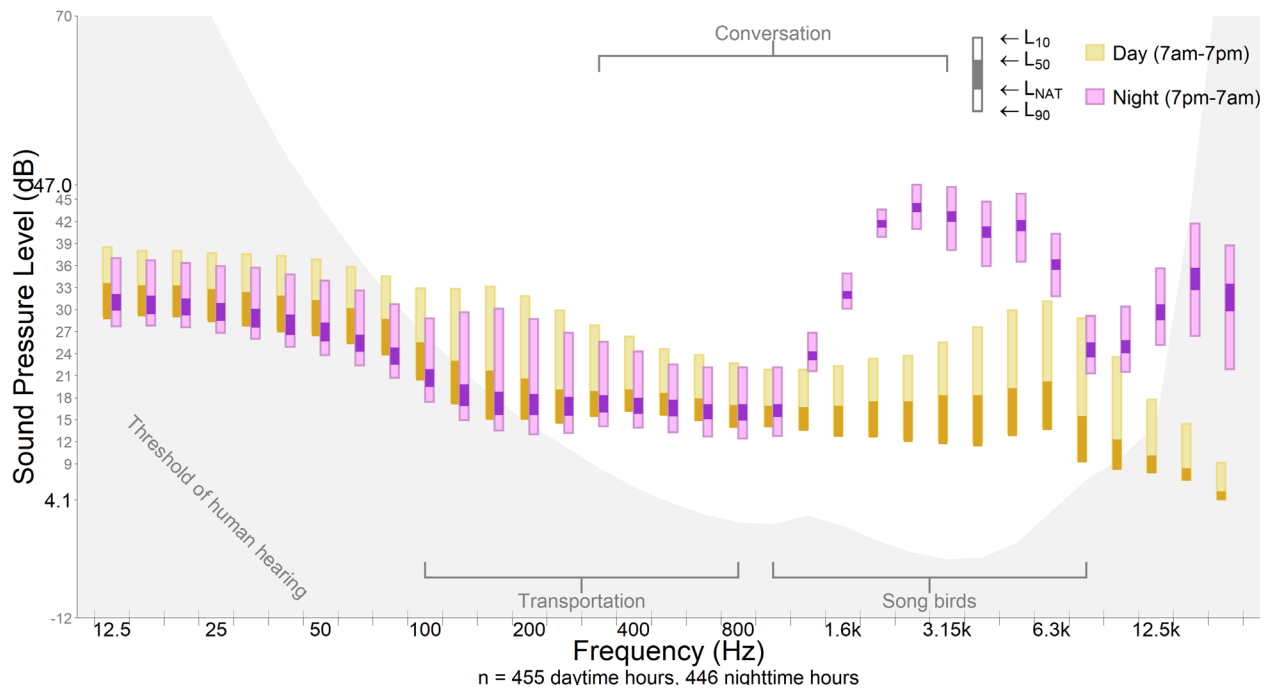


Figure 5. Day and night percentile sound pressure levels for 33 one-third octave bands at SHEN002 in summer.

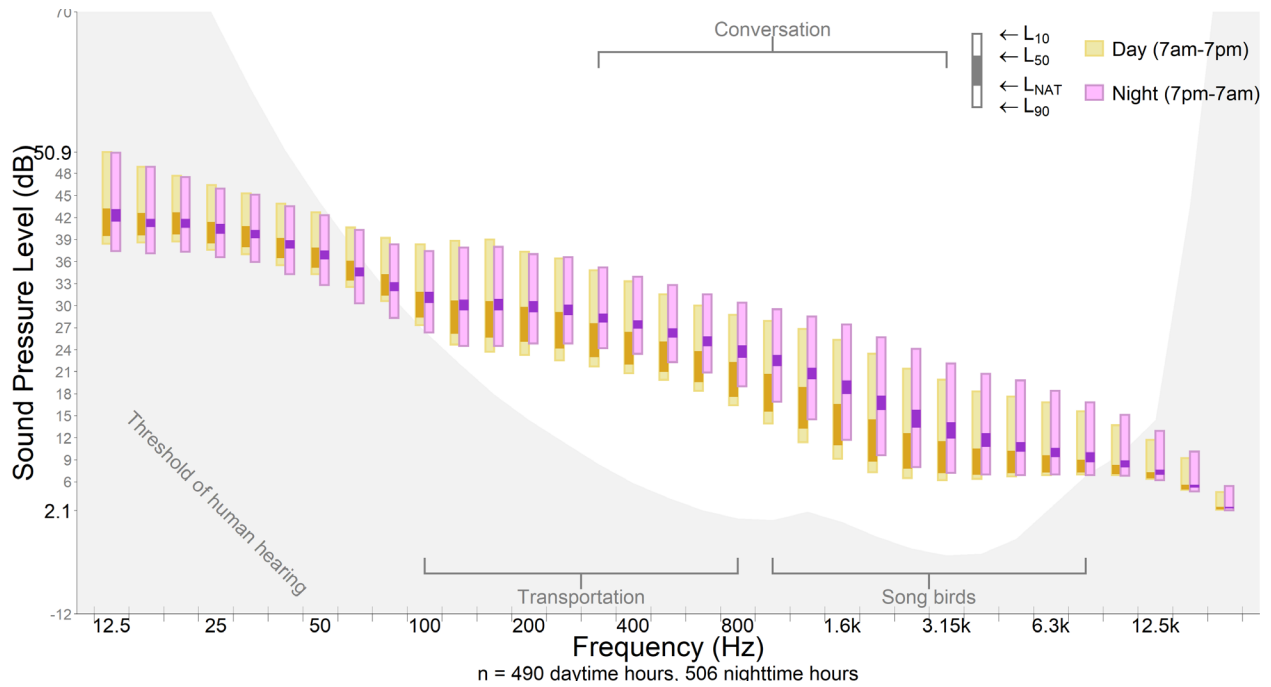


Figure 6. Day and night percentile sound pressure levels for 33 one-third octave bands at SHEN002 in winter.

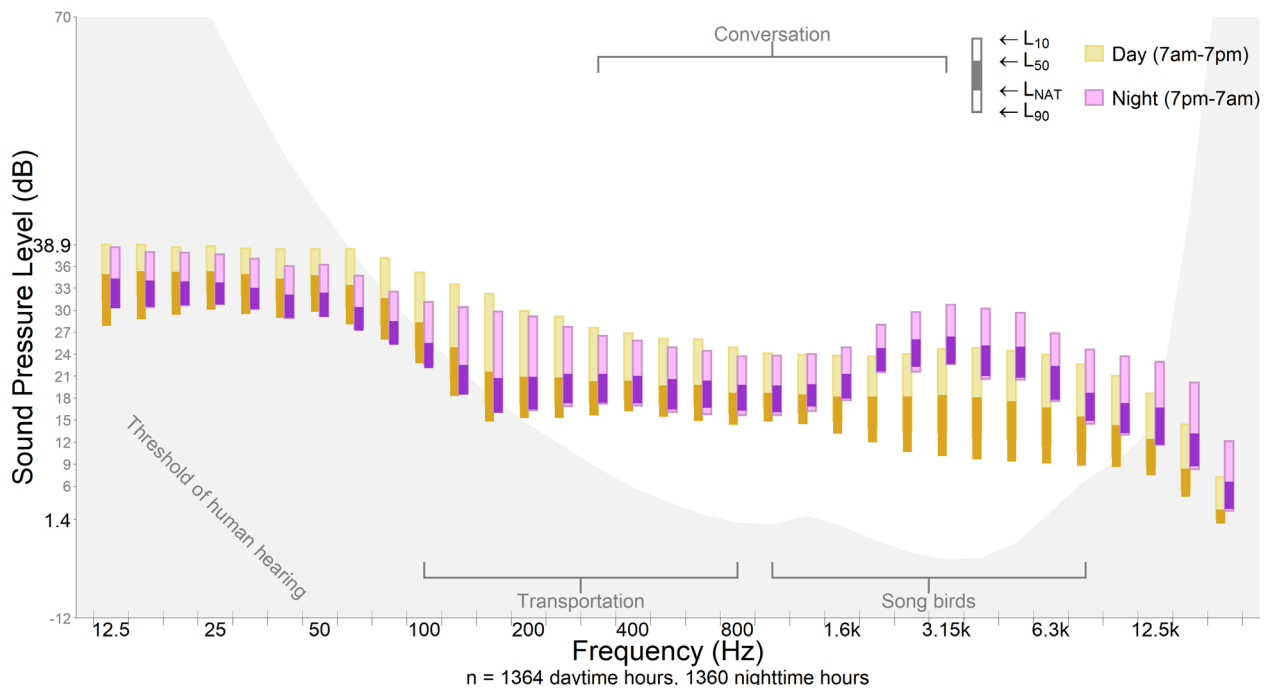


Figure 7. Day and night percentile sound pressure levels for 33 one-third octave bands at SHEN003 in summer.

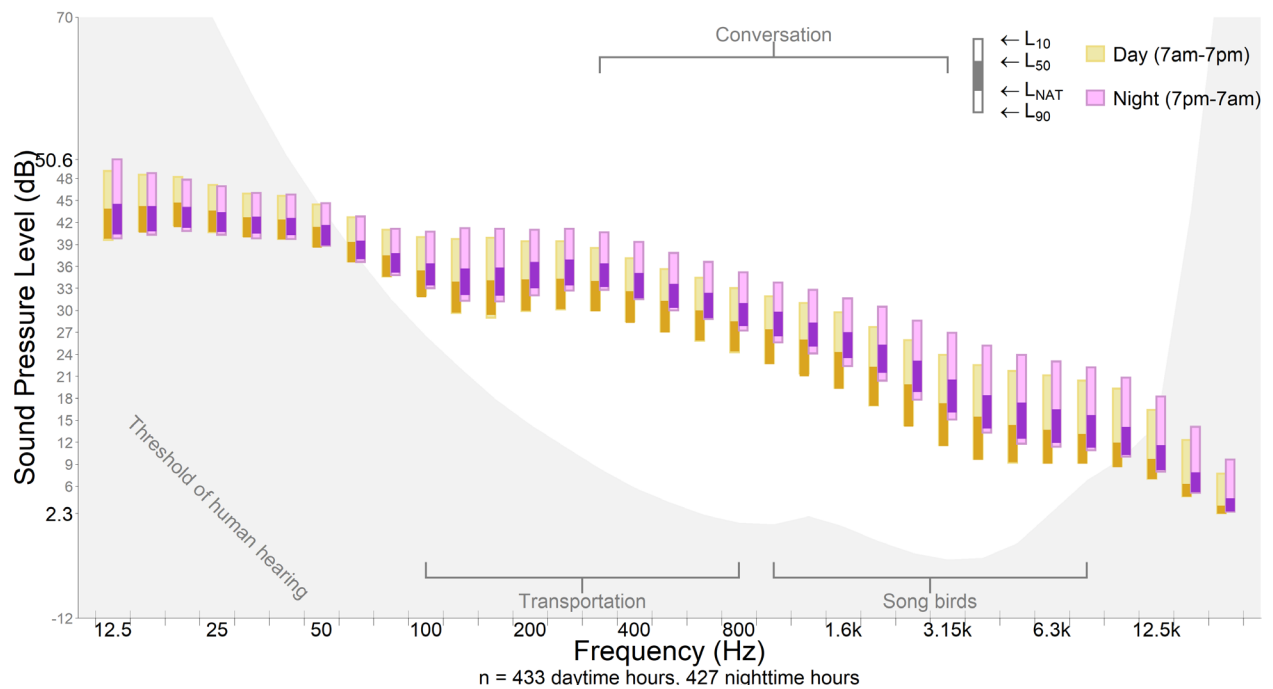


Figure 8. Day and night percentile sound pressure levels for 33 one-third octave bands at SHEN003 in winter.

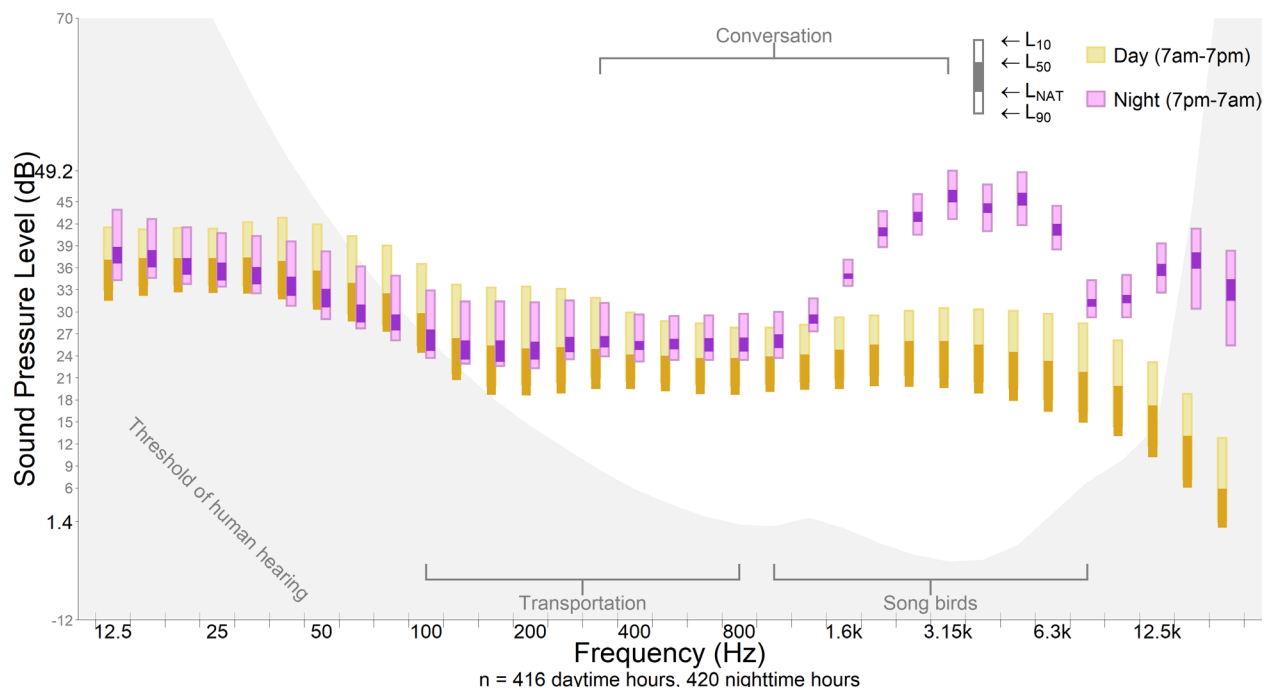


Figure 9. Day and night percentile sound pressure levels for 33 one-third octave bands at SHEN004 in summer.

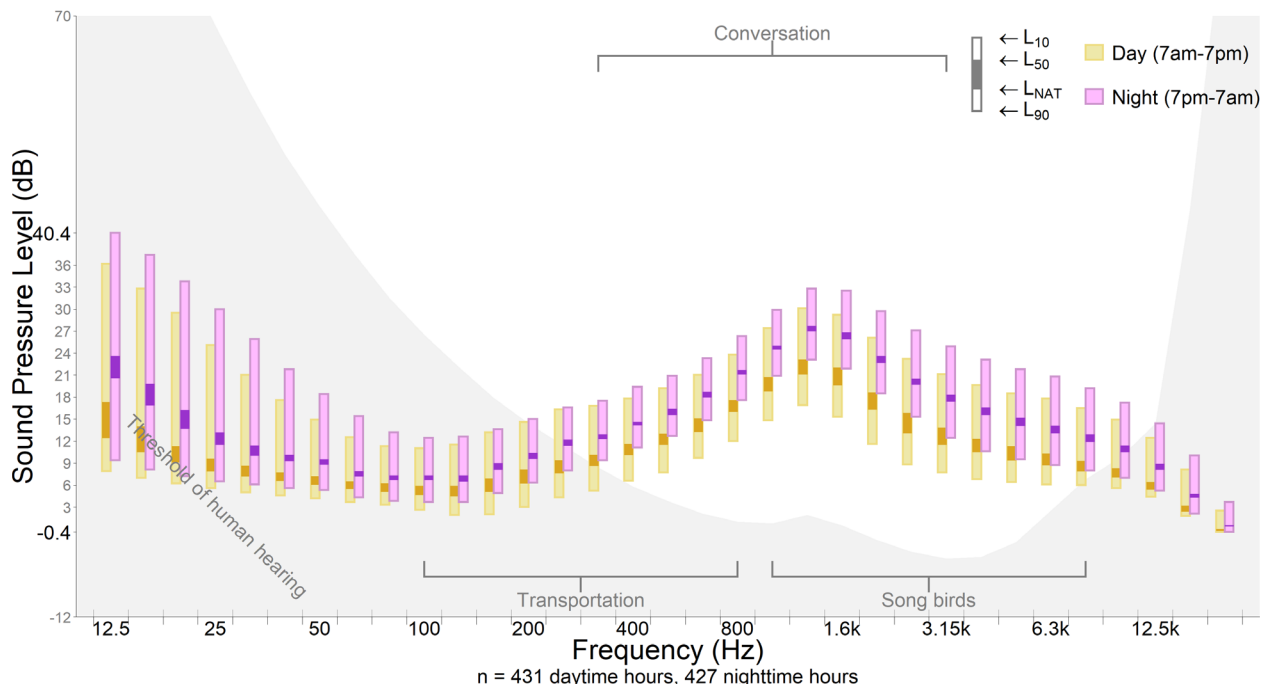


Figure 10. Day and night percentile sound pressure levels for 33 one-third octave bands at SHEN004 in winter.

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 areas of Figure 3–Figure 10 represent 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.

Sound level: Time Above

To understand how acoustic conditions in the park might affect visitors, measured sound levels are compared to sound levels of interest. Specifically, Table 7–Table 8 report 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. 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. For instance, in the full frequency range, the 52 dB ($L_{Aeq,1s}$) level was exceeded at SHEN001 in summer 4.25 % of the time during the day and 19.7 % of the time at night, but in the 20-1,250 Hz range, the 52 dB functional sound level value was very rarely exceeded in daytime or nighttime.

Table 7 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 7. Percent time above metrics for SHEN001, SHEN002, SHEN003, and SHEN004 during summer.

Site ID	Frequency Range	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 ^A	45 dB ^A	52 dB ^A	60 dB ^A	35 dB ^A	45 dB ^A	52 dB ^A	60 dB ^A
SHEN001	Full	12.5–20,000	97.49	48.51	4.25	0.10	99.99	70.13	19.70	0.00
	ANS Weighted ^B	20–1,250	4.16	0.67	0.15	0.00	1.07	0.07	0.01	0.00
SHEN002	Full	12.5–20,000	33.55	6.89	0.73	0.01	90.39	71.95	51.20	0.37
	ANS Weighted ^B	20–1,250	7.02	0.55	0.08	0.00	16.34	0.31	0.04	0.00
SHEN003	Full	12.5–20,000	35.14	1.86	0.26	0.02	58.82	11.70	0.54	0.00
	ANS Weighted ^B	20–1,250	10.86	0.77	0.15	0.01	34.64	0.54	0.03	0.00
SHEN004	Full	12.5–20,000	68.50	8.92	0.57	0.02	93.91	75.74	61.49	1.82
	ANS Weighted ^B	20–1,250	30.81	0.81	0.13	0.01	46.37	1.62	0.05	0.00

^A dB LAeq, 1s re 20 µPa

^B The percent of time ANS-weighted sound levels (20-1,250 Hz) are above functional values.

Table 8. Percent time above metrics for SHEN001, SHEN002, SHEN003, and SHEN004 during winter

Site ID	Frequency Range	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 ^A	45 dB ^A	52 dB ^A	60 dB ^A	35 dB ^A	45 dB ^A	52 dB ^A	60 dB ^A
SHEN001	Full	12.5–20,000	58.29	13.48	0.61	0.01	31.85	2.71	0.17	0.00
	ANS Weighted ^B	20–1,250	56.26	9.60	0.28	0.01	27.45	2.13	0.05	0.00
SHEN002	Full	12.5–20,000	32.82	4.14	0.44	0.02	43.87	16.50	2.31	0.02
	ANS Weighted ^B	20–1,250	29.59	2.76	0.24	0.01	42.21	12.67	0.63	0.01
SHEN003	Full	12.5–20,000	65.45	19.26	1.54	0.05	78.31	34.00	8.53	0.07
	ANS Weighted ^B	20–1,250	57.12	8.35	0.39	0.04	73.85	33.52	4.32	0.04

^A dB LAeq, 1s re 20 µPa

^B The percent of time ANS-weighted sound levels (20-1,250 Hz) are above functional values.

Table 8 (continued). Percent time above metrics for SHEN001, SHEN002, SHEN003, and SHEN004 during winter

Site ID	Frequency Range	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 ^A	45 dB ^A	52 dB ^A	60 dB ^A	35 dB ^A	45 dB ^A	52 dB ^A	60 dB ^A
SHEN004	Full	12.5–20,000	30.58	2.55	0.09	0.00	43.58	14.14	0.90	0.00
	ANS Weighted ^B	20–1,250	15.30	0.41	0.03	0.00	32.17	5.01	0.08	0.00

^A dB L_{Aeq, 1s} re 20 µPa

^B The percent of time ANS-weighted sound levels (20-1,250 Hz) are above functional values.

Sound Level: Percentile Levels

To understand the range of acoustic conditions at the park, percentile sound levels are reported (Figure 11–Figure 18). In Figure 11, the A-weighted percentile sound levels (L_{A90} , $L_{A_{nat}}$, L_{A50} , and L_{A10}) for SHEN001 are shown. 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 11, the L_{A50} (median) sound level for SHEN001 in summer during the 8:00 hour is 43.8 dB. On the other hand, the sound level exceeded 10% of the time (L_{A10}) for the same hour at this site is 49.3 dB, meaning 90% of the measurement period is quieter. High sound levels in the late evening and early morning hours during summer are largely due to insect activity (Figure 11, Figure 13, Figure 15, and Figure 17). Hours where the L_{A50} and the $L_{A_{nat}}$ differ the most are usually hours with the most human-caused noise (in this case, 5:00 – 20:00).

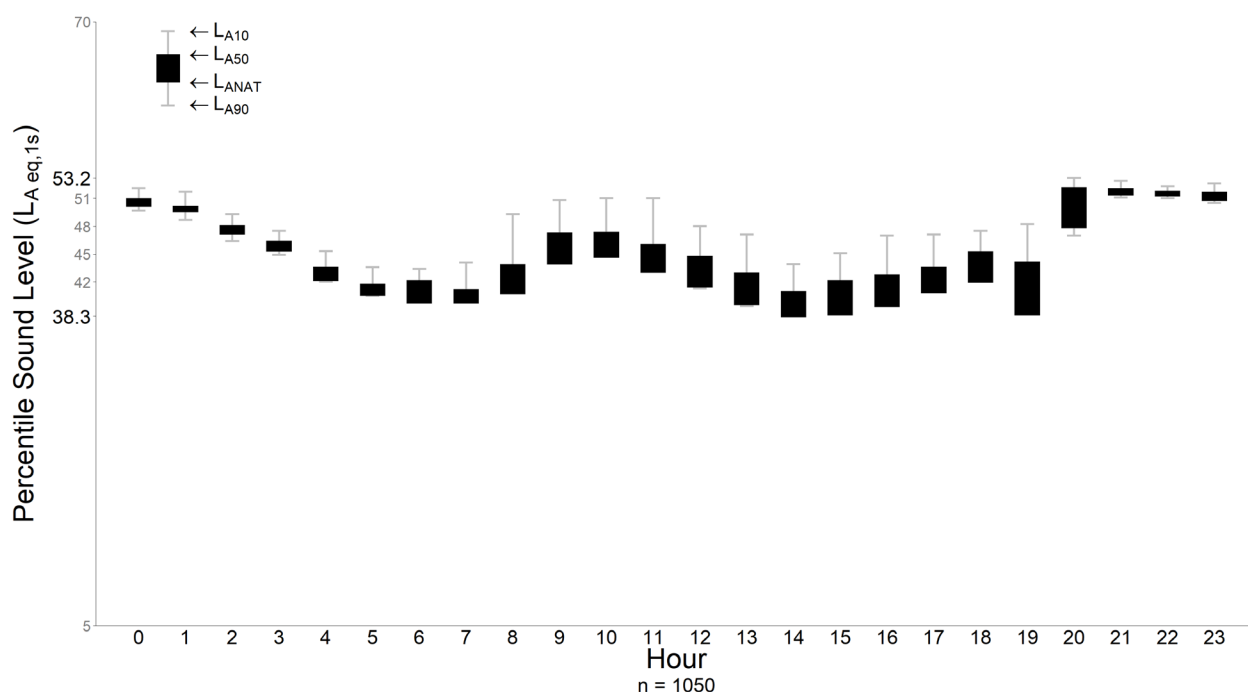


Figure 11. Median percentile sound levels ($L_{Aeq, 1s}$), in dB re 20 μ Pa, at SHEN001 in summer.

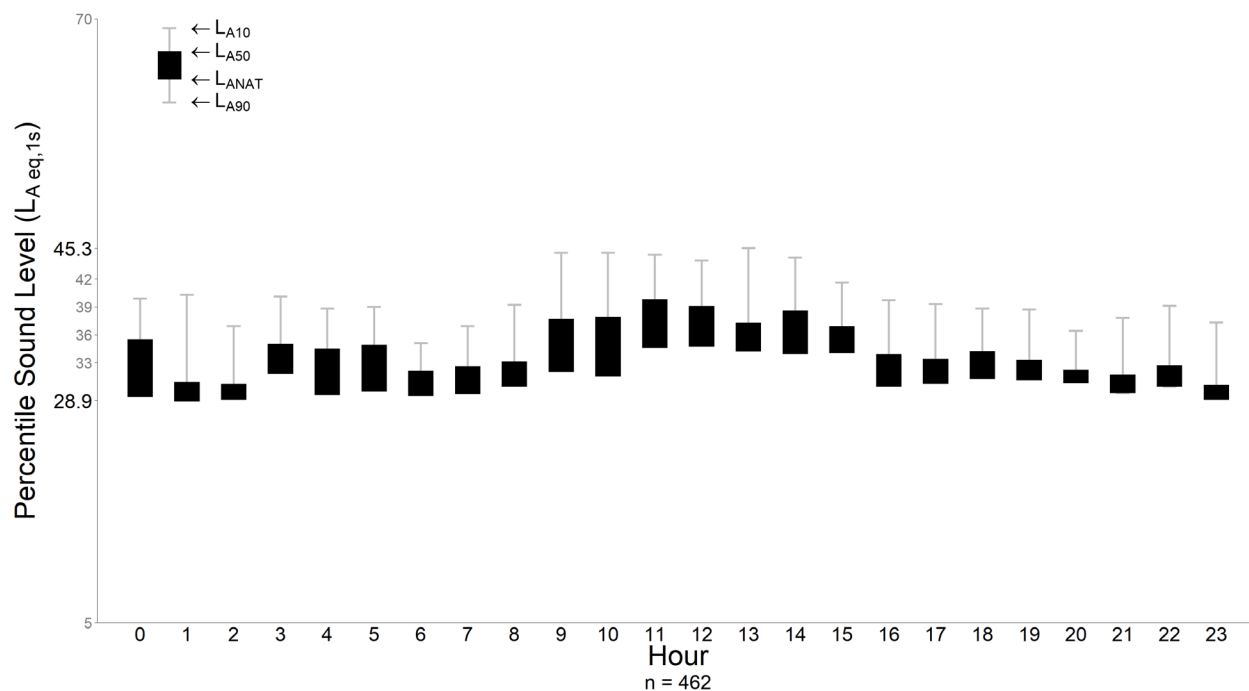


Figure 12. Median percentile sound levels ($L_{Aeq, 1s}$), in dB re 20 μ Pa, at SHEN001 in winter.

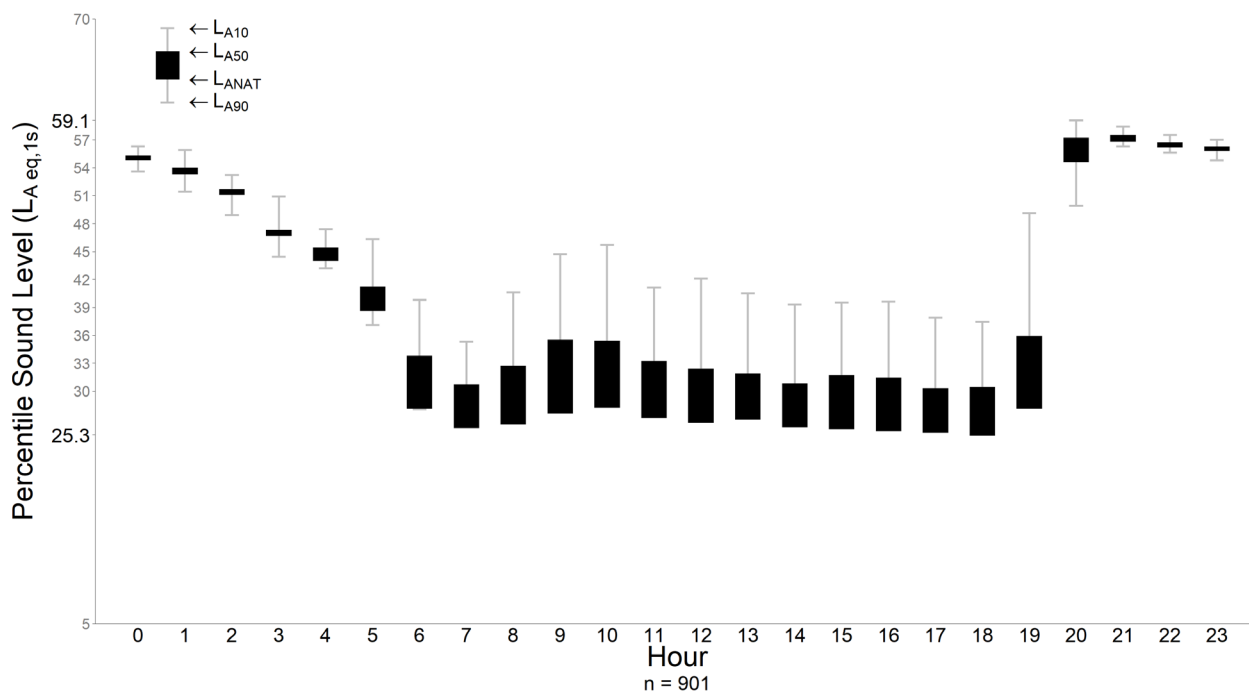


Figure 13. Median percentile sound levels ($L_{Aeq, 1s}$), in dB re 20 μ Pa, at SHEN002 in summer.

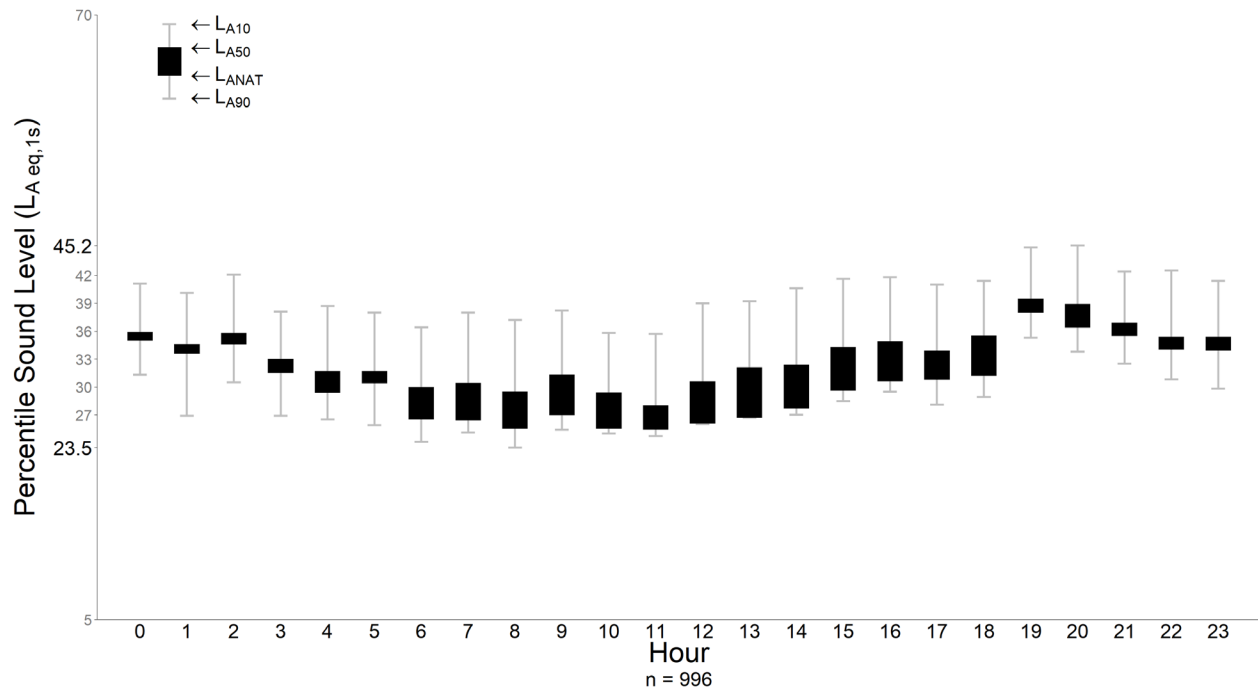


Figure 14. Median percentile sound levels (LAeq, 1s), in dB re 20 µPa, at SHEN002 in winter.

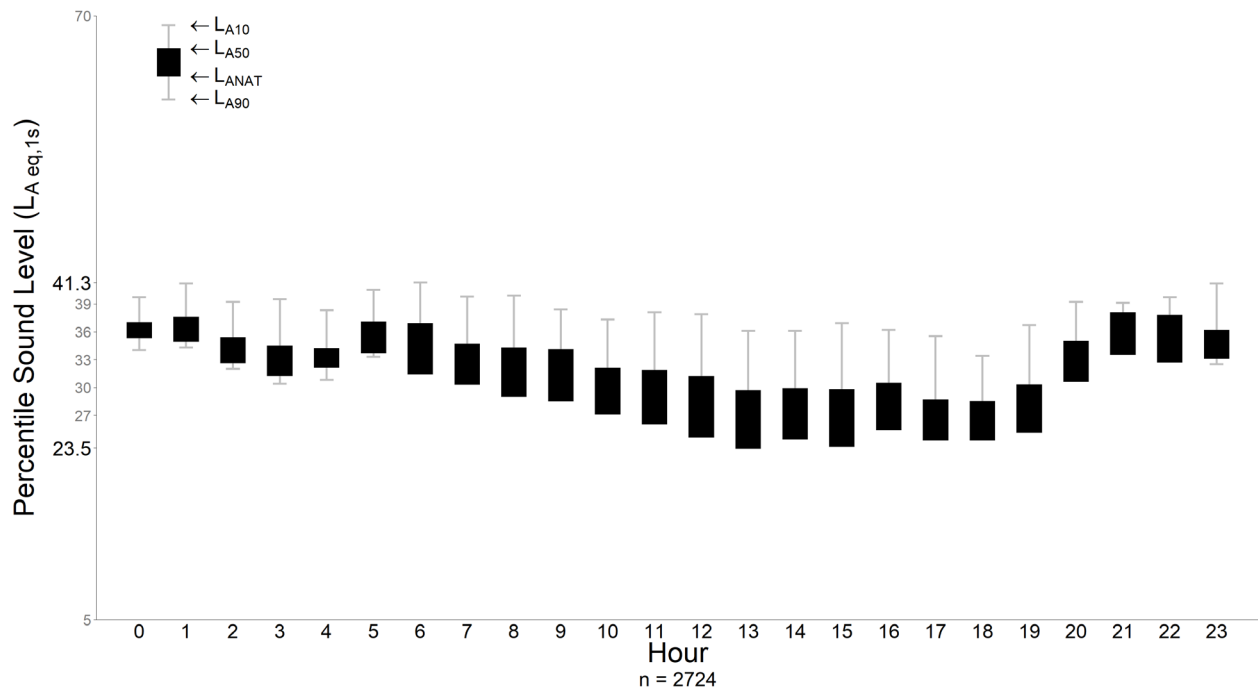


Figure 15. Median percentile sound levels (LAeq, 1s), in dB re 20 µPa, at SHEN003 in summer.

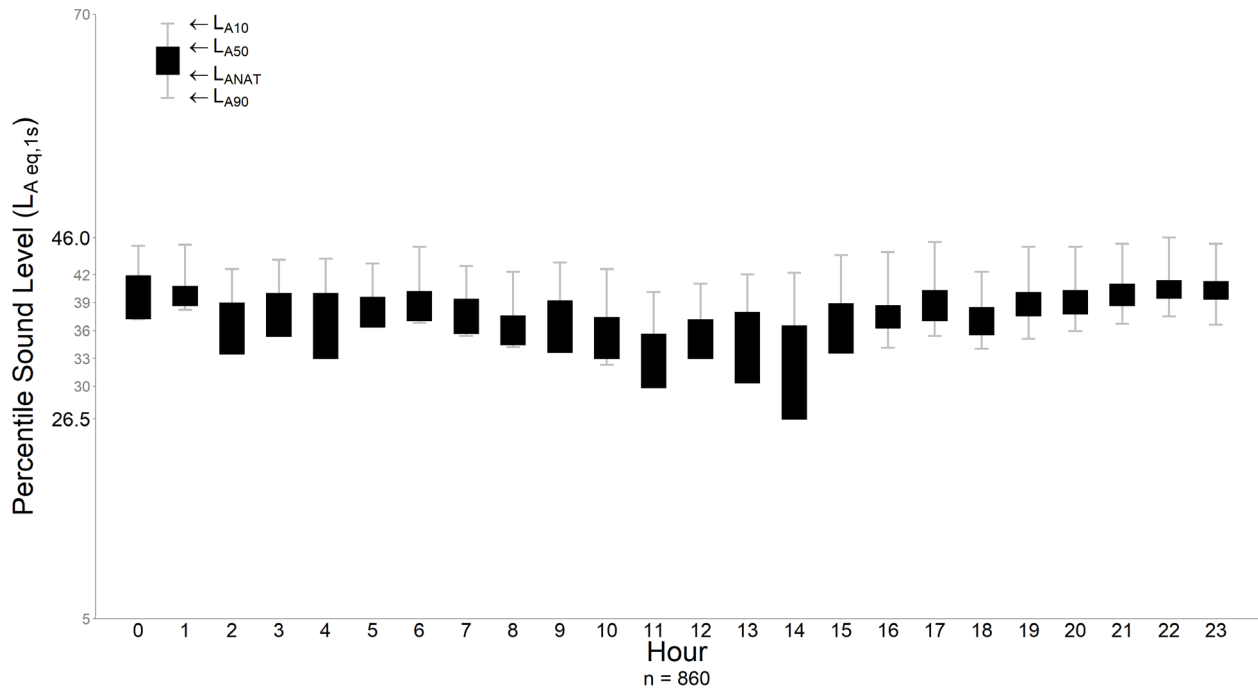


Figure 16. Median percentile sound levels (LAeq, 1s), in dB re 20 µPa, at SHEN003 in winter.

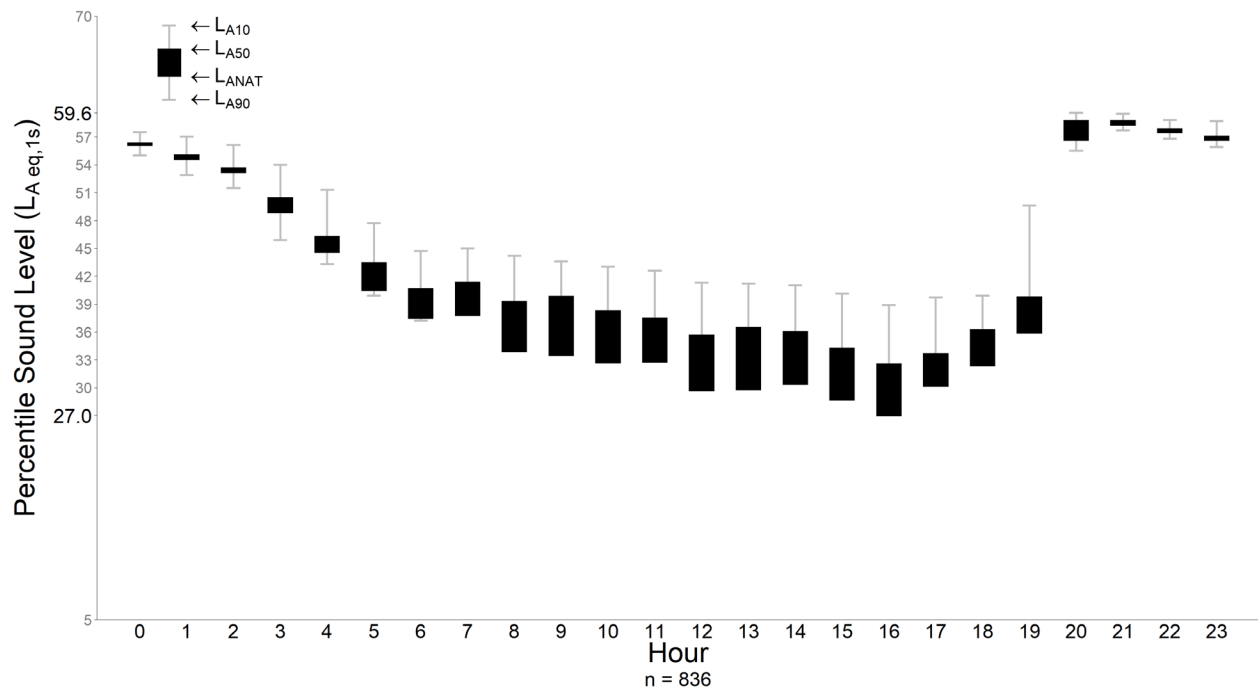


Figure 17. Median percentile sound levels (LAeq, 1s), in dB re 20 µPa, at SHEN004 in summer.

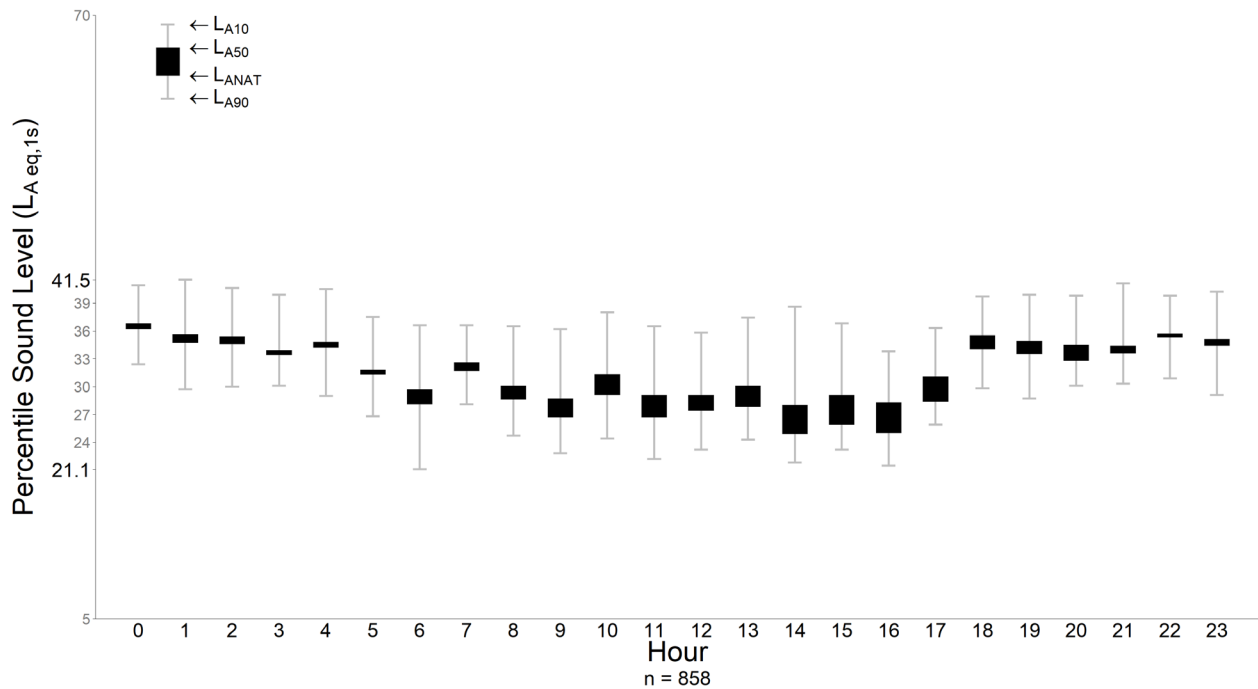


Figure 18. Median percentile sound levels (LAeq, 1s), in dB re 20 µPa, at SHEN004 in winter.

Event duration

Through off-site listening analysis, event duration for all audible sounds is calculated. Table 9–Table 24 list audible natural sounds and noise sources at SHEN001, SHEN 002, SHEN 003, and SHEN004. Mean hourly audibility was calculated over eight days of analysis. See Appendix A for more information on analysis procedures. Figure 19–Figure 26 display hourly audibility for all non-natural sources, as compared to audibility of one noise source of interest (aircraft) for all four sites for winter and summer.

Table 9. Mean hourly time audible (%) for each natural sound source at SHEN001 in summer, n=8 days.

Natural 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
Wind	1.1	1.5	2.2	1.1	6.3	1.9	5.6	2.2	2.2	5.6	8.9	16.7	25.2	24.4	14.8	20.0	22.6	20.0	10.0	10.0	4.8	1.1	3.7	0.4
Rain	0.0	0.0	0.0	0.0	0.0	0.0	0.0	1.9	10.4	11.5	11.1	11.1	11.1	13.3	16.3	4.8	0.7	10.4	4.1	3.3	0.0	0.0	0.0	0.0
Coyote	0.0	0.0	0.4	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	0.0	0.0	0.0	0.0	0.0	0.0	0.4	0.0
Bird	1.1	8.1	2.2	2.6	8.5	14.4	52.6	50.7	37.4	23.0	23.3	21.1	15.9	12.6	18.9	11.9	8.5	10.4	13.3	15.6	5.2	2.2	0.4	1.1
Insects	100.0	100.0	100.0	100.0	99.6	99.6	99.6	99.6	93.3	91.1	99.6	95.6	98.5	94.8	93.7	99.3	98.9	97.0	99.3	97.4	100.0	100.0	99.6	100.
Animal	0.0	0.0	0.4	1.9	4.1	2.2	3.7	5.6	9.3	8.1	0.0	0.7	1.5	2.2	1.5	1.1	1.1	2.2	0.7	3.0	1.5	0.0	0.4	0.0
Natural Other	0.0	0.0	0.4	0.7	0.0	0.0	0.0	0.4	1.1	0.0	0.7	0.0	0.4	0.0	0.0	0.0	0.0	0.0	1.1	0.4	0.0	0.0	0.0	0.0
Wind-induced Natural	0.0	0.0	0.0	0.4	0.0	1.5	1.1	0.7	5.6	6.7	2.2	17.0	28.5	25.9	23.0	24.8	23.7	25.6	8.1	0.4	0.0	0.4	1.1	0.4
Natural Unknown	1.9	7.0	5.9	4.8	3.7	8.1	10.4	10.0	6.7	3.3	3.7	6.3	5.9	5.9	7.0	8.9	8.9	9.6	10.7	8.9	3.3	3.3	3.3	2.2

Table 10. Mean hourly time audible (%) for each natural sound source at SHEN001 in winter, n=8 days.

Natural 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
Wind	2.2	1.1	1.1	4.8	6.3	9.6	3.3	2.2	1.5	3.0	5.6	11.5	11.1	10.0	8.5	10.0	3.3	6.3	3.0	6.7	1.1	5.6	5.6	5.9
Rain	0.0	0.0	0.0	0.0	0.0	0.0	0.0	1.9	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	3.3	11.1	4.1
Flowing Water	97.0	99.6	100.0	100.0	97.0	97.4	100.0	97.0	100.0	97.8	100.0	100.0	93.3	96.7	97.4	100.0	95.9	98.5	100.0	92.2	87.8	87.4	77.4	85.2
Mammal	0.4	0.0	0.0	0.0	0.0	0.0	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	0.0	0.0	0.0	0.0	0.0
Coyote	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	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.7	0.0	0.0	0.0
Bird	0.7	0.7	2.6	1.9	0.0	1.1	2.2	30.4	18.5	23.0	26.3	19.3	15.9	20.7	21.5	27.8	20.7	11.1	3.0	2.6	0.0	0.7	1.9	0.0
Animal	0.0	0.0	0.4	0.0	0.0	0.0	0.4	6.3	0.4	0.0	0.4	2.2	1.9	2.2	2.2	0.4	0.4	0.4	0.7	0.0	0.4	2.2	0.7	0.4
Natural Other	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	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	0.0	0.0	0.0
Wind-induced Natural	13.0	11.1	23.7	33.7	29.3	28.5	25.2	21.1	19.6	31.5	48.9	49.3	66.7	60.7	53.7	43.0	48.1	35.9	39.3	37.4	33.0	35.6	34.8	28.9
Natural Unknown	0.4	1.9	0.4	1.1	0.7	1.1	1.5	0.7	1.5	0.4	0.4	2.6	1.5	1.1	2.2	1.1	1.1	0.0	0.4	0.0	1.5	0.4	0.7	1.9

Table 11. Mean hourly time audible (%) for each noise source at SHEN001 in summer, n=8 days.

Noise 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
Jet	11.1	4.4	7.4	1.5	5.2	16.7	41.1	65.2	50.0	41.5	43.0	38.5	43.3	42.6	44.4	43.7	45.2	57.4	57.8	60.7	46.7	37.8	29.6	14.8
Propeller Aircraft	4.1	0.4	0.0	0.4	0.0	0.7	3.0	4.1	5.6	14.4	10.7	17.4	8.5	14.1	11.5	16.7	11.1	9.3	7.8	3.3	3.0	4.8	5.6	3.3
Helicopter	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.4	0.4	0.4	0.0	1.9	0.0	0.4	0.0	0.0	0.0	0.0	0.0
Vehicle	0.7	0.0	0.4	1.1	1.1	0.4	0.4	1.1	1.1	0.4	1.1	0.7	1.9	0.4	0.0	0.4	0.4	1.1	1.1	1.1	2.2	0.4	0.0	0.0
Automobile	1.9	0.4	2.6	5.6	6.3	5.9	5.2	1.9	1.5	0.7	3.7	1.1	2.6	1.1	2.6	3.3	2.2	1.5	2.2	1.9	1.9	1.9	1.5	1.5
Rumble Strip	0.0	0.0	0.0	0.0	0.0	0.0	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	0.0	0.0	0.0	0.0	0.0
Motorcycle	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.4	0.0	0.0	0.4	0.0	0.0	0.0	0.4	0.0	0.0	0.4	0.0	0.0	0.0
Truck (6+ tires)	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.7	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
Heavy Equipment	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.4	0.7	3.3	0.4	0.4	0.4	0.0	0.4	0.0	0.0	0.0	0.0	0.0	0.0	0.0

Table 11 (continued). Mean hourly time audible (%) for each noise source at SHEN001 in summer, n=8 days.

Noise 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
Train Rumble	10.4	13.3	20.7	14.8	28.9	20.7	18.1	10.7	10.7	11.1	5.9	0.4	3.7	2.2	5.6	1.1	1.5	0.0	0.0	0.0	0.7	0.0	2.2	1.5
Train Whistle	0.0	0.0	0.4	0.4	0.7	0.0	1.9	0.7	0.7	0.4	0.7	0.0	0.4	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
Voices	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	3.7	2.6	0.0	0.4	1.1	0.0	0.0	13.7	1.9	0.4	0.0	0.0	0.0	0.0	0.0
Walking	0.0	0.0	0.0	0.0	0.0	0.0	0.0	1.5	0.0	5.6	2.2	0.4	0.4	0.7	0.0	0.0	0.4	0.7	0.4	1.1	0.0	0.0	0.0	0.0
Gunshot	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.4	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.4	0.0	0.0	0.0	0.0
Dog	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	0.7	0.0
Non-natural Unknown	20.0	13.7	21.1	34.1	29.6	31.5	17.8	15.9	18.1	14.1	23.3	23.3	18.1	18.9	23.0	23.3	15.2	13.3	15.6	17.8	10.4	16.7	11.9	23.7
Unknown	0.4	0.0	0.0	0.4	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.4	0.0	0.4	0.0	0.0	0.4	0.0	0.0	0.0	0.0	0.4	0.0

Table 12. Mean hourly time audible (%) for each noise source at SHEN001 in winter, n=8 days.

Noise 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
Jet	4.1	5.2	7.8	1.9	3.0	7.4	12.2	37.8	22.6	18.9	14.8	18.1	21.9	22.6	35.2	30.0	27.8	32.6	38.1	37.0	21.5	23.0	17.4	10.4
Propeller Aircraft	3.3	0.0	0.0	1.1	0.7	1.1	2.2	0.0	4.1	8.1	8.9	6.3	8.1	8.5	10.7	10.0	8.1	3.7	1.1	3.3	1.1	3.3	0.0	0.0
Helicopter	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	1.1	0.0	0.0	0.7	1.5	0.7	0.0	0.0	0.0	1.5	0.0	0.0	0.0
Vehicle	5.9	5.2	3.7	6.7	3.0	6.7	5.9	9.6	6.7	3.7	6.7	3.7	5.9	3.7	3.0	6.3	2.6	1.1	3.0	7.0	9.3	4.8	7.8	8.9
Automobile	4.4	4.1	1.1	4.4	4.4	7.8	7.8	9.6	4.1	4.1	3.0	5.6	1.5	1.1	1.1	1.5	0.7	1.9	5.2	1.9	0.4	0.4	1.1	0.4
Rumble Strip	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	0.4	0.0
Motorcycle	0.0	0.0	0.0	0.0	0.0	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	0.0	0.0	0.0	0.0	0.0	0.0
Trains	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.4	0.0	0.0	0.0	0.0	0.0	0.4	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
Train Rumble	62.6	77.8	82.6	81.5	72.6	64.1	69.3	44.8	68.5	65.6	66.7	58.9	45.2	39.3	28.9	30.4	51.1	43.3	44.4	40.0	51.5	50.4	53.7	63.0
Train Whistle	0.0	0.0	0.0	1.1	1.1	0.0	1.5	0.4	1.9	3.7	1.1	1.1	1.5	0.0	0.7	0.0	0.7	0.7	0.0	0.0	0.0	0.4	0.7	0.0
Voices	0.0	0.0	0.0	0.0	0.0	0.0	0.4	0.0	0.7	0.0	0.7	1.1	1.5	0.0	0.0	0.0	0.0	0.0	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	0.0	0.4	0.7	0.4	1.1	1.9	0.4	0.0	0.0	0.4	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
Gunshot	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.7	1.9	0.0	0.0	0.7	1.9	1.9	0.0	0.0	0.0	0.0	0.0	0.0	0.0
Dog	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.7	0.0	0.7	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.7	0.0	0.0	0.0	0.0	0.0
Non-natural Unknown	15.9	10.0	7.8	1.9	5.9	7.0	5.9	7.8	4.4	5.6	5.6	4.8	9.3	10.4	8.1	8.1	4.1	5.9	4.8	5.2	3.3	4.1	6.3	4.4
Unknown	0.0	0.4	0.0	0.0	0.0	0.0	0.0	0.0	0.0	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	0.0	0.0

Table 13. Mean hourly time audible (%) for each natural sound source at SHEN002 in summer, n=8 days.

Natural 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
Wind	0.4	0.0	3.0	11.1	11.1	11.1	10.7	1.9	0.7	0.0	0.4	3.0	3.0	2.2	1.1	1.1	1.9	1.9	0.0	0.0	0.0	0.0	4.4	3.7
Rain	0.0	0.0	0.0	0.0	0.0	0.4	11.1	7.4	4.1	1.9	0.4	3.3	5.6	4.4	1.9	4.4	7.4	2.2	0.7	1.5	0.0	0.0	0.0	0.0
Flowing Water	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	2.6	3.3	0.7	1.5	1.5	0.0	0.0	0.0	0.0
Thunder	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	0.4	0.0

Table 13 (continued). Mean hourly time audible (%) for each natural sound source at SHEN002 in summer, n=8 days.

Natural 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
Bird	0.0	0.0	0.0	0.7	0.0	7.0	51.1	49.6	47.0	35.2	20.0	8.9	8.5	11.1	7.8	11.5	9.6	8.1	7.4	16.3	3.0	0.0	0.0	0.0
Insects	100.0	99.6	100.0	100.0	100.0	100.0	66.3	52.6	74.8	88.9	85.2	69.3	58.1	53.0	52.2	55.2	76.3	75.2	81.1	82.6	88.5	88.9	88.9	88.9
Animal	0.0	0.0	0.0	0.0	0.7	0.0	0.7	0.0	0.0	0.4	0.0	0.0	0.0	0.0	0.0	0.0	0.4	0.0	0.0	0.0	0.0	0.0	0.0	0.0
Natural Other	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.4	0.7	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.7	0.0	0.0	0.0	0.0
Wind-induced Natural	14.8	26.7	46.7	42.6	37.4	31.5	33.0	31.1	27.4	13.3	17.4	36.3	37.4	36.7	35.2	34.1	33.3	38.5	20.4	24.1	13.7	21.5	25.9	31.9
Natural Unknown	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.7	0.0	0.0	1.1	0.7	3.7	2.2	1.9	1.9	0.4	1.5	0.0	0.0	0.0	0.0

Table 14. Mean hourly time audible (%) for each natural sound source at SHEN002 in winter, n=8 days.

Natural 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
Wind	2.6	1.5	2.6	2.6	1.1	1.9	3.0	4.1	1.9	0.7	1.9	3.0	1.9	0.7	1.9	1.5	1.9	1.5	1.1	7.4	10.7	17.4	18.1	23.0
Wind, Strong	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	0.4	0.0	0.0
Rain	18.9	15.9	11.5	11.9	13.0	11.5	12.2	11.1	11.1	19.3	21.5	11.5	11.1	16.7	6.7	13.0	11.1	11.1	11.1	11.1	11.1	11.1	11.1	15.6
Flowing Water	11.1	11.1	11.1	11.1	11.5	11.1	11.1	11.1	11.1	15.9	14.1	11.1	12.2	15.6	21.5	19.6	21.1	21.9	18.1	11.1	11.1	11.1	11.1	11.1
Thunder	0.4	0.0	0.0	0.4	0.0	0.0	0.0	0.4	0.4	0.0	0.0	1.1	0.4	0.7	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	0.0	0.0	0.0	0.0	0.0	0.7	0.0	0.0	0.0	0.0	1.9	1.9	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
Squirrel	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	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
Bird	0.0	0.4	0.0	0.4	0.0	0.4	7.0	40.4	30.0	29.6	20.0	15.6	12.2	23.0	18.1	27.0	33.7	11.1	1.5	0.0	0.7	0.4	0.0	0.0
Animal	0.4	0.0	0.4	0.0	0.0	0.0	0.0	0.0	0.4	0.4	1.1	1.1	1.1	0.7	1.1	1.1	0.7	0.7	0.4	0.0	0.0	0.4	0.0	0.0
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	0.0	0.0	0.0	0.4	0.0	0.0
Wind-induced Natural	77.4	77.4	83.3	75.6	81.5	82.6	68.1	54.1	58.1	46.7	60.0	58.1	60.0	59.6	47.8	54.8	66.3	78.5	80.7	83.3	81.1	82.2	84.1	84.4
Natural Unknown	12.6	8.1	4.1	3.7	8.9	5.9	6.7	3.7	13.3	19.3	21.5	21.1	16.3	13.7	13.7	14.1	12.6	7.8	5.6	4.4	3.0	2.2	4.8	2.2

Table 15. Mean hourly time audible (%) for each noise source at SHEN002 in summer, n=8 days.

Noise 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
Jet	8.9	8.1	3.3	2.6	1.5	13.3	29.6	40.7	41.1	19.3	27.8	16.3	35.2	40.4	30.4	35.2	36.3	34.8	39.3	45.9	41.1	30.0	30.0	22.2
Propeller Aircraft	0.0	0.0	0.0	1.1	0.0	0.0	3.3	3.7	6.3	8.5	11.1	10.4	5.6	5.9	7.0	11.9	7.0	4.8	5.6	1.9	1.9	3.0	3.3	1.1
Helicopter	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.7	0.0	0.0	2.2	3.3	0.7	0.4	0.0	0.0	0.7	0.7	0.4	1.5	0.0	0.0	0.0	0.0
Vehicle	0.0	0.4	1.9	1.1	0.7	3.0	4.1	2.6	1.1	6.3	2.6	1.9	1.5	4.4	1.9	1.9	0.4	4.4	0.7	4.1	0.7	1.9	2.2	1.1
Alarm, Horn	0.0	0.0	0.0	0.0	0.0	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	0.0	0.0	0.0	0.0	0.0	0.0
Train Rumble	0.0	0.7	0.0	1.5	16.7	22.2	25.6	22.2	11.5	17.0	8.1	7.8	7.4	4.1	6.3	11.1	14.4	13.7	13.0	11.5	1.5	0.7	0.0	0.4
Train Whistle	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.4	0.0	0.4	0.0	0.0	0.0	0.0	0.4	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
Voices	0.0	0.0	0.0	0.0	3.0	1.5	3.3	6.7	0.7	7.8	19.3	34.4	35.9	33.3	42.6	39.3	23.7	11.5	15.6	1.5	0.4	0.0	0.0	0.0
Walking	0.0	0.0	0.0	0.0	3.0	1.5	1.9	2.2	0.7	5.2	7.8	16.3	16.7	14.8	18.1	15.9	8.9	7.8	7.8	0.7	0.4	0.0	0.0	0.0
Portable Audio Device	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	0.4	0.0	0.0	0.0	0.4	0.0	0.0	0.0	0.0	0.0	0.0

Table 15 (continued). Mean hourly time audible (%) for each noise source at SHEN002 in summer, n=8 days.

Noise 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
Gunshot	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.4	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
Dog	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	0.4	0.0	0.0	0.0	0.0	0.0
Non-natural Unknown	6.3	7.8	9.6	8.1	8.5	12.6	17.0	21.1	25.6	34.1	29.6	34.8	30.7	27.8	33.0	24.8	22.6	23.3	26.7	19.6	10.7	8.5	2.6	5.6
Unknown	0.0	0.0	0.4	0.0	0.4	0.0	0.0	0.0	0.7	0.0	0.0	0.0	0.0	0.4	0.0	0.0	0.0	1.5	0.7	0.0	0.0	0.0	0.0	0.0

Table 16. Mean hourly time audible (%) for each noise source at SHEN002 in winter, n=8 days.

Noise 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	0.4	0.0	0.0	0.0	0.0	1.1	1.9	0.7	0.7	0.4	0.0	0.0	0.7	1.5	0.4	0.4	0.4	0.0	0.0	0.4	0.7	0.4	2.2	0.0
Jet	8.9	5.6	5.9	2.6	4.4	8.5	21.5	36.3	32.2	24.4	31.9	32.6	36.7	33.7	38.9	32.2	32.6	33.7	30.7	20.4	27.8	18.1	14.1	15.2
Propeller Aircraft	1.9	0.4	0.0	0.0	0.0	0.0	1.9	0.7	1.9	6.7	15.6	4.4	6.3	10.4	11.9	12.2	4.8	3.7	1.1	1.1	0.4	1.5	1.5	1.1
Helicopter	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	1.1	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
Vehicle	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.4	0.0	0.0	0.0	0.4	1.5	1.1	0.7	0.4	0.4	0.0	0.0	0.0	0.0	0.0
Automobile	0.0	0.0	0.0	0.0	0.0	0.0	1.1	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
Motorcycle	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	0.4	0.0	0.0	0.0
Train Rumble	5.6	3.7	9.3	9.3	10.7	1.5	5.6	7.0	15.2	15.9	6.7	10.0	9.6	10.7	6.3	10.0	8.9	7.8	6.3	6.3	7.8	7.0	3.3	1.1
Train Whistle	0.0	0.4	0.7	0.0	0.4	0.0	1.1	0.4	0.0	0.0	0.0	0.0	0.4	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
People	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	3.0	1.5	0.7	0.4	0.4	0.0	0.0	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	4.1	4.1	6.7	1.5	3.7	15.9	24.4	21.9	25.6	21.9	11.9	7.0	0.0	0.7	1.5	0.0	0.0	0.0
Walking	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	2.2	1.9	1.9	0.0	0.7	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
Portable Audio Device	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	0.4	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
Gunshot	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	0.4	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
Buildings	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	0.4	0.0
Construction	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	0.4	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
Non-natural Unknown	3.7	1.5	1.5	5.2	7.0	15.2	13.7	8.5	10.7	17.4	17.8	15.2	12.2	14.8	9.3	8.9	10.0	3.0	4.1	3.3	2.6	1.9	0.0	1.1
Unknown	0.7	1.5	1.1	0.4	0.7	1.5	1.5	4.8	5.2	4.8	3.7	3.0	3.7	3.0	3.3	2.6	1.9	1.5	3.7	1.5	1.5	3.0	2.2	1.5

Table 17. Mean hourly time audible (%) for each natural sound source at SHEN003 in summer, n=8 days.

Natural 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
Wind	0.4	0.0	0.4	0.0	0.0	0.7	0.0	0.0	0.4	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.4	0.4	0.0	0.0	0.0	0.4	0.0	0.4
Water	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	1.9	0.0	1.5	0.0	0.4	1.5	0.0	0.0	0.0	0.0	0.0	0.0	0.0
Rain	0.0	1.1	0.0	0.7	3.3	9.6	5.9	0.4	0.0	0.4	0.0	0.0	2.6	0.4	0.0	2.2	4.8	1.1	1.9	1.1	1.1	0.4	0.4	0.0
Flowing Water	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	4.1	2.6	3.0	2.2	0.0	4.1	4.8	4.1	2.2	0.0	0.0	0.0	0.0
Bird	0.0	1.9	0.0	0.7	1.5	4.4	24.1	34.8	33.7	23.0	14.8	11.9	19.3	13.7	8.1	7.8	7.8	10.4	10.7	23.7	13.7	0.4	0.0	0.4
Insects	44.4	46.3	39.3	35.9	27.8	11.5	18.1	24.8	25.6	28.5	33.0	23.3	17.4	20.4	23.0	23.0	27.8	27.0	26.7	26.7	77.0	95.2	90.7	87.0

Table 17 (continued). Mean hourly time audible (%) for each natural sound source at SHEN003 in summer, n=8 days.

Natural 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
Animal	0.4	0.0	0.4	0.0	0.4	0.4	1.1	0.4	0.7	0.0	0.7	0.7	0.7	0.4	0.0	0.0	0.0	0.4	0.0	0.0	0.4	0.0	0.4	0.0
Natural Other	0.0	0.0	0.4	0.0	0.0	0.4	0.0	0.4	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.4	0.0	0.0	0.7	0.4	0.4	
Wind-induced Natural	93.7	82.6	88.9	81.5	73.7	74.8	74.8	74.1	72.6	74.1	64.4	59.6	55.2	47.4	61.9	53.3	47.8	53.3	45.6	47.0	56.3	53.3	49.6	54.1
Natural Unknown	4.8	2.6	4.8	5.6	8.5	8.9	7.4	4.8	3.3	2.2	5.2	6.3	4.1	7.0	7.0	8.9	6.3	5.9	8.1	5.9	8.1	5.2	1.9	8.5

Table 18. Mean hourly time audible (%) for each natural sound source at SHEN003 in winter, n=2 days.

Natural 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
Wind	1.7	6.7	3.3	0.0	0.0	0.0	0.0	0.0	0.0	1.7	0.0	0.0	0.0	1.7	1.7	0.0	1.7	1.7	0.0	0.0	1.7	1.7	3.3	1.7
Water	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	1.7	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
Rain	31.7	21.7	6.7	0.0	0.0	0.0	0.0	0.0	0.0	20.0	13.3	0.0	15.0	50.0	28.3	50.0	50.0	50.0	50.0	50.0	50.0	50.0	53.3	53.3
Bird	5.0	5.0	5.0	1.7	8.3	0.0	0.0	70.0	58.3	40.0	48.3	25.0	15.0	0.0	18.3	11.7	15.0	15.0	20.0	15.0	6.7	8.3	18.3	5.0
Amphibian *	0.0	0.0	0.0	0.0	0.0	0.0	0.0	1.7	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
Animal	0.0	1.7	3.3	0.0	1.7	0.0	1.7	1.7	5.0	1.7	1.7	1.7	1.7	0.0	3.3	0.0	0.0	1.7	0.0	3.3	1.7	3.3	6.7	5.0
Wind-induced Natural	50.0	50.0	68.3	66.7	56.7	63.3	63.3	65.0	48.3	38.3	58.3	43.3	60.0	55.0	30.0	30.0	73.3	75.0	83.3	85.0	76.7	55.0	51.7	50.0
Natural Unknown	6.7	1.7	6.7	13.3	1.7	13.3	8.3	1.7	3.3	16.7	13.3	18.3	6.7	1.7	13.3	0.0	0.0	1.7	1.7	8.3	1.7	3.3	8.3	3.3

* Amphibian was misidentified and was confirmed to be a bird.

Table 19. Mean hourly time audible (%) for each noise source at SHEN003 in summer, n=8 days.

Noise 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	0.7	0.0	0.0	0.0	0.0	0.4	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.4	0.0	0.0	0.4	0.0	
Jet	7.0	7.4	1.5	0.4	0.4	11.1	10.0	18.5	27.4	11.5	14.4	5.9	25.2	25.9	21.1	20.0	25.2	24.1	24.4	31.1	35.6	24.4	30.0	23.3
Jet, Military	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.7	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
Propeller Aircraft	0.0	0.4	0.0	0.7	0.0	0.0	1.9	3.7	3.0	4.4	7.0	9.6	4.1	5.2	4.4	12.2	5.6	8.1	3.0	4.1	2.6	4.4	2.2	0.7
Helicopter	0.0	0.0	0.0	0.0	0.0	0.0	0.0	1.1	0.0	1.5	1.1	0.0	0.7	0.7	0.0	1.5	1.1	2.2	0.0	1.1	0.0	0.0	0.7	0.0
Vehicle	1.9	1.1	1.5	1.5	1.1	2.6	3.7	2.6	10.0	6.7	12.2	17.0	8.5	10.0	9.6	11.1	11.1	6.7	11.5	8.1	5.9	7.0	5.9	13.0
Alarm, Horn	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.4	1.5	0.0	0.0	0.4	0.4	2.2	0.7	0.7	0.4	0.4	0.0	0.0	0.0	0.0	0.7
Rumble Strip	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	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	0.0	0.0
Motorcycle	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.7	0.4	0.0	0.4	0.0	0.0	0.0	0.0	0.7	1.9	0.7	0.0	0.0	0.0
Train	0.0	0.4	0.4	2.6	2.6	0.0	3.0	0.0	1.5	3.7	0.7	10.0	4.1	1.9	6.3	2.6	6.3	1.9	0.0	0.0	0.0	3.7	0.0	0.0
Train Rumble	27.4	37.0	43.0	37.4	34.8	42.2	49.6	57.0	57.4	52.2	53.7	47.8	41.9	41.9	42.2	40.7	32.6	35.2	35.9	28.9	29.6	31.5	26.7	23.7
Train Whistle	0.4	2.2	1.9	1.1	3.0	0.0	4.4	7.4	4.1	1.5	1.9	0.0	0.0	0.4	0.7	0.0	0.0	0.7	0.0	1.5	1.9	0.7	0.4	0.0
People	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.4	0.0	0.0	0.4	0.4	1.1	0.0	0.4	0.4	0.7	0.7	0.0	0.0	0.0	0.0
Voices	0.0	0.0	2.6	0.0	0.0	0.0	0.4	2.2	7.4	13.0	35.2	56.3	55.9	61.1	51.9	44.8	47.8	33.0	30.7	20.4	3.0	0.0	0.0	0.0
Walking	0.0	0.0	0.0	0.0	0.0	0.0	0.4	0.7	3.7	10.4	20.7	37.0	37.0	41.1	34.8	35.2	34.1	27.4	24.1	19.6	3.0	0.0	0.0	0.0
Portable Audio Device	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	0.4	0.0	0.0	0.0	0.0	0.0	0.0

Table 19 (continued). Mean hourly time audible (%) for each noise source at SHEN003 in summer, n=8 days.

Noise 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
Gunshot	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	1.9	0.0	0.0	0.0	0.0
Dog	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.4	0.0	0.4	0.0	0.4	0.0	0.4	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
Horse	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	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	0.0
Buildings	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	0.4	0.0	0.0	0.0	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	2.2	0.0	0.0	0.0	0.0	0.0	0.0	0.7	5.9	1.5	0.0	0.0	0.0	0.0	0.0	0.0
Non-natural Unknown	17.0	20.4	21.5	25.6	11.9	20.4	24.1	18.9	14.1	21.9	18.5	20.7	24.4	21.5	19.6	18.1	16.7	22.2	24.4	18.1	15.9	14.1	16.3	13.7
Unknown	0.4	0.0	0.7	0.0	2.6	0.7	0.4	1.5	2.2	3.0	1.9	1.9	1.1	1.1	4.8	4.1	4.1	1.1	0.7	1.5	1.1	0.4	7.4	1.1

Table 20. Mean hourly time audible (%) for each noise source at SHEN003 in winter, n=2 days.

Noise 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
Jet	11.7	3.3	1.7	1.7	6.7	3.3	11.7	15.0	18.3	13.3	5.0	16.7	25.0	18.3	23.3	35.0	15.0	25.0	20.0	15.0	20.0	23.3	8.3	13.3
Propeller Aircraft	0.0	0.0	0.0	0.0	0.0	0.0	3.3	3.3	0.0	10.0	5.0	6.7	10.0	6.7	8.3	8.3	1.7	0.0	0.0	1.7	1.7	3.3	0.0	0.0
Vehicle	3.3	1.7	11.7	5.0	3.3	1.7	5.0	1.7	11.7	18.3	21.7	33.3	5.0	25.0	33.3	28.3	20.0	20.0	16.7	10.0	0.0	6.7	1.7	0.0
Alarm, Horn	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	1.7	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
Train	0.0	0.0	0.0	0.0	0.0	1.7	8.3	0.0	8.3	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	13.3
Train Whistle	0.0	0.0	0.0	1.7	0.0	1.7	1.7	0.0	6.7	5.0	1.7	0.0	3.3	0.0	0.0	1.7	0.0	0.0	0.0	0.0	0.0	0.0	0.0	6.7
People	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	6.7	6.7	1.7	1.7	0.0	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	0.0	1.7	11.7	0.0	20.0	40.0	33.3	23.3	28.3	16.7	11.7	0.0	0.0	0.0	0.0	1.7	0.0
Walking	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	3.3	1.7	0.0	15.0	30.0	20.0	6.7	15.0	6.7	10.0	0.0	0.0	0.0	0.0	0.0	0.0
Dog	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	1.7	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
Non-natural Other	1.7	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	0.0
Non-natural Unknown	65.0	65.0	91.7	88.3	93.3	80.0	51.7	61.7	51.7	70.0	56.7	60.0	48.3	55.0	56.7	38.3	26.7	26.7	26.7	18.3	31.7	28.3	40.0	33.3
Unknown	3.3	0.0	6.7	0.0	1.7	0.0	1.7	3.3	5.0	5.0	6.7	3.3	1.7	11.7	5.0	3.3	6.7	0.0	3.3	5.0	5.0	3.3	6.7	0.0

Table 21. Mean hourly time audible (%) for each natural sound source at SHEN004 in summer, n=8 days.

Natural 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
Wind	0.0	0.0	0.0	0.0	3.3	4.4	0.0	0.0	0.0	2.2	10.7	11.1	11.1	11.1	11.1	11.1	11.1	11.1	11.1	11.1	11.9	10.7	11.1	11.1
Rain	0.0	0.0	0.0	5.9	8.1	17.0	9.3	7.4	11.1	11.9	11.1	19.3	11.9	0.7	4.8	0.4	1.5	8.5	9.6	1.1	0.0	0.0	0.0	0.0
Thunder	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	0.7	0.0	0.0	3.7	0.7	0.0	0.0	0.0	0.0	0.0
Bird	0.0	0.0	0.4	0.4	0.0	0.7	39.6	50.4	63.7	51.5	33.7	17.0	29.3	26.7	18.5	26.3	24.8	18.5	18.1	16.3	0.0	0.0	0.0	0.0
Insects	100.0	100.0	100.0	100.0	99.6	94.1	37.4	33.0	40.0	28.9	9.6	19.6	11.5	24.8	26.7	28.1	34.1	26.7	37.8	50.0	96.3	100.0	99.6	94.4
Animal	0.0	0.0	0.0	0.0	0.7	0.4	0.0	1.9	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.7	0.0	0.0	0.0	0.0	0.0
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	0.4	1.1	0.4	0.0	0.0	0.0	0.0	0.0
Wind-induced Natural	27.8	23.3	26.3	48.5	50.0	50.4	50.0	57.8	53.0	62.6	70.7	71.5	67.4	68.5	67.4	55.9	44.1	56.7	59.6	61.5	45.2	48.9	47.8	52.2
Natural Unknown	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.4	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.4	0.4	0.0	0.0	0.0	0.0

Table 22. Mean hourly time audible (%) for each natural sound source at SHEN004 in winter, n=8 days.

Natural 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
Wind	15.9	13.3	10.7	3.7	4.1	4.4	7.0	13.3	5.9	7.4	8.5	4.1	6.3	5.6	3.3	3.0	0.4	2.6	13.7	14.1	27.0	25.6	30.7	20.7
Rain	2.6	5.2	11.5	13.0	0.0	2.6	1.1	11.5	10.4	5.9	15.2	14.8	15.6	12.6	11.1	10.0	12.6	15.6	11.1	27.4	23.3	22.2	26.7	30.4
Mammal	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.4	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.4	0.0	0.0	0.0	0.0	0.0	0.0	0.0
Bird	0.7	0.4	2.2	0.4	0.7	0.7	1.1	14.4	5.2	3.0	5.9	6.7	5.2	15.9	17.4	9.3	8.1	1.5	1.5	1.1	1.1	0.7	0.0	0.4
Animal	0.7	3.0	4.1	3.3	5.6	3.7	3.3	0.7	3.3	3.7	4.1	11.1	8.5	4.4	6.3	4.8	1.5	1.1	0.4	2.2	1.1	0.7	0.7	0.0
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	0.0	0.0	0.0	0.0	0.0	0.4
Wind-induced Natural	86.7	84.8	76.3	71.1	67.8	67.8	61.1	65.6	70.0	64.4	63.0	66.7	60.4	52.2	49.6	37.4	55.9	51.5	39.6	41.9	60.0	60.4	65.6	63.3
Natural Unknown	7.4	1.5	0.7	0.4	2.6	3.7	3.3	2.2	3.7	4.4	0.7	1.5	4.1	7.8	10.0	11.1	9.6	6.3	3.7	1.1	0.0	2.6	0.4	0.4

Table 23. Mean hourly time audible (%) for each noise source at SHEN004 in summer, n=8 days.

Noise 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	0.4	0.0	0.4	0.4	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
Jet	7.8	6.3	5.9	0.7	3.3	16.7	21.9	43.3	44.4	40.4	21.1	20.0	24.1	30.0	19.3	40.4	34.1	30.0	34.8	34.4	37.4	14.8	19.6	14.8
Propeller Aircraft	0.4	0.4	0.0	0.0	0.0	0.4	0.4	3.0	7.4	7.0	8.1	7.0	8.1	8.9	7.4	9.3	8.5	5.9	3.7	7.4	0.7	1.1	1.5	0.4
Helicopter	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.7	0.0	0.7	0.4	0.4	0.4	0.0	0.0	0.7	0.0	2.2	0.7	0.0	0.4	0.0	0.0	0.0
Vehicle	1.5	0.0	0.0	0.4	0.0	0.7	0.7	1.1	4.1	1.5	5.9	6.7	10.4	7.4	11.5	8.9	13.3	14.1	13.7	13.3	1.5	0.0	0.0	0.0
Train Rumble	4.1	8.5	17.8	30.0	44.1	48.9	47.4	33.0	36.7	40.4	61.9	50.7	53.3	40.7	58.9	31.5	34.8	32.6	22.2	23.3	16.7	14.8	8.5	8.9
Train Whistle	0.0	0.0	0.0	0.0	0.0	0.0	0.4	1.9	0.4	0.4	0.0	0.0	0.0	0.0	0.0	0.4	0.0	0.0	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	0.0	0.7	2.6	1.9	4.1	4.4	6.3	6.3	6.3	8.5	4.8	0.4	1.1	0.0	0.0	0.0	0.0
Walking	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.7	0.7	3.0	0.4	1.9	5.2	2.2	0.0	0.0	0.0	0.0	0.0	0.0
Gunshot	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	0.4	0.0	0.0	0.0	0.0	0.0
Dog	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	0.4	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	0.4	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
Non-natural Unknown	1.1	3.7	6.7	3.0	3.0	1.5	6.3	3.7	3.3	7.0	2.6	5.9	6.3	9.6	7.0	9.3	9.3	9.6	17.0	9.3	8.5	4.8	0.7	4.1
Unknown	10.7	7.8	1.1	9.3	3.7	0.0	0.0	0.4	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.4	0.0	0.0	0.0	0.0	0.0	0.0

Table 24. Mean hourly time audible (%) for each noise source at SHEN004 in winter, n=8 days.

Noise 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
Jet	3.3	3.0	2.6	0.0	1.5	5.2	13.3	20.4	19.6	22.2	11.9	13.3	12.2	18.1	23.0	28.5	24.1	24.8	18.9	15.9	28.9	13.3	8.5	8.5
Propeller Aircraft	0.0	0.0	0.0	0.4	0.0	0.4	0.7	0.4	1.5	1.9	5.6	2.2	2.2	2.6	3.3	3.7	1.1	2.6	4.1	0.0	0.4	2.2	2.6	1.1
Helicopter	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.7	0.0	0.0	0.4	0.0	0.4	0.4	0.0	0.0	0.0	0.0	0.7	0.0
Vehicle	0.0	0.0	0.0	0.0	0.4	0.4	1.1	1.5	0.4	0.4	1.9	6.3	5.2	1.9	3.0	5.9	3.3	7.0	0.4	1.1	0.0	0.0	0.0	0.0
Alarm, Horn	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	0.4	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
Train Rumble	0.0	0.7	0.0	0.0	2.6	0.4	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.7	0.0	0.0	0.0	0.0	0.0	0.0	0.0

Table 24 (continued). Mean hourly time audible (%) for each noise source at SHEN004 in winter, n=8 days.

Noise 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
Train Whistle	1.1	1.1	0.0	0.0	0.7	0.4	2.6	0.7	1.1	0.0	0.7	0.0	0.0	0.0	0.0	0.0	0.0	0.4	0.7	0.0	3.7	1.1	0.7	0.0
Voices	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	1.5	0.0	1.5	0.0	0.4	7.4	3.3	1.5	0.7	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	0.0	0.0	0.0	0.7	0.0	1.5	0.7	0.4	6.3	3.0	1.1	0.0	0.0	0.0	0.0	0.0	0.0	0.0
Gunshot	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.4	0.7	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
Non-natural Unknown	6.3	3.7	8.1	2.6	3.3	2.2	2.6	1.1	4.4	7.0	4.4	3.3	4.1	7.4	6.3	5.2	3.3	5.9	1.5	8.1	3.0	0.0	0.4	0.4
Unknown	1.5	1.1	1.1	2.2	1.1	0.4	1.1	1.5	0.0	0.4	0.4	0.4	0.4	0.4	0.4	0.7	0.0	0.0	0.0	0.0	0.0	0.0	0.0	1.1

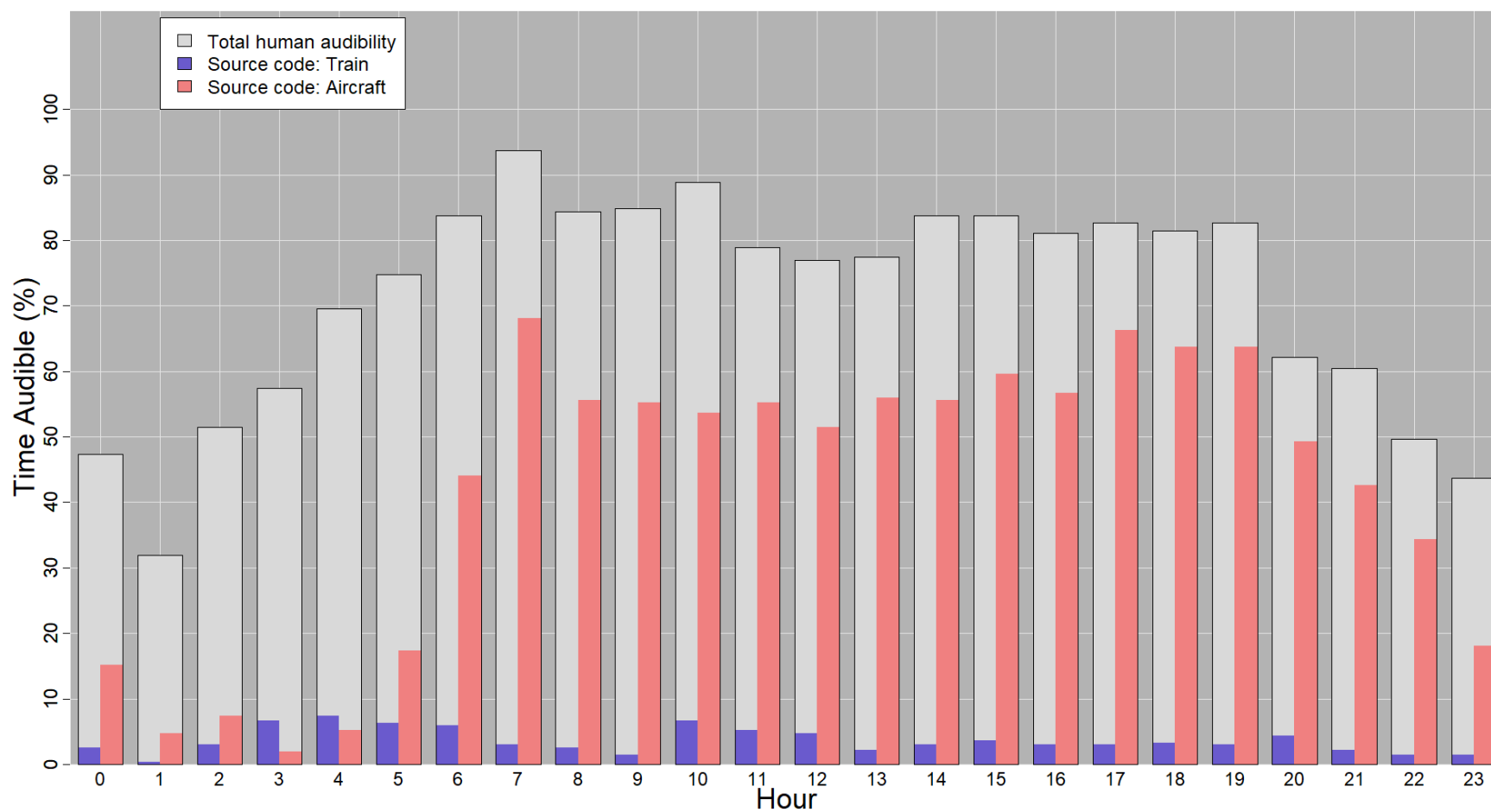


Figure 19. Hourly time audible for aircraft and all noise sources at SHEN001 in summer.

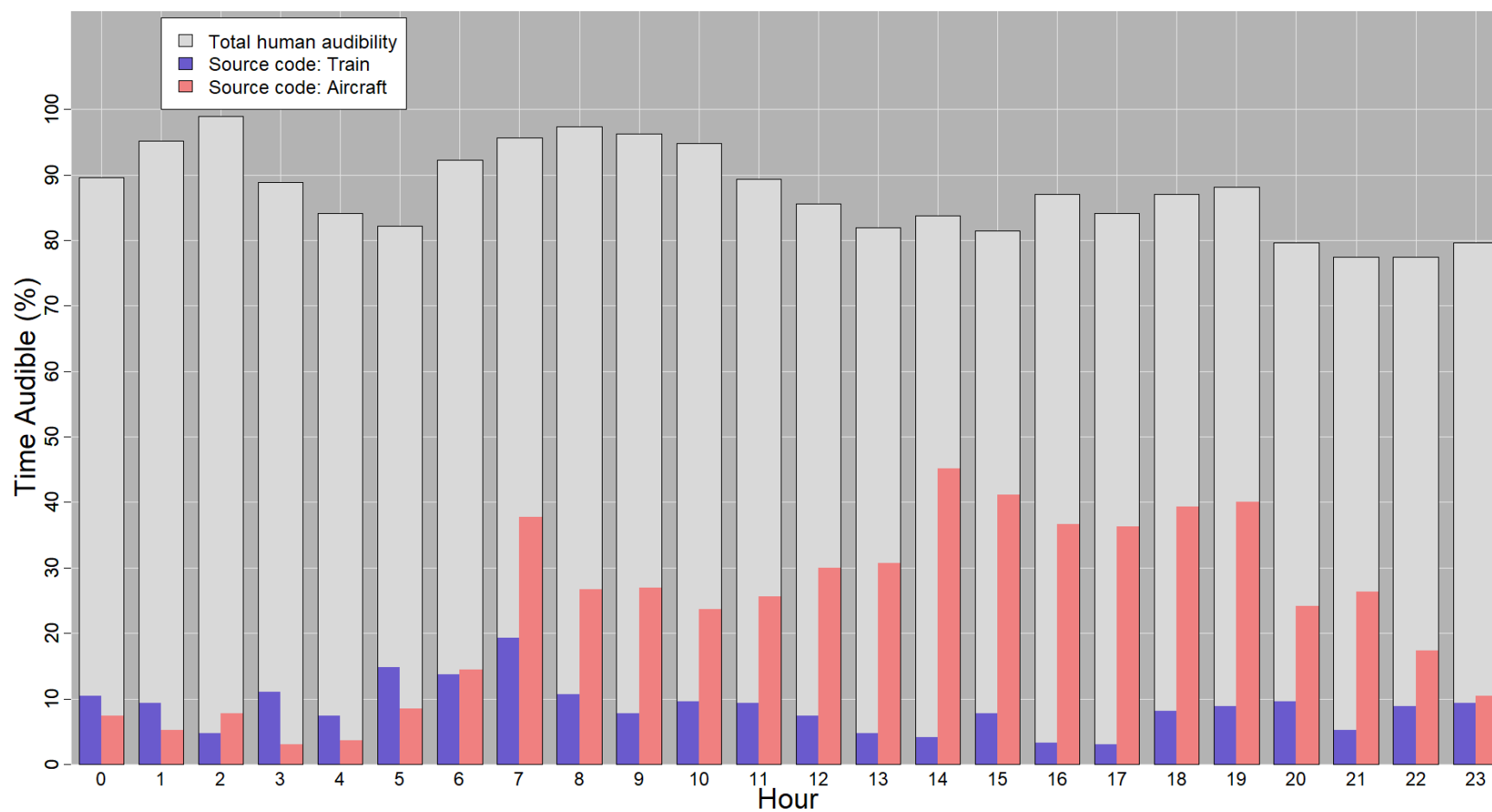


Figure 20. Hourly time audible for aircraft and all noise sources at SHEN001 in winter.

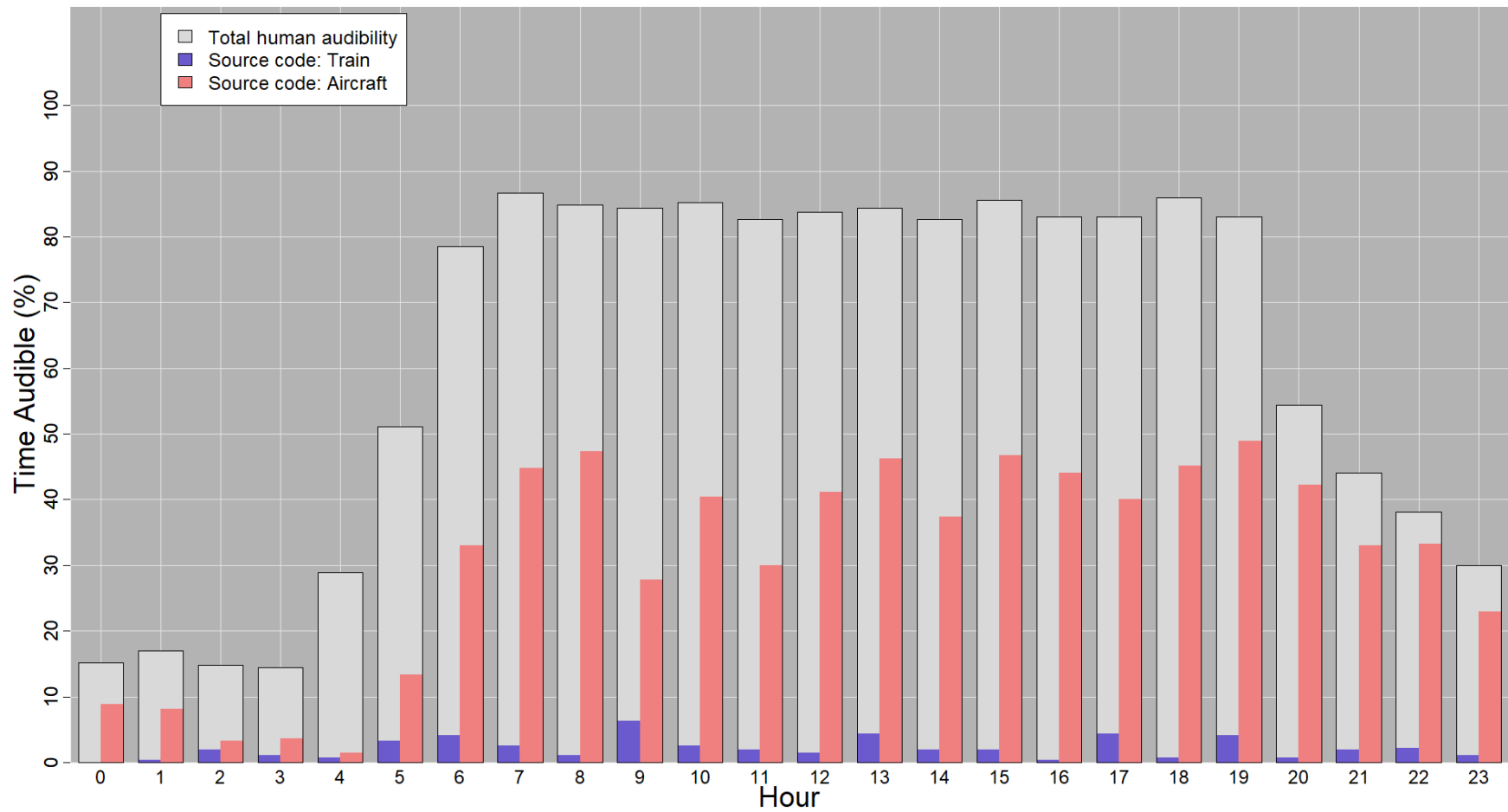


Figure 21. Hourly time audible for aircraft and all noise sources at SHEN002 in summer.

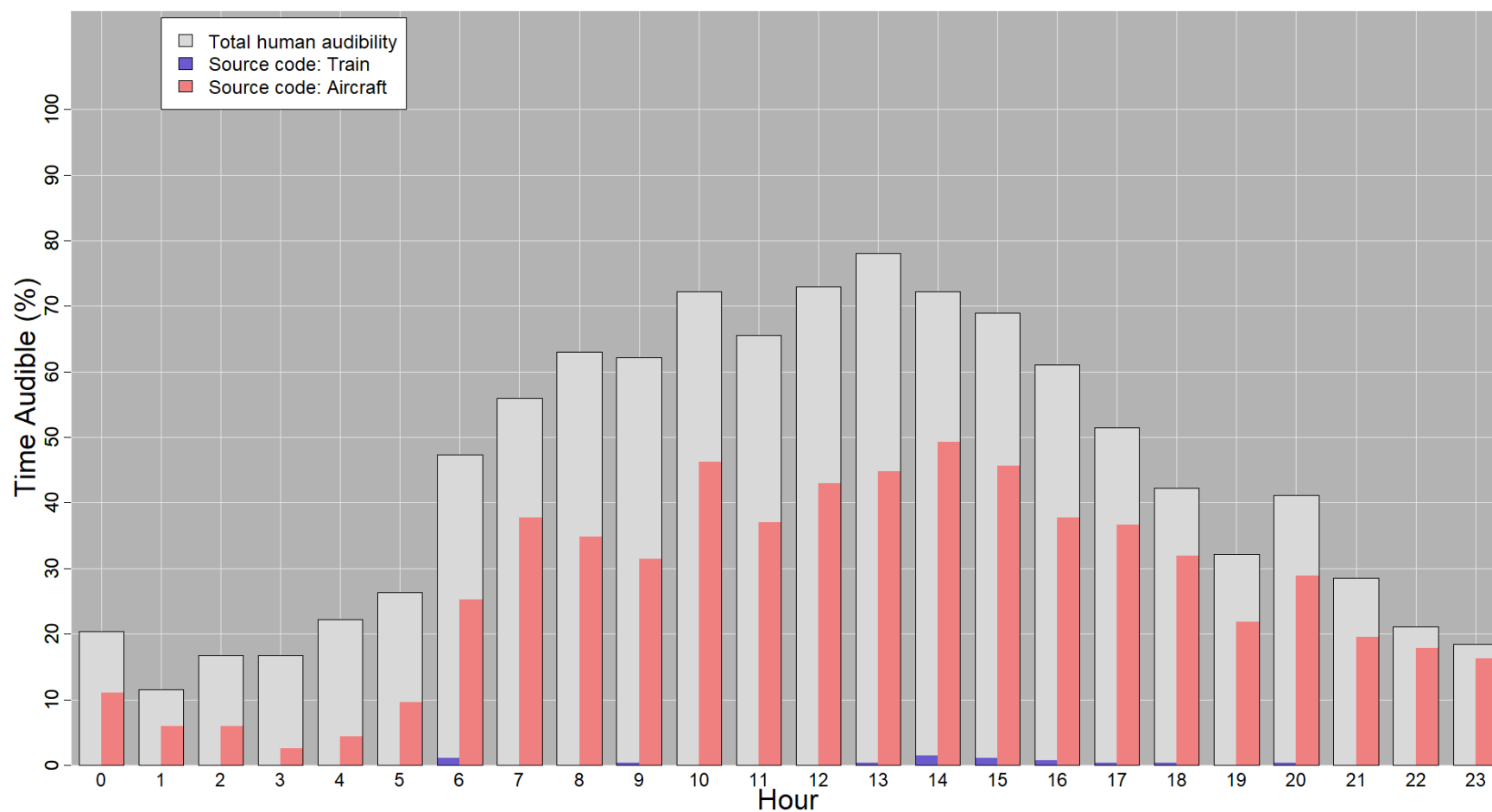


Figure 22. Hourly time audible for aircraft and all noise sources at SHEN002 in winter.

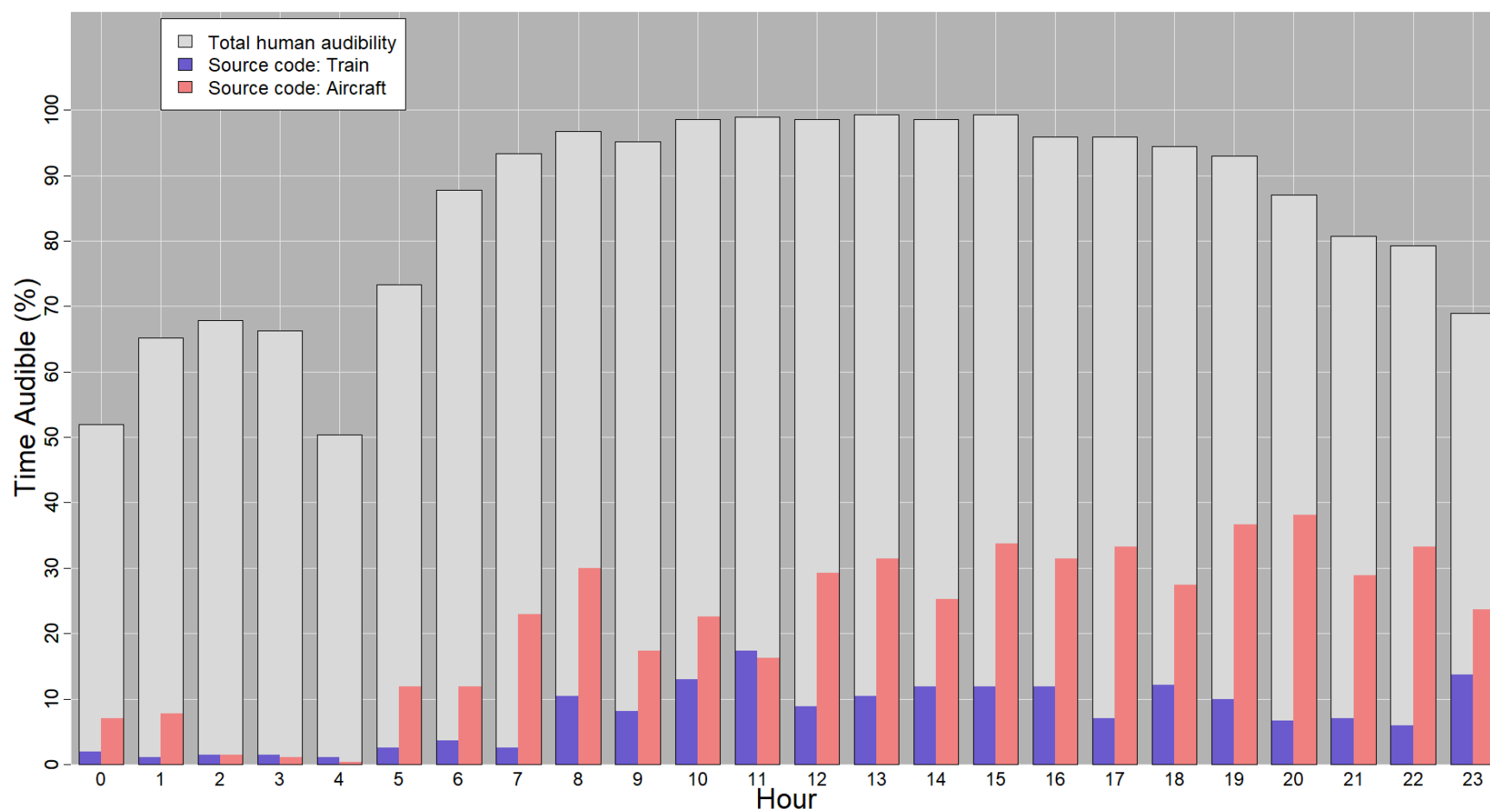


Figure 23. Hourly time audible for aircraft and all noise sources at SHEN003 in summer.

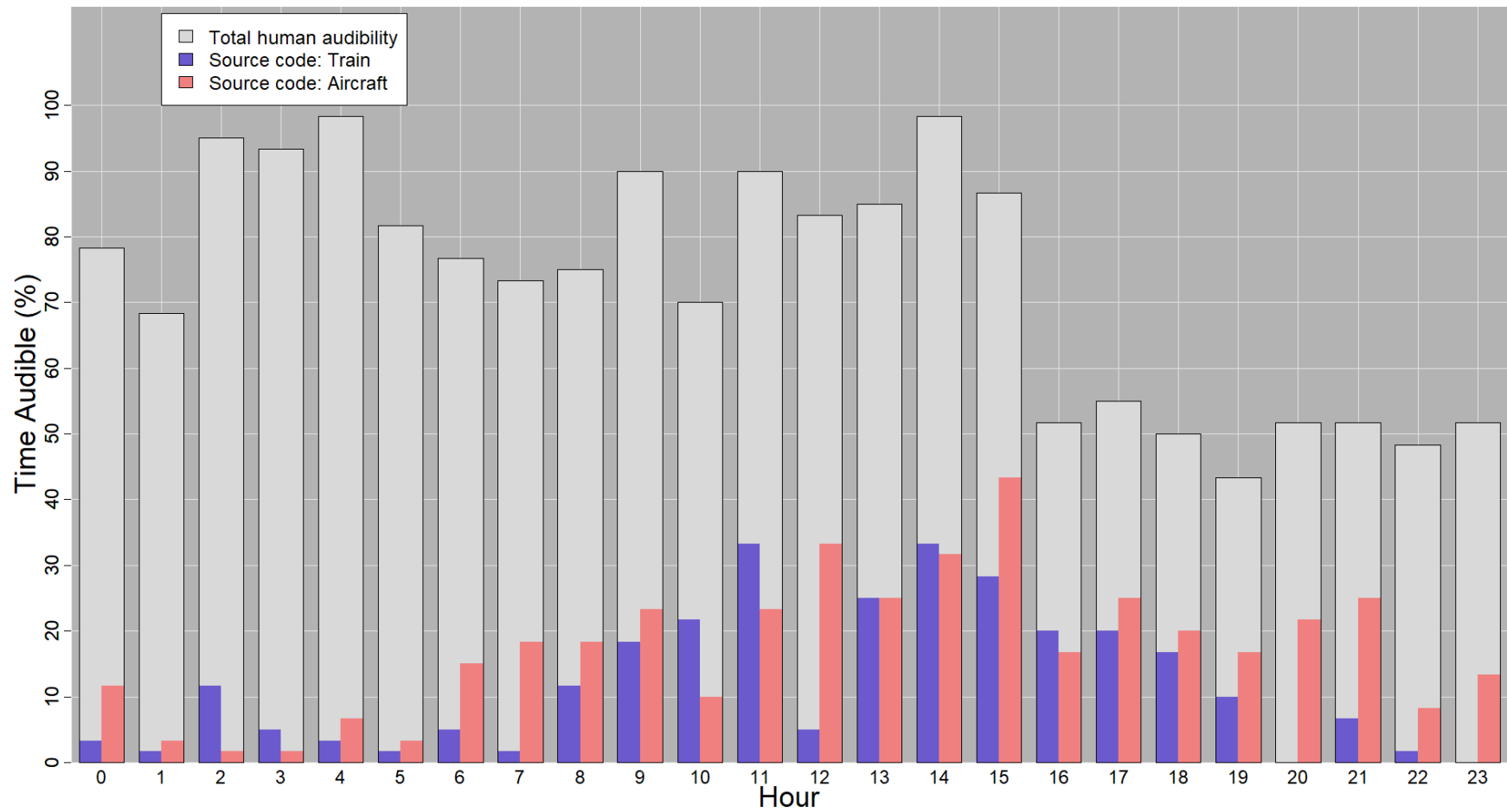


Figure 24. Hourly time audible for aircraft and all noise sources at SHEN003 in winter.

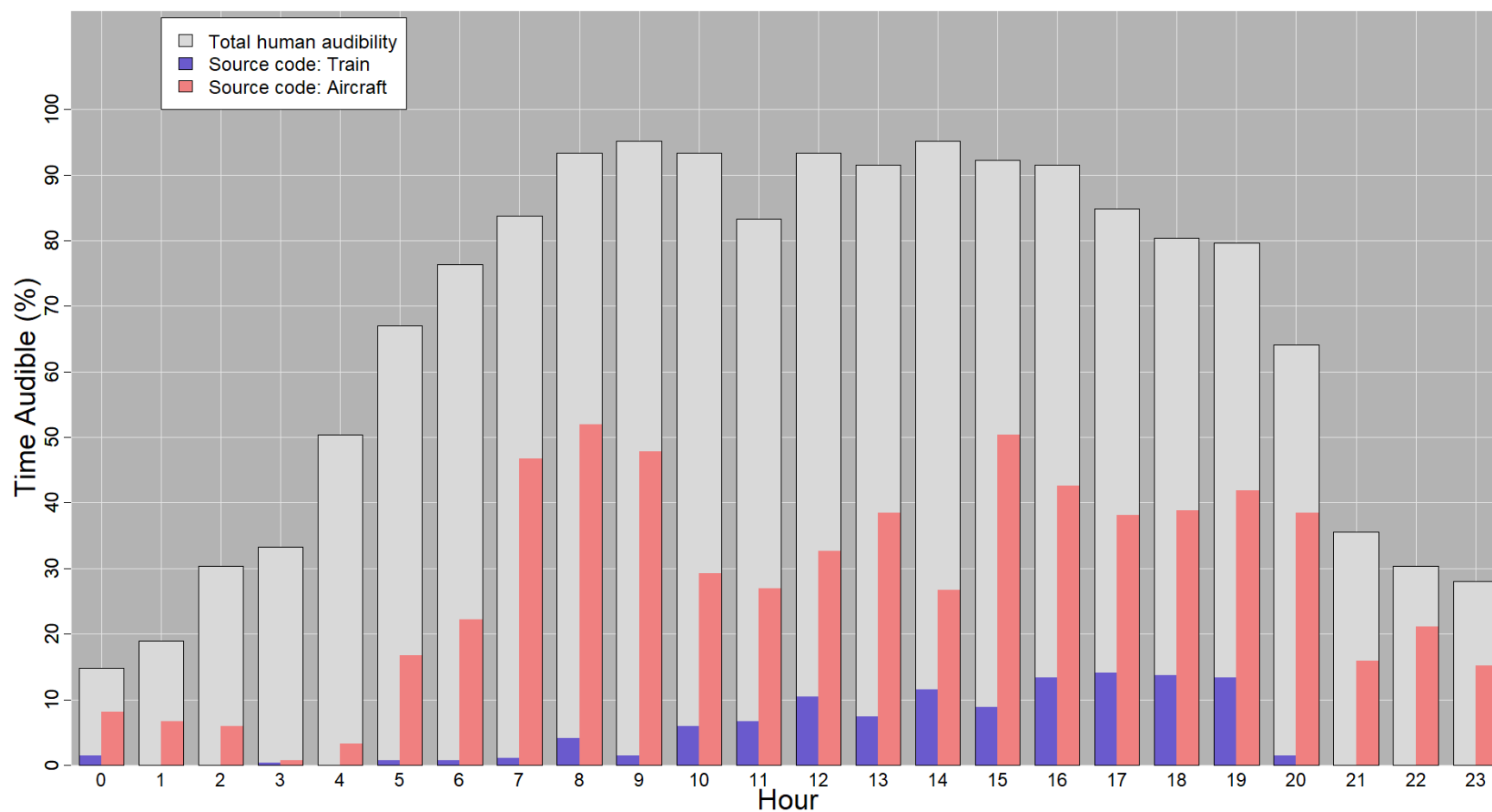


Figure 25. Hourly time audible for aircraft and all noise sources at SHEN004 in summer.

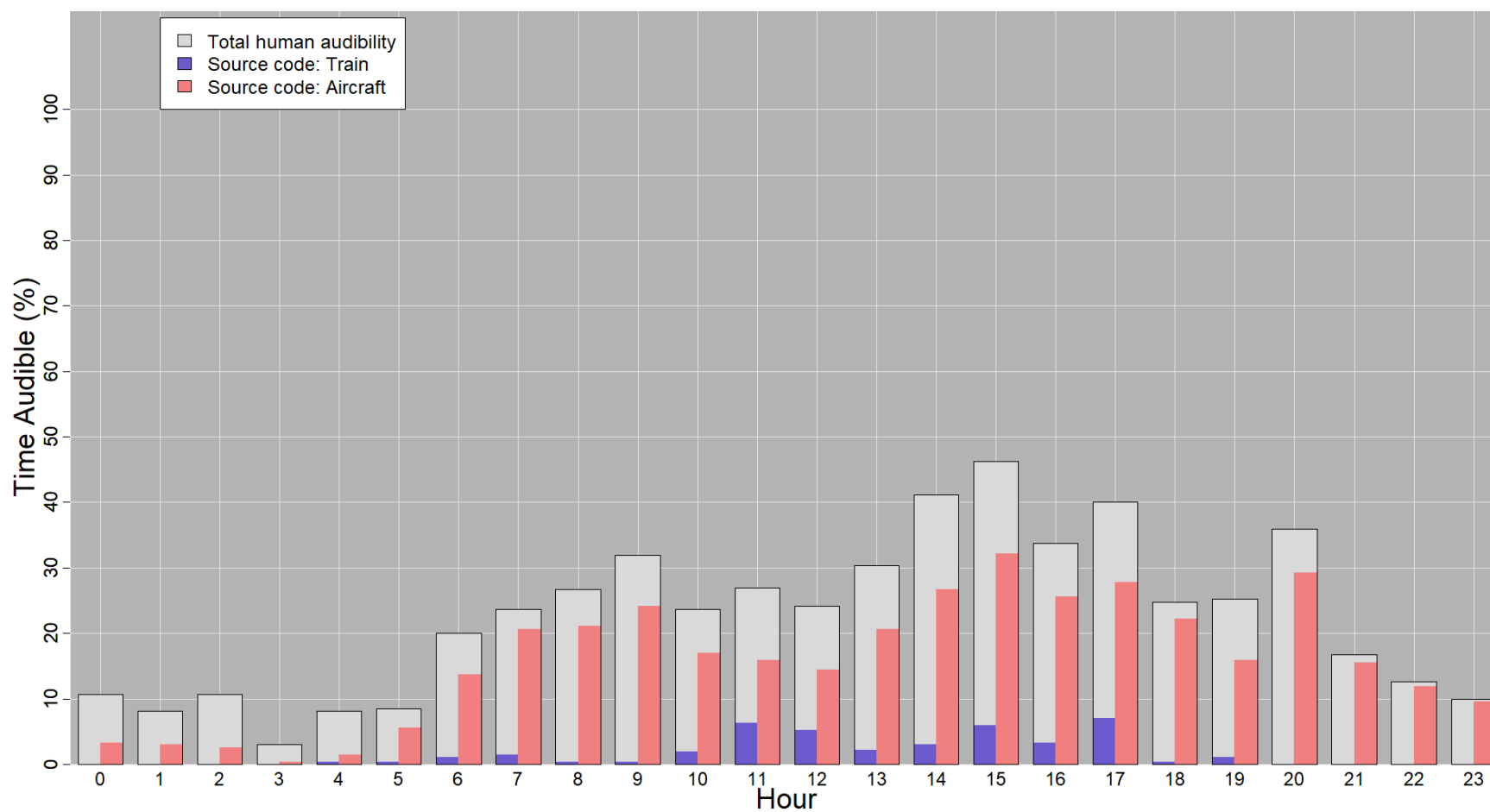


Figure 26. Hourly time audible for aircraft and all noise sources at SHEN004 in winter.

Conclusions

Acoustic monitoring allows parks to gain insight into levels of extrinsic noise and biologic 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 SHEN in areas used by visitors near the Appalachian Trail and other popular hiking trails and vistas in 2016–2017.

Results from SHEN001, SHEN002, SHEN003, and SHEN004 included measures of existing ambient sound levels, calculations of sound source audibility through off-site listening, and estimates of natural ambient sound levels. Sound source analysis revealed that noise is audible about 62–85 % of the time during summer and 23–87 % of the time during winter among study sites when averaged across all hours of the day.

During the summer monitoring period, aircraft were the most commonly heard source of noise at SHEN001 and SHEN002, and second most common at SHEN003 and SHEN004 with a 24-hour mean audibility of 21.8–41.7 % (Table 9–Table 23), but audibility was above 50% for all hours from 07:00 to 19:00 at SHEN001. Trains were the most commonly heard source of noise at SHEN003 and SHEN004 with a 24-hour mean audibility of 32.1–41.8 %.

During the winter monitoring period, aircraft were the most commonly heard source of noise at SHEN002 and SHEN004, and the second most common at SHEN001 and SHEN003 with a 24-hour mean audibility of 15.9–26.9 % (Table 10–Table 24). Trains were the most commonly heard source of noise at SHEN001 with a 24-hour mean audibility of 56.6 % but was as high as 82.6 % during the 02:00 hour.

A non-natural unknown noise source was commonly heard among sites and seasons with a 24-hour mean audibility ranging from 3.9–52.7% and was the most commonly heard source of noise at SHEN003 during winter (52.7%). Listeners often described this as the sound of a distant engine or a “deep rumble” but could not discern whether the sound originated from an aircraft, train, vehicle, or other type of motor. These sounds were categorized as “non-natural unknown” during that analysis process.

Natural sources such as wind, rain, and wildlife were commonly audible at all SHEN sites in 2016–2017, with insects and thunder often audible during summer. However, it is possible that the wildlife sources are underrepresented in this report because the late summer measurements did not coincide with the most biologically active periods of SHEN, which occur in the late spring through middle summer. Still, it was common to document songbirds, barred owls, and cicadas during the sampling period.

During the study period, computed natural ambient sound levels ranged from 25.7–40.9 dB (L_{Anat}) during the day and 32.2–52.9 dB (L_{Anat}) at night during summer, and 27.7–34.0 dB during the day and 29.7–37.3 dB at night during winter. Insects contributed a significant amount of energy to the acoustic environment during summer nights, as shown in Figure 11–Figure 18, as particularly high sound levels above 1.6 kHz. Existing sound level (encompassing natural and noise sources)

measurements ranged from 31.1–44.4 dB (L_{A50}) during the day and 35.5–54.1 dB (L_{A50}) at night during the summer, and 29.8–38.0 during the day and 32.3–40.5 dB at night during the winter. During the summer monitoring period, SHEN002 had the lowest noise audibility among sites across all hours of the day and had the lowest percent time above metrics during daytime in three of four key sound levels (35 dB, 52 dB, and 60 dB). This is likely because the site is further away from regional airports and more geologically shielded from train routes than the other sites. Conversely, SHEN001 had the highest time audible among sites for aircraft noise and other non-natural sounds, likely due to its proximity to a regional airport and several smaller municipal airports. While jet noise was common throughout the day, it was most prominent from 0500–2200 and likely a result of the most active flight times at nearby Dulles, National and Baltimore airports. SHEN001 also had moments where propeller aircraft contributed up to 17% of the hourly noise. This is likely due to daytime noise from small airports in the Shenandoah Valley. Notably, during the quietest aircraft hours, train noise became more prominent. In the summers from 2400–0600 and winters throughout the day, train rumble and whistle were the predominant noise sources (Table 11–12). During winter, SHEN003 had the greatest percent time above metrics during day and night in all key sound levels except for the daytime 45 dB level of the ANS frequency band, where the greatest time above occurred at SHEN001. Lowest percent time above metrics during the day occurred at SHEN004, and SHEN001 had the lowest during the night. The variation in sound levels between summer and winter appear to be driven by both seasonal and diurnal changes in transportation regimes.

For a broader context for the acoustic conditions at SHEN, 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 summer sound levels indicated that only 23% of the continental United States was predicted to have an existing ambient sound level above 40 dB ($L_{A50, 12 \text{ hr}}$), and only 1% of the continental U.S. was predicted to have an existing daytime ambient sound level above 50 dB ($L_{A50, \text{existing}}$) (Mennitt *et al.* 2013). Consider, though, that daily sound levels reported in this report for SHEN001, SHEN002, SHEN003, and SHEN004 can be influenced by both natural and non-natural sources.

Based on the results of this study, visitors to SHEN are unlikely to experience a significant noise-free interval near the monitoring sites, though SHEN004 in winter has markedly less noise than others. Among field sites, noise tended to be audible less during the nighttime hours (Figure 11–Figure 18, Table 9–Table 24). 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 (LAeq, x).³ Of the papers reviewed, 20% showed impacts to terrestrial wildlife at or below noise levels of 50 dB (LAeq, 1s) (Shannon *et al.* 2016).

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 the park sounded like in 2016–2017. Sound level data as well as continuous digital audio recordings will be stored at the Natural Sounds and Night Skies Division office in Fort Collins, Colorado for archiving purposes.

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

Literature Cited

- Acoustical Society of America. 2014. Methods to Define and Measure the Residual Sound in Protected Natural and Quiet Residential Areas, Melville, NY. ANSI/ASA S3/SC1.100-2014.
- Barber J.R., C. Crooks, and K. Fristrup. 2010. The costs of chronic noise exposure for terrestrial organisms. *Trends in Ecology and Evolution* 25:180–189.
- Berglund, B., T. Lindvall, and D. H. Schwela (Eds.). 1999. HWO. Guidelines for community noise. World Health Organization, Geneva.
- Environmental Protection Agency. 1974. Information on Levels of Noise Requisite to Protect the Public Health and Welfare with an Adequate Margin of Safety.
- Environmental Protection Agency. 1982. National Ambient Noise Survey. Office of Noise Abatement and Control, Washington, DC.
- Haas, G.E., and T. J. Wakefield. 1998. National parks and the American public: A national public opinion survey on the national park system. Washington D.C. and Fort Collins, CO.: National Parks and Conservation Association and Colorado State University.
- Haralabidis Alexandros, S., K. Dimakopoulou, F. Vigna-Taglianti, M. Giampaolo, A. Borgini, M. L. Dudley, G. Pershagen, G. Bluhm, D. Houthuijs, W. Babisch, M. Velonakis, K. Katsouyanni, and L. Jarup. 2008. Acute effects of night-time noise exposure on blood pressure in populations living near airports. *European Heart Journal Advance Access*. Published online February 12, 2008.
- Harris, C. M. 1998. Handbook of Acoustical Measurements and Noise Control, 3rd ed. McGraw-Hill, New York.
- McDonald, C. D., R. M. Baumgarten, and R. Iachan. 1995. Aircraft management studies: National Park Service Visitors Survey. HMMH Report No. 290940.12; NPOA Report No. 94-2, National Park Service, U.S. Department of the Interior.
- Mennitt, Daniel, et al. 2013. Mapping sound pressure levels on continental scales using a geospatial sound model. *Proceedings of Inter-Noise*. 1–11.
- National Park Service. 2005. Acoustic and soundscape studies in National Parks: Draft, Fort Collins, Colorado.
- National Park Service. 2006a. Management Policy 4.9: Soundscape Management.
- National Park Service. 2006b. Management Policy 8.2.3: Use of Motorized Equipment.
- Rapoza, A., Sudderth, E., & Lewis, K. 2015. The relationship between aircraft noise exposure and day-use visitor survey responses in backcountry areas of national parks. *The Journal of the Acoustical Society of America*, 138(4), 2090–2105.

- Shannon G, Angeloni LM, Wittemyer G, Fristrup KM, Crooks KR. 2014. Road traffic noise modifies behaviour of a keystone species. *Anim Behav.* 94:135–141.
- Shannon G., M. F. McKenna, L. M. Angeloni, K. R. Crooks, K. M. Fristrup, E. Brown, K. A. Warner, M. D. Nelson, C. White, J. Briggs, S. McFarland, G. Wittemyer. 2016. A synthesis of two decades of research documenting the effects of noise on wildlife. *Biological Reviews* 91(4), 982–1005.
- Suter, A. H. 1991. Noise and its Effects. Administrative Conference of the United States. Available at: <http://www.nonoise.org/library/suter/suter.htm> (accessed 17 January 2014).
- Templeton, D. (Ed.). 1997. Acoustics in the built environment: advice for the design team. Architectural Press, Oxford
- Weinzimmer, D., Newman, P., Taff, D., Benfield, J., Lynch, E., & Bell, P. 2014. Human responses to simulated motorized noise in national parks. *Leisure Sciences*, 36(3), 251–267.

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 (Figure 27). 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 compute the $L_{A_{nat}}$ for the site.

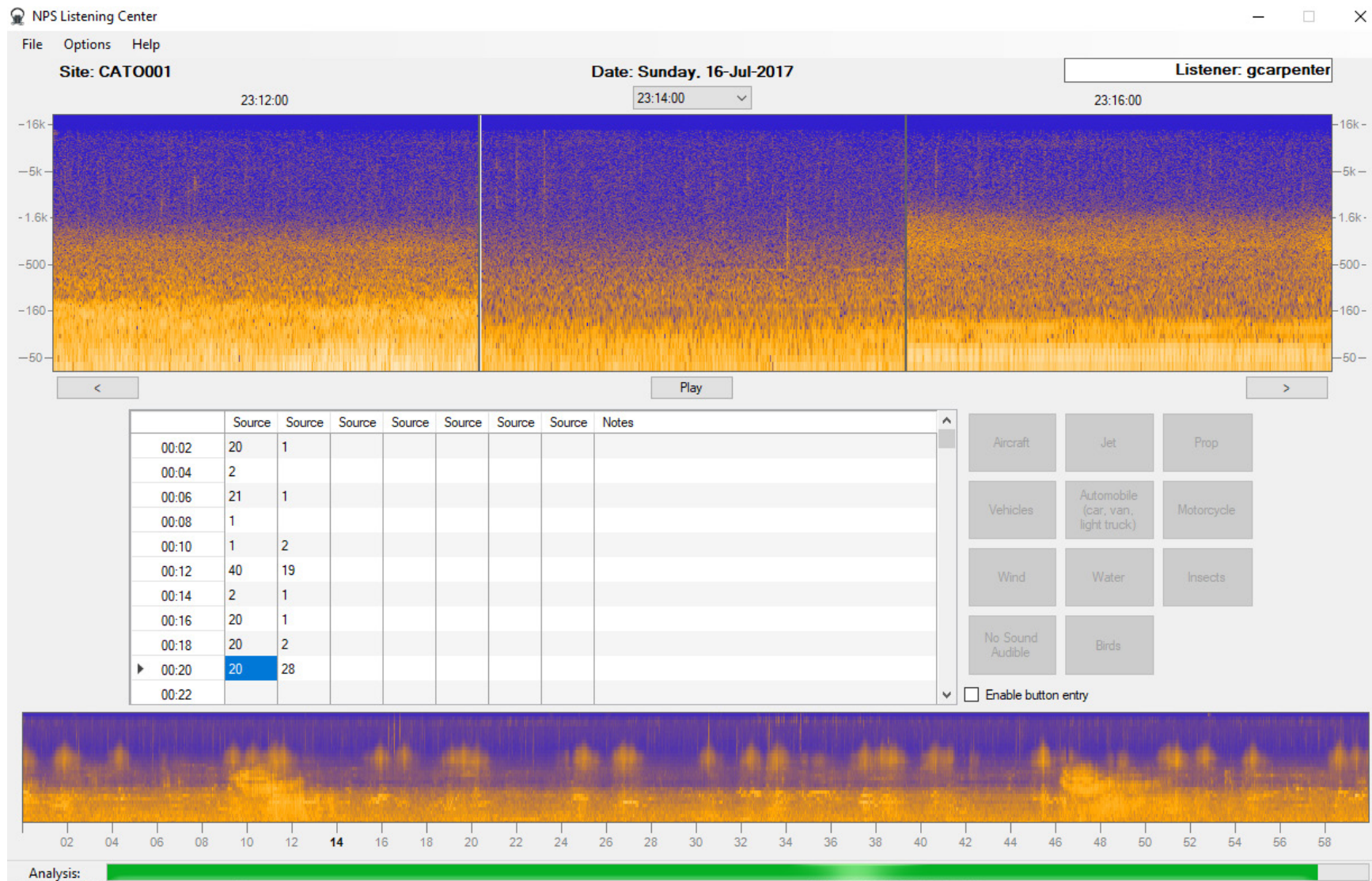


Figure 27. Screen shot of Listening Center. Three ten second samples are displayed side by side. Audible sound sources and annotations are recorded in the spreadsheet cells below.

The Department of the Interior protects and manages the nation's natural resources and cultural heritage; provides scientific and other information about those resources; and honors its special responsibilities to American Indians, Alaska Natives, and affiliated Island Communities.

NPS 134/190287, October 2023

National Park Service
U.S. Department of the Interior



[Natural Resource Stewardship and Science](#)

1201 Oakridge Drive, Suite 150
Fort Collins, CO 80525