



Sleeping Bear Dunes National Lakeshore

Acoustic Monitoring Report, 2022



Acoustic monitoring in Sleeping Bear Dunes National Lakeshore.
NPS / WARREN DEEDS

Sleeping Bear Dunes National Lakeshore: Acoustic monitoring report, 2022

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Abstract

This study was conducted in response to Technical Assistance Request (TAR) 20133, which identified a need for a baseline acoustic inventory within a discontinuous parcel of Sleeping Bear Dunes National Lakeshore (SLBE). Although the Bow Lakes parcel is frequented by visitors seeking a quiet refuge away from crowds, it is bordered by three privately owned and operated sand and gravel mines. The park needs information about existing and natural ambient sound levels to evaluate the effects of mining noise on the parcel. In March–April 2022, the Natural Sounds and Night Skies Division (NSNSD) gathered acoustic data at two sites in the Bow Lakes parcel in SLBE, discontinuous from the popular areas along the shoreline as well as the Sleeping Bear Dunes Wilderness but bordered by three privately owned and operated sand and gravel mines. On average, noise was present 71.2–77.3% of the time at these sites, with vehicles the most common identifiable source of non-natural noise, audible an average of 22.9–23.2% of the time, and heavy equipment the main contributor. Existing median ambient sound levels (L_{A50}) ranged from 24.1–24.2 dB at night and 30.2–30.9 dB during the day. Natural ambient sound levels (L_{Anat}) ranged from 20.9 dB at night to 26.9–27.6 during the day. The median influence of noise on the acoustic environment, defined as the difference between L_{A50} and L_{Anat} , was 3.2–3.3 dB, representing a detectable increase in sound levels due to anthropogenic noise. In the A-weighted frequency range, the sound level of 35 dB ($L_{Aeq, 1s}$), indicative of quiet environments, was exceeded 14.27–14.35% of the day and 7.36–10.49% of the night. All other key sound levels (i.e., 45 dB and above) were exceeded less than 0.4% of the time. To summarize, the Bow Lake parcel receives consistent but low-level anthropogenic noise that would be noticeable to a listener. A geospatial sound model designed to estimate sound levels over larger areas predicts existing median sound level (L_{50}) of 37.0 dBA and a median natural L_{50} of 33.6 dBA across the park, with lower sound levels in the Wilderness Area and Bow Lakes parcel and localized effects from anthropogenic noise, especially along M-22.

List of Terms or Acronyms

A-weighting: A-weighting is applied to sound levels 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, and 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 [R2020]). 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. 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 (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 (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}): 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 during which no human-caused sounds are audible.

Time Above: Within a defined 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.

Executive Summary

This report presents acoustic data gathered by the Natural Sounds and Night Skies Division (NSNSD) at Sleeping Bear Dunes National Lakeshore (SLBE), Michigan, from March to April 2022. Data were collected at two sites (SLBE001 and SLBE002), with the goal of providing park managers with information about the acoustic environment, sources of noise, and the natural and existing ambient sound levels within the Bow Lakes parcel, a unit that is discontinuous from the popular areas along the shoreline as well as the Sleeping Bear Dunes Wilderness, and is bordered by three privately owned and operated sand and gravel mines.

For these deployments, a calibrated sound level meter measured sound pressure level (SPL) continuously every second, an anemometer collected accompanying wind speed data, and a digital audio recorder collected audio recordings used to document sound sources.

In this document, “sound pressure level” refers to broadband (12.5 Hz–20,000 Hz), A-weighted, 1-second time averaged sound level ($L_{Aeq, 1s [12.5-20,000 \text{ Hz}]}$), 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 sources.

Table 1. Sound level examples.

Park Sound Sources	Common Sound Sources	Sound Level dB ^A
Volcano crater (HALE)	Human breathing at 3 m	10
Leaves rustling (CANY)	Whispering	20
Crickets at 5 m (ZION)	Residential area at night	40
Conversation at 5 m (WHMI)	Car at 15 m, 30 mph	60
Cruiser motorcycle at 15 m (BLRI)	Curbside of busy street	80
Thunder (ARCH)	Jackhammer at 2 m	100
Military jet at 100 m AGL (YUCH)	Train horn at 1 m	120

^A 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, existing ambient sound levels (L_{A50}) at the monitoring sites within SLBE were between 30.2–30.9 dB during the day and 24.1–24.2 dB at night during the sampling period. 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 ($L_{Aeq, 1s}$), is used by the NPS as an indicator of overall quality of the acoustic environment. Beyond this level, noise begins to negatively affect the visitor experience in an

otherwise natural acoustic environment (Pilcher et al., 2009; Watts et al., 2020; Betchkal et al., 2023). Moreover, sound events as low as 35 dB can adversely affect sleeping humans (Haralabidis *et al.* 2008). 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). As wildlife begin to exhibit signs of disturbance at noise levels as low as 40 dB (Shannon et al. 2016), 45 dB also represents a conservative estimate of negative effects on wildlife. The third value, 52 dB ($L_{Aeq, 1s}$), is based on the EPA’s analysis of speech interference for an individual speaking in a raised voice to an audience at 10 meters (EPA 1974)—an acoustic level that would affect interpretive presentations in parks. The final value, 60 dB ($L_{Aeq, 1s}$), marks the point at which normal voice communications at 1 meter begin to be interrupted (EPA 1974); sounds at or exceeding this level would affect conversation between visitors and/or staff. Notably, 0.00% of acoustic data collected at SLBE during the sampling period reached this level.

Table 2. Percent time above metrics for acoustic records collected in Sleeping Bear Dunes National Lakeshore from March to April 2022.

Site ID	Frequency Range	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
SLBE001	Full (12.5–20,000)	26.81	1.22	0.11	0.00	14.44	1.11	0.04	0.00
	ANS (20–1,250) ^B	14.35	0.37	0.03	0.00	7.36	0.17	0.01	0.00
SLBE002	Full (12.5–20,000)	23.92	0.79	0.09	0.00	14.97	0.56	0.03	0.00
	ANS (20–1,250) ^B	14.27	0.37	0.04	0.00	10.49	0.13	0.01	0.00

^A dB $L_{Aeq, 1s}$ re 20 μ Pa

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

Sound levels are often measured over narrow frequency bands (typically in one-third octave bands between 12.5 Hz–20,000 Hz) because these smaller bands closely represent how humans distinguish between frequencies of sound. In this study, we examine how often sound levels exceeded the key values mentioned above in two frequency ranges. The top value in each split-cell of Table 2 uses the full frequency range (12.5 Hz–20,000 Hz) collected, whereas the bottom value focuses on frequencies affected by low frequency noise sources (20–1,250 Hz). The focus on low frequency noise sources—a modification to A-weighting (referred to as A-weighted Natural Sounds (ANS) weighting, ASA/ANSI S3/SC1.100-2014 [2020])—eliminates high-frequency sounds such as leaves rustling, equipment noise, and bird calls, allowing for more accurate comparisons of low-frequency ambient sound levels across different land use types (e.g., urban, protected areas; ASA/ANSI S3/SC1.100-2014 [2020]). It also helps distinguish between ambient sound level measurements in quiet environments. For instance, in the full frequency range, the 35 dB ($L_{Aeq, 1s}$) level was exceeded at SLBE001 26.81% of the time during the day and 14.44% of the time at night. In the 20–1,250 Hz range, the 35 dB functional sound level value was exceeded less often, at 14.35% of the time during the day and 7.36% of the time at night.

After data collection was complete, trained technicians calculated how often noise sources were audible. See the Methods section for protocol details, equipment specifications, and metrics calculations. Sound source analysis revealed that noise was audible 71.2–77.3% of the time during the sampling period at study sites when averaged across all hours of the day (Table 3). Aside from unidentifiable non-natural unknown noises, the most common identifiable noise sources observed during this study were vehicles (22.9–23.2% of the time), including heavy equipment and alarms or horns. Natural sources such as wind, rain/precipitation, and songbirds were also commonly audible. Natural ambient sound levels (L_{Anat}) ranged between 26.9–27.6 dB during the day and 20.9 dB at night¹. Increased natural ambient sound levels during day and night varied by location and were likely caused by diurnal winds and site-specific bird activity. Existing ambient sound levels (L_{A50}) were between 30.2–30.9 dB during the day and 24.1–24.2 dB at night, indicating an average increase of 3.2–3.3 dB above natural ambient sound levels at each site (Table 3). Given the logarithmic scale of decibels, an increase of 3 dB indicates a doubling of sound pressure, with the difference perceptible by most human listeners.

Based upon these findings, the acoustic environment at SLBE is affected by anthropogenic noise, though natural sounds are still quite audible and sound levels overall are still fairly quiet.

Table 3. Summary of summer noise sources and sound levels at two Sleeping Bear Dunes NL 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		c. Median Natural Ambient (L_{Anat}) in dB	
	Noise	Aircraft	Non- natural Unknown	Vehicles	L_{A50} Day	L_{A50} Night	L_{Anat} Day	L_{Anat} Night
SLBE001	71.2	6.3	48.0	22.9	30.9	24.1	27.6	20.9
SLBE002	77.3	7.8	52.0	23.2	30.2	24.2	26.9	20.9

¹ When anthropogenic noise is audible at a site 75% of the time or more, the calculated L_{nat} becomes inaccurate. These values are the best estimates possible for SLBE002.

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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). Acoustic 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 acoustic issues raised by Congress, NPS Management Policies, and NPS Director's Orders. The NSNSD works to protect, maintain, or restore acoustic 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 acoustic monitoring, data processing, park planning support, and comparative analyses of acoustic 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."

NPS Management Policies 2006 Chapter 4.9 provides direction for management of natural soundscapes:

"The National Park Service will preserve, to the greatest extent possible, the natural soundscapes of parks..."

"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 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 under Management Policies 2006 Chapter 8.2.3, “[t]he 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 2006c). However, the desired acoustic 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 Management Policies 2006 §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).

Director’s Order 47, Soundscape Preservation and Noise Management (2000) builds on the principles set out in Management Policies, directing park management how and when to consider acoustic resources. 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.

Focal Park Unit

Established in 1970, Sleeping Bear Dunes National Lakeshore (SLBE) protects 71,199 acres of forests, wetlands, lakes, streams, glacial features, and, of course, grand dunes along the shores of Lake Michigan. In addition to the natural features and processes, the park unit also includes a historic lighthouse, historic town and historic farm district, several campgrounds, and numerous hiking trails. Nearly all of North and South Manitou Islands and some dune formations in mainland Michigan were designated the Sleeping Bear Dunes Wilderness in 2014, for a total of 32,557 acres (Figure 1). While parts of the park can get quite busy—as of 2023, there were more than 1.5 million recreational visits—the wilderness is still a place to “get away from all the noises” (Sleeping Bear Dunes 2024).

In the words of one wilderness recreationist, “It’s quiet enough, it’s still enough, to where the sound of the birds does cut through that air. It’s a place that retains that stillness year-round.”

In 1982, Congress added the “Bow Lakes” parcel to the Lakeshore, a separate 1000-acre area that contains notable post-glacial topography, including numerous kettle ponds, hills, bogs, wildflowers, and woods inland from the lake. A 3.1-mile hiking trail was completed in 2019, enabling visitors to access the unique terrain on foot, skis, or snowshoes. According to NPS personnel, the Bow Lakes parcel offers visitors a respite from the bustle of the extremely popular areas along the shoreline.

The Final General Management Plan/Wilderness Study/Environmental Impact Statement issued in 2008 describes the following desired conditions: “Natural soundscapes are preserved, and sounds of modern society are minimized. Visitors to the National Lakeshore have opportunities in most parts of the park to hear natural sounds.” Strategies to fulfil this goal include collecting baseline acoustic data and enforcing noise regulations to “continue to control existing and potential land-based noise sources” (2008, p. 23).

Mining is one of the foremost land-based noise sources of concern, especially in the Bow Lakes parcel, which is bordered by three privately owned and operated sand and gravel mines. This is the first study to collect acoustic data in SLBE and the Bow Lakes parcel (Figure 1), crucial to improving understanding of baseline conditions and evaluating the effects of mining activity on the park’s acoustic environment.



Figure 1. Study site in Sleeping Bear Dunes National Lakeshore, Michigan, USA. NPS / NSNSD

Study Area

This report presents the results of an acoustic inventory conducted in 2022 at SLBE (Table 4). Both acoustic monitoring units were placed within the Bow Lakes parcel (Figure 1), amid deciduous woodland between Kettle Trail and external sand and gravel mines.

Table 4. Metadata for acoustic monitoring at SLBE, 2022.

Site	Site Name	Dates	Vegetation	Latitude	Longitude
SLBE001	–	03/09/2022– 04/21/2022	Deciduous woods	44.82628	-85.91322
SLBE002	Kettle Trail	03/10/2022– 04/13/2022	Deciduous woods	44.82619	-85.91383

Data were collected from 09 and 10 March to 13 and 21 April 2022. The study period occurred during late winter and early spring, when trees were leafless, visitation lower, and noise from external activity would travel farther unimpeded by vegetation. Snow, rain, or a slushy combination fell on 70% of the days, for a total of 6.4 inches of rain-equal precipitation. Snow cover melted off by mid-March. Daily high temperatures ranged from 67°F down to 21°F, with lows from 46°F down to 9°F, with averages of 43°F and 28°F, respectively (NOAA Climate Data Online). Winds were fairly calm, peaking midday and early afternoon and only occasionally gusting up to 9 m/s (20 mph). At SLBE001, winds were predominantly south-southwesterly averaging about 2 m/s (4.5 mph), while at SLBE002, winds were south-southeasterly, also at about 2 m/s.

Methods

Automatic Monitoring

A Larson Davis sound level meter (SLM) type 831-A was deployed at one monitoring site. The SLM is a hardware-based, real-time analyzer which constantly records one-third octave band sound pressure level (SPL) data. This Larson Davis-based site met American National Standards Institute (ANSI) Type 1 standards (ANSI 1968 [R2020], 1983 [R2006], 1992 [2018]) for accurate survey-grade instrumentation. The sound level meter provided the information needed to calculate metrics described below in Calculation of Metrics.

Acoustic monitoring equipment is used by many practitioners to determine noise levels in different environments, both indoors and outdoors. The NPS uses equipment like that used by other practitioners but has developed a unique configuration that stands up to the potentially harsh environment encountered in national parks (National Park Service 2013). 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 (see details below on the acoustic record). An anemometer was attached to a tripod and placed approximately 10 feet from the microphone to capture local wind conditions.

The sampling station consisted of:

1. Type 1 sound level meter
2. Microphone with environmental shroud
3. Preamplifier
4. 12 V battery pack
5. Ultrasonic anemometer (wind speed)
6. Digital audio recorder

The sampling station was designed to collect:

1. Flat-weighted, time-average sound level ($L_{Zeq, 1s}$) for each one-third octave frequency band, 12.5–20,000 Hz in dB re 20 μ Pa [collected by Type 1 sound level meter].
2. A-weighted, time-average sound level ($L_{Aeq, 1s [12.5-20000 \text{ Hz}]}$) in dB re 20 μ Pa [collected by Type 1 sound level meter].
3. Continuous meteorological data for wind speed [collected by anemometer].
4. Continuous digital audio recordings.

Monitoring Period

To ensure that the data set accounts for daily differences and represents the typical range of conditions at a site, acoustic monitoring studies typically monitor a minimum of 25 days (NPS 2005). For this study, the monitoring period was 35–44 days.

Calculation of Metrics

The status of the acoustic environment can be characterized by sound level (L_{A50} , L_{Anat} , L_{A90} , L_{A10} , L_{Aeq}) and frequency content (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 m/s to eliminate error from microphone artifacts). 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):

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

where

P_H = 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 graphical format in the following sections.

Off-Site Listening

Listening Center Software Analysis

Off-site analysis is completed by listening to the audio record while simultaneously viewing its spectrogram representation (for more information on Listening Center software, see Appendix A). For each site (SLBE001–002), auditory analysis was used to calculate the audibility of sound sources at each location. Trained technicians at Pennsylvania State University listened back to 9–11 days of the audio record. Technicians considered only a subsample of each day representing the first 10 seconds of every two-minute period. Whenever they detected an audible sound within each subsample, they categorized the sound source. This allows for estimation of the temporal extent of audibility for each source type. The total percent time noise was audible can then be used to calculate the natural ambient sound level (L_{Anat}) for each hour (see Equation 1 above for more information). For any off-site audio playback listening, technicians used Bose QuietComfort Noise Canceling headphones to minimize limitations imposed by the office acoustical environment.

Results

Frequency content

To determine the influence that noise has on the acoustic environment, it is useful to examine percentile metrics across the frequency spectrum. 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 narrower bands, each encompassing one-third of an octave. These narrow bands closely represent how humans distinguish between frequencies of sound. The percentile sound levels for 33 one-third octave band frequencies over the day and night periods are shown in Figures 2 and 3.

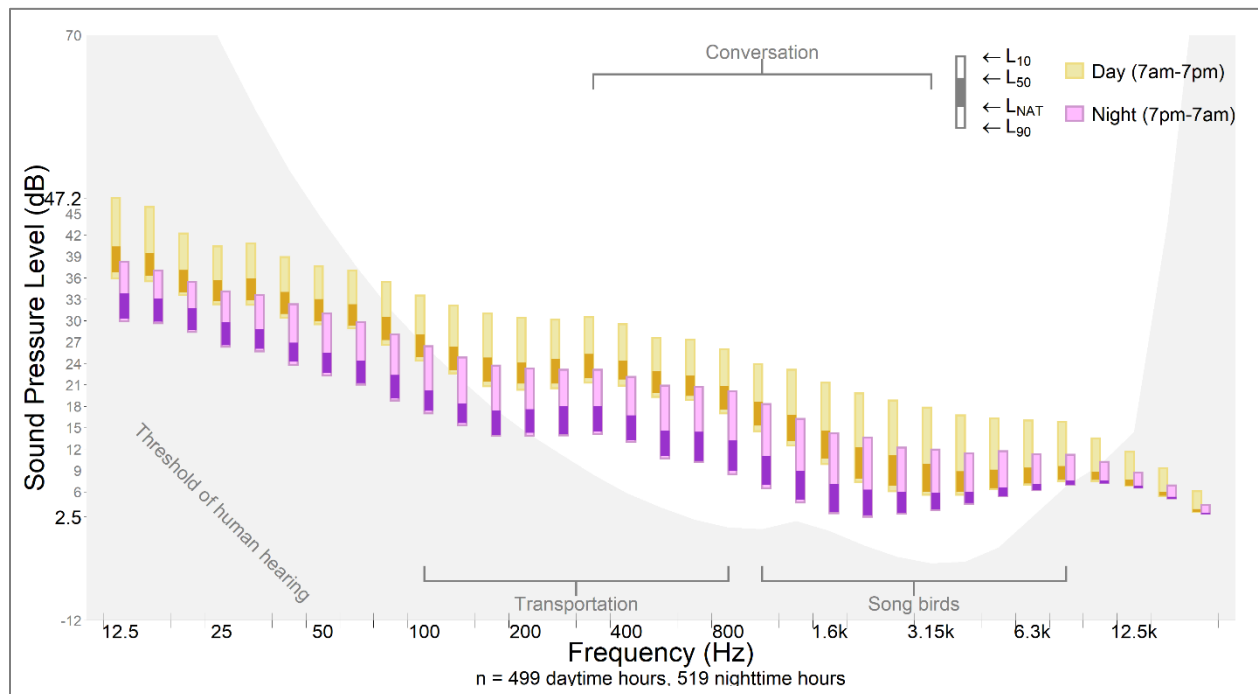


Figure 2. Day and night percentile sound pressure levels for 33 one-third octave bands at SLBE001 from March to April 2022. For each bar, the bold color indicates the range of existing (L_{50} ; upper) and natural (L_{nat} ; lower) sound pressure levels. Sound levels depicted are not A-weighted. NPS / NSNSD

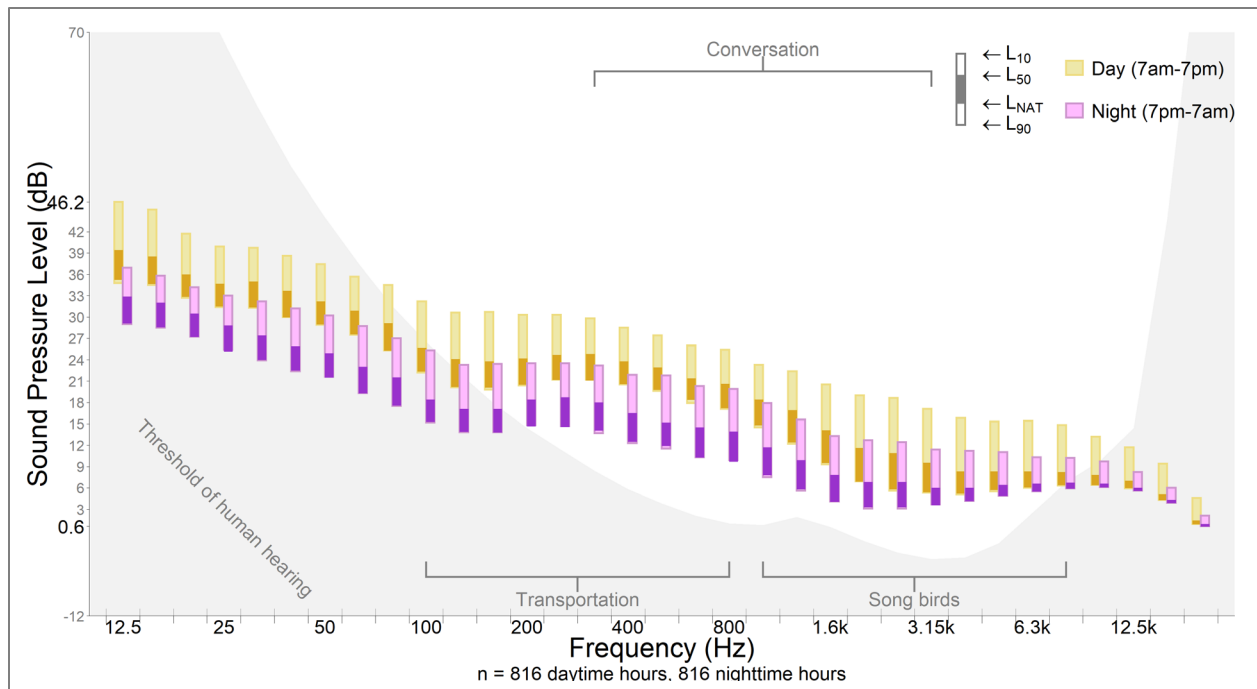


Figure 3. Day and night percentile sound pressure levels for 33 one-third octave bands at SLBE002 from March to April 2022. For each bar, the bold color indicates the range of existing (L_{50} ; upper) and natural (L_{nat} ; lower) sound pressure levels. Sound levels depicted are not A-weighted. NPS / NSNSD

Examining the sound energy in each one-third octave band (usually, in combination 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 Figures 2 and 3 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 5 reports the percent of time that measured sound levels ($L_{Aeq,1s}$) were above four key functional effect levels 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 percentage of ANS-weighted sound levels (20–1,250 Hz) that were above functional effect levels. Most motorized human-caused noise is confined to the truncated, lower-frequency range, while many natural sounds, including insects and songbirds, are higher in pitch. ANS weighting eliminates high-frequency sound (leaf rustle, 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 [R2020]). This frequency weighting scheme improves ambient sound level measurements in quiet environments.

The first functional effect in Table 5 occurs around 35 dB ($L_{Aeq,1s}$), which is used by the NPS as an indicator of overall quality of the acoustic environment. Beyond this level, noise begins to negatively affect the visitor experience in an otherwise natural acoustic environment (Pilcher et al., 2009; Watts et al., 2020; Betchkal et al., 2023). Moreover, sound events as low as 35 dB can adversely affect sleeping humans (Haralabidis *et al.* 2008). In this study, the 35 dB ($L_{Aeq,1s}$) effect level was exceeded at SLBE001 more than a quarter (26.81%) of the time during the day and more than an eighth of the time (14.44%) at night in the full frequency range. SLBE002 experienced slightly less time above 35 dB during the day (23.92%), but slightly more at night (14.97%). In the 20–1,250 Hz range, the 35 dB functional sound level value was exceeded 14.27–14.35% of the time during the day and 7.36–10.49% of the time at night.

Table 5. Percent time above metrics for acoustic records collected in Sleeping Bear Dunes National Lakeshore March–April 2022.

Site ID	Frequency Range	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
SLBE001	Full (12.5–20,000)	26.81	1.22	0.11	0.00	14.44	1.11	0.04	0.00
	ANS (20–1,250) ^B	14.35	0.37	0.03	0.00	7.36	0.17	0.01	0.00
SLBE002	Full (12.5–20,000)	23.92	0.79	0.09	0.00	14.97	0.56	0.03	0.00
	ANS (20–1,250) ^B	14.27	0.37	0.04	0.00	10.49	0.13	0.01	0.00

^A dB $L_{Aeq,1s}$ re 20 μ Pa

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

The second functional effect is expected to occur around 45 dB ($L_{Aeq,1s}$). This level addresses the World Health Organization’s recommendations that noise levels inside bedrooms remain below 45 dB ($L_{Aeq,1s}$) (Berglund et al. 1999). As wildlife begin to exhibit signs of disturbance at noise levels as low as 40 dB (Shannon et al. 2016), 45 dB also represents a conservative estimate of negative effects on wildlife. The third value, 52 dB ($L_{Aeq,1s}$), is based on the EPA’s analysis of speech interference for an individual speaking in a raised voice to an audience at 10 meters (EPA 1974)—an acoustic level that would affect interpretive presentations in parks. During the sampling period at SLBE, sound levels exceeding 52 dB ($L_{Aeq,1s}$) occurred a mere 0.09–0.11% of the time during the day and 0.03–0.04% of the time during the night. The final value, 60 dB ($L_{Aeq,1s}$), marks the point at which

normal voice communications at 1 meter begin to be interrupted; sounds at or exceeding this level could begin to affect conversation between visitors and/or staff at SLBE. Notably, 0.00% of sound pressure level data collected at SLBE during the sampling period reached this level.

Sound Level: Percentile Levels

Percentile sound levels help quantify the range of acoustic conditions at the park. Table 6 lists day and night A-weighted percentile sound levels for the sampling period at SLBE.

Table 6. Summary sound levels at Sleeping Bear Dunes National Lakeshore in spring 2022. Included for each site are 90th percentile (L_{A10}), existing (L_{A50}), natural (L_{Anat}), and 10th percentile (L_{A90}) 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).

Site ID	Time	L_{A10}	L_{A50}	L_{Anat}	L_{A90}
SLBE001	Day	36.3	30.9	27.6	27.2
	Night	29.9	24.1	20.9	20.8
SLBE002	Day	35.5	30.2	26.9	26.7
	Night	29.5	24.2	20.9	20.9

Figure 4 shows hourly summaries for the A-weighted percentile sound levels (L_{A90} , L_{Anat} , L_{A50} , and L_{A10}), 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, at SLBE001, L_{A50} (median) sound level peaked during the 13:00 hour at about 33 dB, yet the sound level exceeded 10% of the time (L_{A10}) for the same hour at this site was 38.6 dB, meaning 90% of the measurement period was quieter. At both sites, the quietest L_{A50} and L_{A10} , as well as the lowest natural ambient sound levels (L_{Anat}), occurred within the early morning hours of 1:00 a.m. and 2:00 a.m. In general, higher natural ambient sound levels occurred in the early afternoon hours, perhaps due to wind (Figure 5).

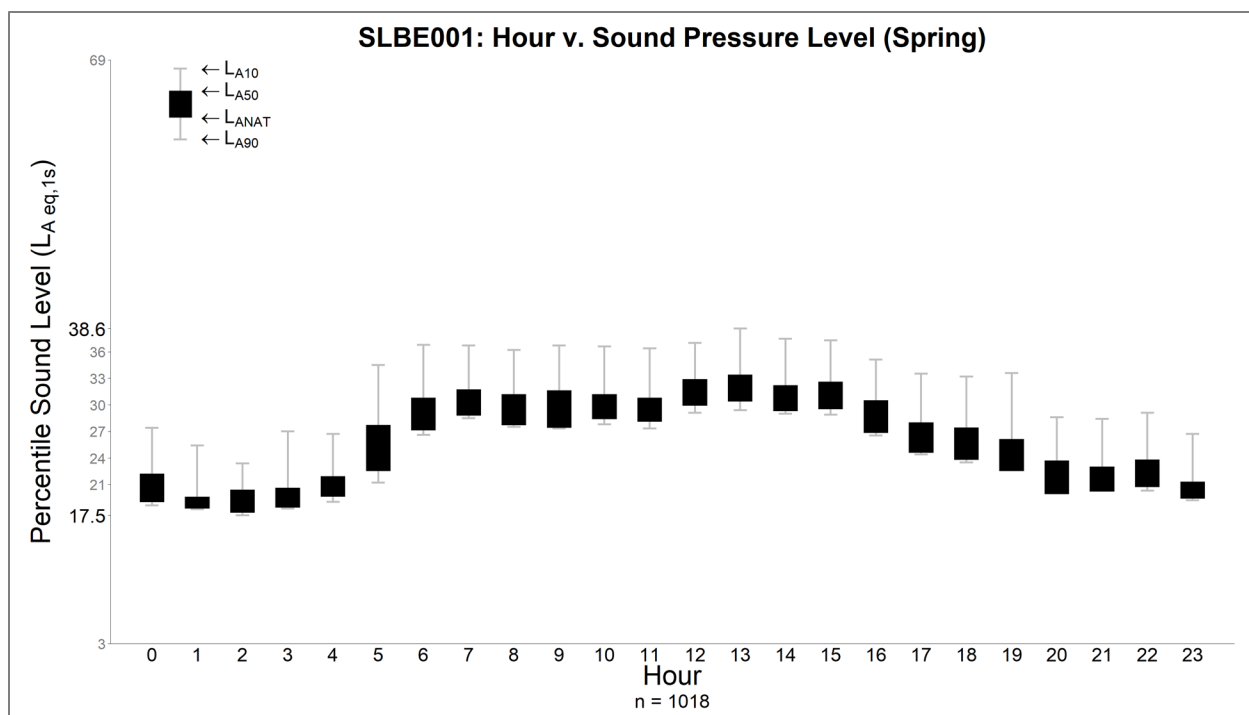


Figure 4. Median percentile sound levels ($L_{Aeq,1s}$), in dB re 20 μ Pa, at SLBE001 from March to April 2022. NPS / NSNSD

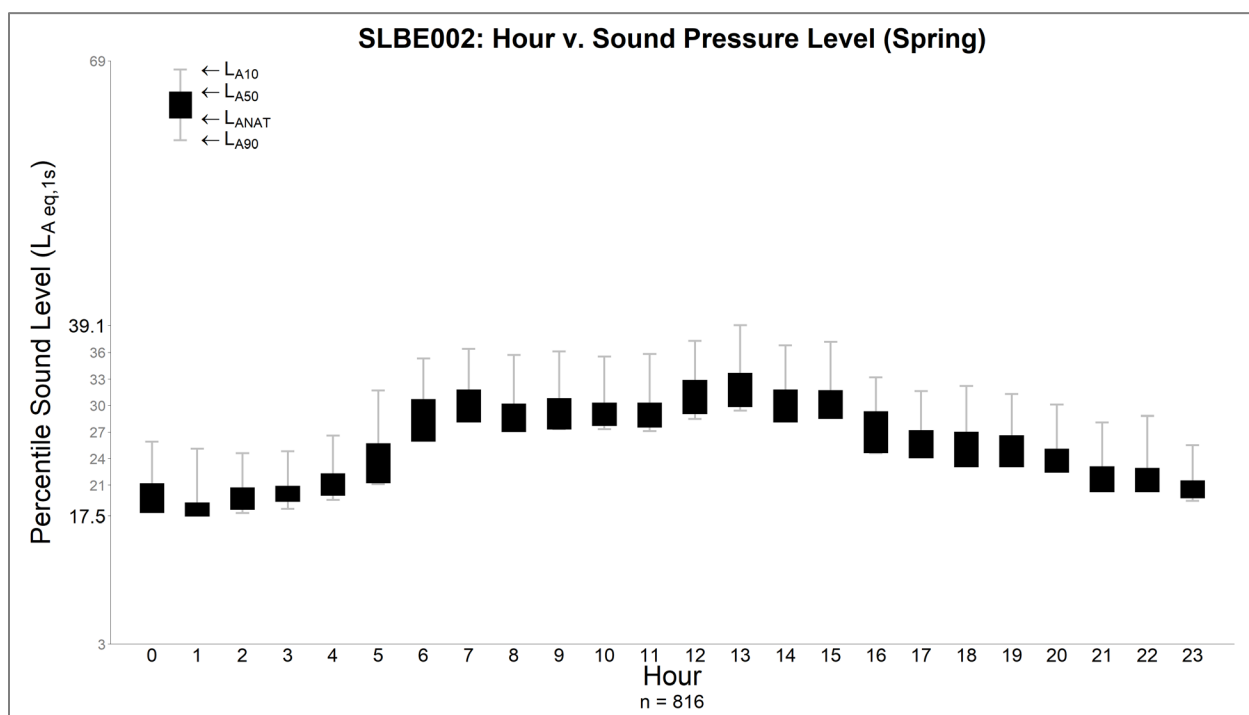


Figure 5. Median percentile sound levels ($L_{Aeq,1s}$), in dB re 20 μ Pa, at SLBE002 from March to April 2022. NPS / NSNSD

The spans of the black bars in Figures 4 and 5 indicate the difference between the L_{A50} (upper extent, representing the existing sound level) and the L_{Anat} (lower extent, representing natural conditions). Larger bars indicate hours with the most human-caused noise. At both sites in SLBE, existing sound levels are closest to natural conditions in the overnight hours, with the greatest departure from natural conditions in the early morning (5:00–6:00 a.m.) and late afternoon to early evening (4:00–6:00 p.m.). Except for the quietest hours overnight, the bars typically span more than 3 dB, especially during crepuscular and daytime hours (Figures 4 and 5). To translate this into functional effects on humans and wildlife, an increase in background sound level of 3 dB decreases the listening area by 50%. For example, if a predator can hear a potential prey animal in an area of 100 square feet in a setting with natural ambient sounds, that animal’s ability to hear would be reduced to 50 square feet if background sound levels increased 3 dB (Barber *et al.* 2009.) Table 7 summarizes the impact of anthropogenic noise on the natural ambient acoustic environment at SLBE in terms of an increase in dBA (by 3.2–3.3) and reduction in listening area (by 52.1–53.2%).

Table 7. Summary of the impact ($(L_{A50})-(L_{Anat})$) and reduction in listening area at two Sleeping Bear Dunes NL sites in the Spring season. Included for each site is the impact and reduction in listening area (%) during a) day (0700–1900); b) night (1900–0700), and c) combined (24-hr).

Site ID	Day		Night		Combined	
	Impact (dBA)	Listening Area Reduction (%)	Impact (dBA)	Listening Area Reduction (%)	Impact (dBA)	Listening Area Reduction (%)
SLBE001	3.3	53.2	3.2	52.1	3.2	52.7
SLBE002	3.3	53.2	3.3	53.2	3.3	53.2

Sound Sources and Duration

Through off-site listening analysis at the Listening Lab, trained technicians at the Listening Lab identify audible sounds and calculate the percentage of time each sound is audible for each hour, over a 9–11 day listening period (a representative subset of the acoustic deployment). A separate dataset representing the entire results—all identified sound sources, across all hours of the day—is published to the NPS Datastore (Olstad 2022).

Figures 6 and 7 distill and display the key information from that analysis, including the hourly time audible for top noise sources and hourly audibility for all non-natural sounds. At both SLBE001 and SLBE002, noise was audible more than 60% of the time across all hours, with evenings (6:00–9:00 p.m. hours) having the highest percentages, and midday typically lower, aside from a dip in time audible at SLBE002 in the early morning, 2:00–4:00 a.m. hours. Vehicles, including heavy equipment, were one of the top noise sources at each site, increasing during late morning (9:00 a.m. hour) at SLBE001 and mid-morning (6:00–8:00 a.m. hours) at SLBE002. “Non-natural unknown” noise sources were even more common, audible up to 70% of the time at SLBE002 overnight (midnight hour). Between the two noise sources, audibility patterns may be reversed (higher at day for vehicles; higher at night for “unknown”) due to an inability to process noise sources, with a

greater number of nighttime noise sources being unfamiliar and/or unidentifiable to Listening Lab technicians.

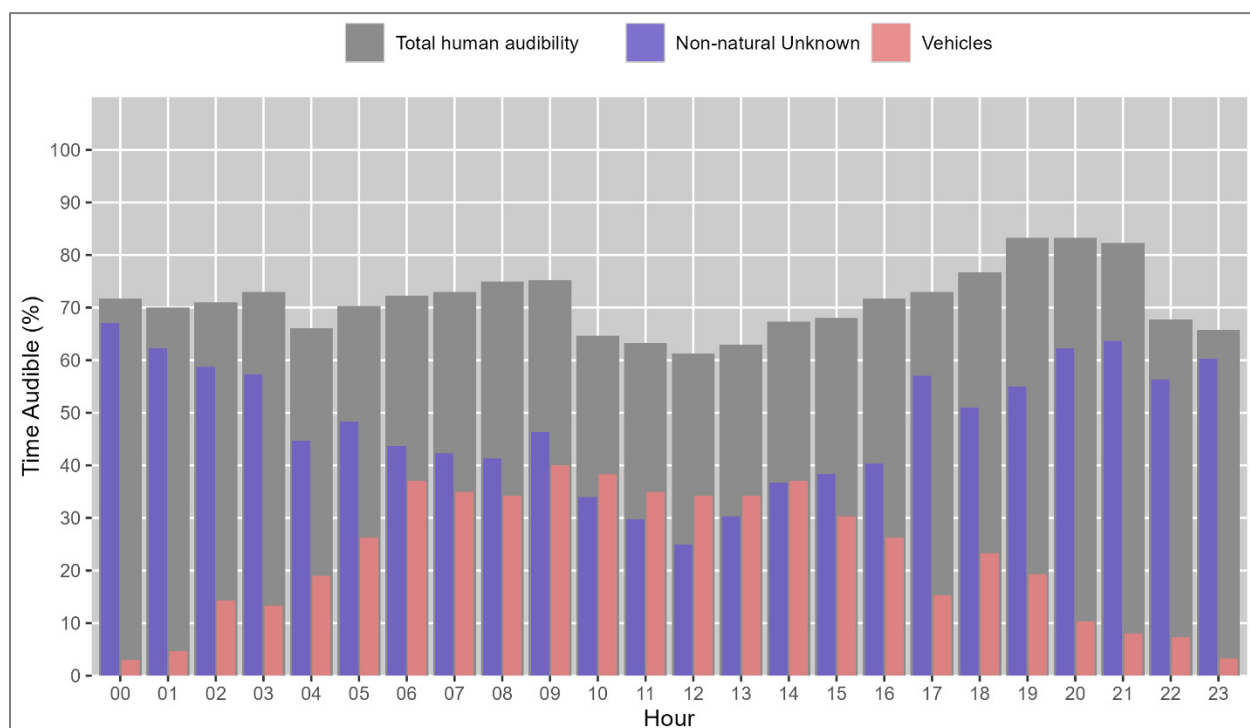


Figure 6. Hourly time audible for top noise sources and all noise sources at SLBE001 from March to April 2022. NPS / NSNSD

Heavy equipment was audible more than 20% of the time between 6:00 a.m. and 3:00 p.m. hours at SLBE001 and 5:00 and 8:00 a.m. hours at SLBE002, reaching 36.7% of the time during the 6:00 hour at SLBE002. Noise during these crepuscular hours may be especially impactful to wildlife and visitors seeking a quiet morning hike along Kettle Trail. Alarms or horns were also audible a notable noise source, audible more than 10% of the time most morning and early afternoon hours. If the sonic frequency of the alarms is fairly shrill, wildlife and visitors may perceive them as particularly annoying (Buxton et al, 2019). However, for these monitoring locations—near known operations of heavy machinery and distant from roads and parking lots—it's likely but unverifiable that these alarms or horns were back-up safety beepers associated with heavy machinery. Compared to other NPS locations, noise from aircraft is less frequently audible at SLBE, with jets being most common, though audible less than 10% of the time, except during the 9:00 p.m. hour.

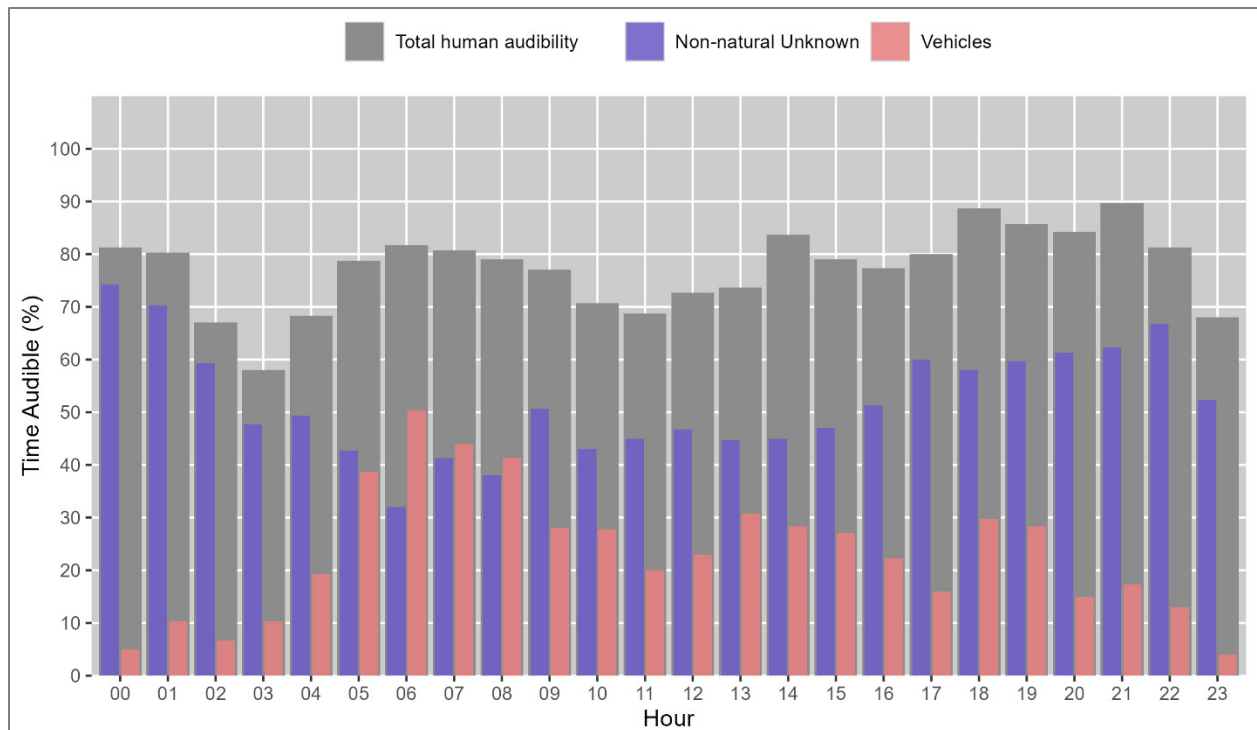


Figure 7. Hourly time audible for top noise sources and all noise sources at SLBE002 from March to April 2022. NPS / NSNSD

Common natural sounds include rain or dripping, audible 20% mid-morning to 51.3% overnight at SLBE001 and 10% (early afternoon) to 55.3% overnight at SLBE002. Light winds were audible up to 51.7% of the time at SLBE001, typically increasing during midday hours and calming to a low of 20% time audible overnight. Light winds weren't as audible at SLBE002, only reaching 35.7% time audible and calming to 8% overnight, though strong, masking winds more common, reaching up to 9.3% time audible late morning. Birdsongs were the most common natural daytime sound at both sites, audible up to 62.3% of the time at SLBE001 and 75.7% of the time at SLBE002. Birdsongs peaked during late morning hours (6:00–9:00 a.m. hours) and tended to taper off by evening, especially after the 7:00 p.m. hour.

Conclusions

This study arose from a Technical Assistance Request from SLBE, which sought acoustic monitoring to better understand baseline acoustic conditions and evaluate potential effects of sand and gravel mining on the park's Bow Lakes parcel. Acoustic measurements allow parks to gain insight into levels of intrinsic and extrinsic noise and biological activity. The results can help estimate the effects of noise on park visitors and wildlife, as well as the condition of the acoustic environment.

To carry out this study, two monitoring sites were placed in the Bow Lakes parcel, between the Kettle Trail and sand and gravel mines. Sound level meters, digital audio recorders, and anemometers collected continuous data from early March to mid-April 2022. Results include measures of existing ambient sound levels, calculations of sound source audibility through off-site listening, and modeled existing and natural ambient sound levels (see Appendix C).

Several metrics can be determined using the full SPL record. Existing median sound levels (L_{A50}) averaged 30.55 dB during daytime hours and 24.15 dB during nighttime hours. They were highest midday, 17:00–21:00. Functional effect levels at the ANS-weighted frequencies help isolate noise source impacts at various endpoints. In this frequency range at SBLE, the most sensitive sound level considered, 35 dB ($L_{Aeq, 1s}$), was commonly exceeded: 23.92–26.81% of the day and 14.44–14.97% of the night (Table 5). However, sound levels exceeded 52 dB ($L_{Aeq, 1s}$) a mere 0.09–0.11% of the time during the day and 0.03–0.04% of the time during the night.

Overall, the existing median sound levels (L_{A50}) at SBLE were 3.2–3.3 dBA higher than the natural ambient sound levels (L_{Anat}), resulting in a 52–53% reduction in the listening area. Off-site listening to a subset of the data reveals that anthropogenic noise was audible 71.2–77.3% of the time, with vehicles—including heavy machinery—the most common identifiable noise source, and alarms or horns another common noise. Aircraft were audible every hour of the day, but less commonly than at monitoring sites elsewhere. Wind, rain, and birds contributed energy to the natural sound level. Further acoustic analysis, such as artificial intelligence techniques like BirdNET, could generate species lists and daily call patterns from this dataset.

Based on the results of this study, visitors to and wildlife at the Bow Lakes parcel of SLBE will experience moderate exposure to anthropogenic noise—low-level but consistent. 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} , as a composite of multiple metrics with varying time averaging). Of the papers reviewed by Shannon et al., 20% showed impacts to terrestrial wildlife at or below noise levels of 50 dB ($L_{Aeq, 1s}$) (2016).

The information presented in this report can be used to inform park managers and planners, and it will also serve as a permanent record of sound levels measured at SLBE001 and SLBE002 in the spring of 2022. Sound level data as well as continuous digital audio recordings will be archived with the Natural Sounds and Night Skies Division office in Fort Collins, Colorado.

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Appendix A: Site Photos

Figures 8 and 9 are photos of the sites used in this study.



Figure 8. SLBE001 acoustic monitoring site, March 2022. NPS / NSNSD



Figure 9. SLBE002 acoustic monitoring site, March 2022. NPS / NSNSD

Appendix B: Office Listening Lab Software

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 extracts the first 10 seconds from every 2-minute period of the day (Figure 10). This results in 16 hours of audio data being analyzed per site. Each sound category is assigned a numeric source identification code, which is entered into the Listening Center software each time the listener hears a sound in that category. These numbers are eventually used to compute the L_{Anat} for the site.

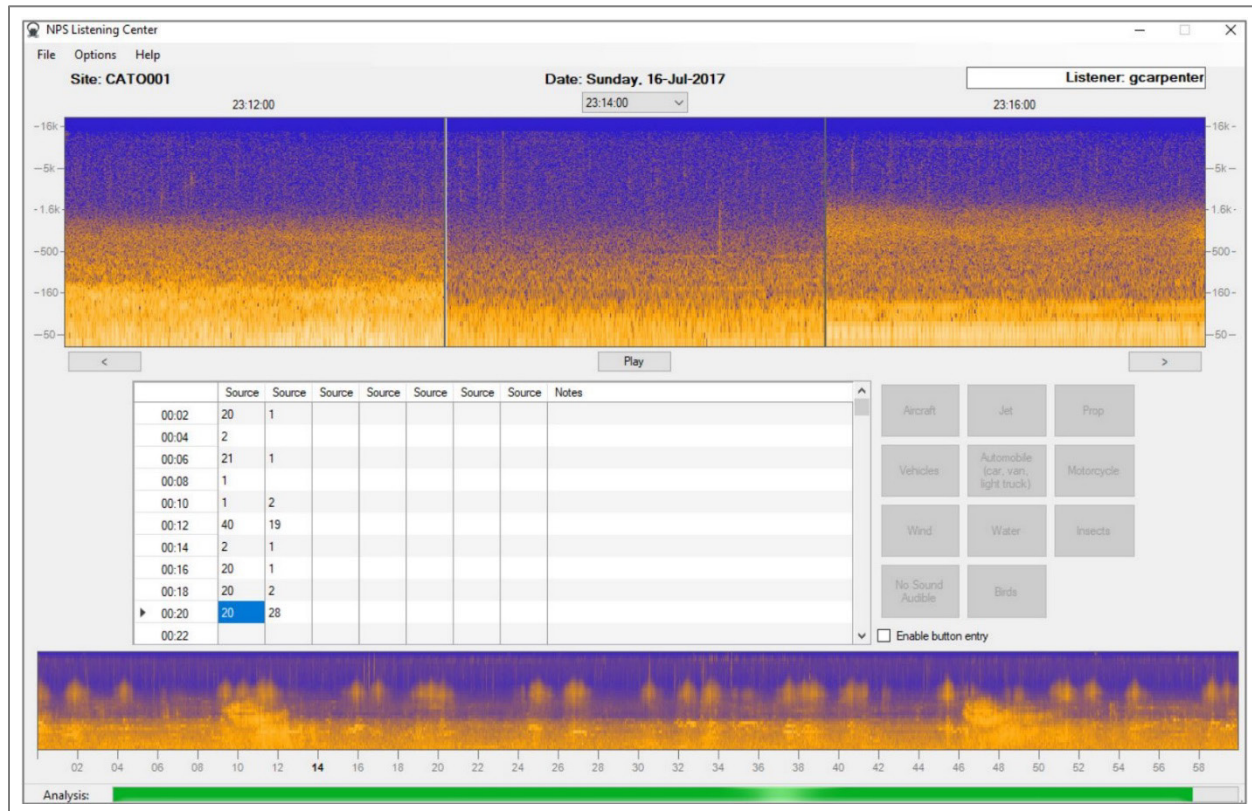


Figure 10. A screen shot of NPS Listening Center software. NPS / NSNSD

Appendix C: Modeled Impact Levels

NSNSD developed a model (Mennitt et al. 2014; NPS 2021) that predicts the median sound level using measurements made in hundreds of national park sites as well as 109 explanatory variables such as location, climate, land cover, hydrology, wind speed, and proximity to noise sources such as roads, railroads, and airports. The resulting model predicts sound levels anywhere in the contiguous United States, Hawaii, and Alaska, and estimates how much lower these sound levels would be in the absence of human activities. Each pixel in the graphics shown in Figures 11-13 represents the acoustic conditions on a typical summer day for an area of 270 x 270 meters.

Within SLBE, the model predicted an existing median $L_{50 \text{ existing}}$ of 37.0 dBA, with a maximum of 41.9 dBA near Glen Arbor and Empire and along M-22, and a minimum of 34.4 in parts of the Wilderness Area north and south of Desert Scenic Drive and on South Manitou Island (Figure 11). The Bow Lakes parcel was modeled to be fairly quiet, however, the model may not recognize and account for the sand and gravel mines.

Removing modeled anthropogenic noise, the model predicted a median natural $L_{50 \text{ natural}}$ of 33.6 dBA in SLBE, with Bow Lakes parcel one of the naturally quietest areas in the park, toward 32.7 dBA (Figure 12). The modeled difference between the existing and predicted natural sound level ($L_{50 \text{ impact}}$) at SLBE, shown in Figure 13, provides a measure of how much anthropogenic noise is increasing the existing sound level above the natural sound level on an average summer day in the park. Across SLBE, the median modeled sound level impact is 3.5 dBA, ranging from a low of 1.3 dBA in the least impacted and still quietest areas such as the Wilderness on South Manitou Island to 8.3 dBA in the most impacted areas, especially near M-22. For context, throughout the continental United States, the average impact was modeled to be 4.8 dBA, with a maximum impact of up to 33.7 dBA.

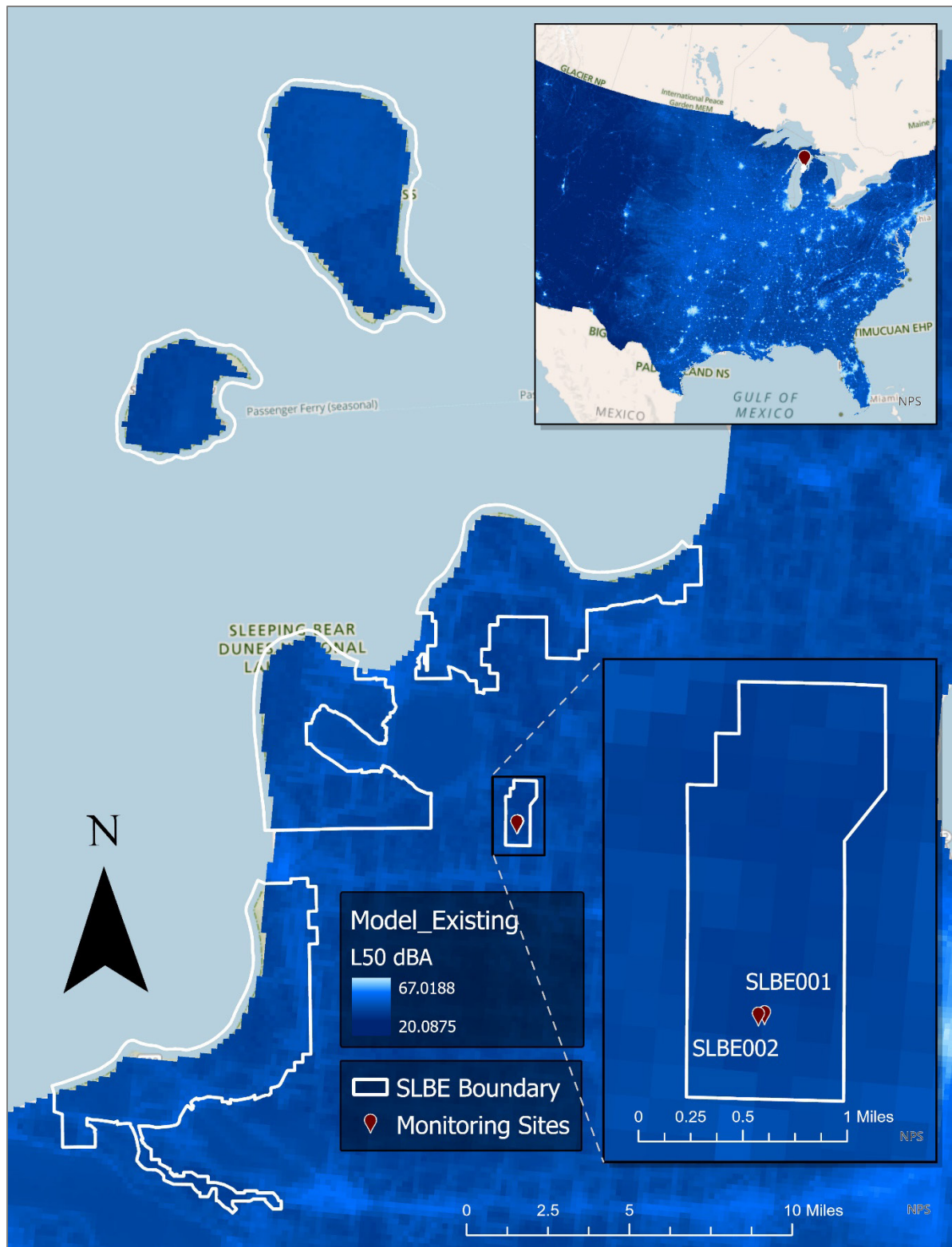


Figure 11. Map of predicted existing acoustic sound levels in SLBE for an average summer day. The color scale indicates median (L_{50} existing) sound pressure level (in A-weighted decibels, or dBA), with 270-meter resolution. NPS / NSNSD

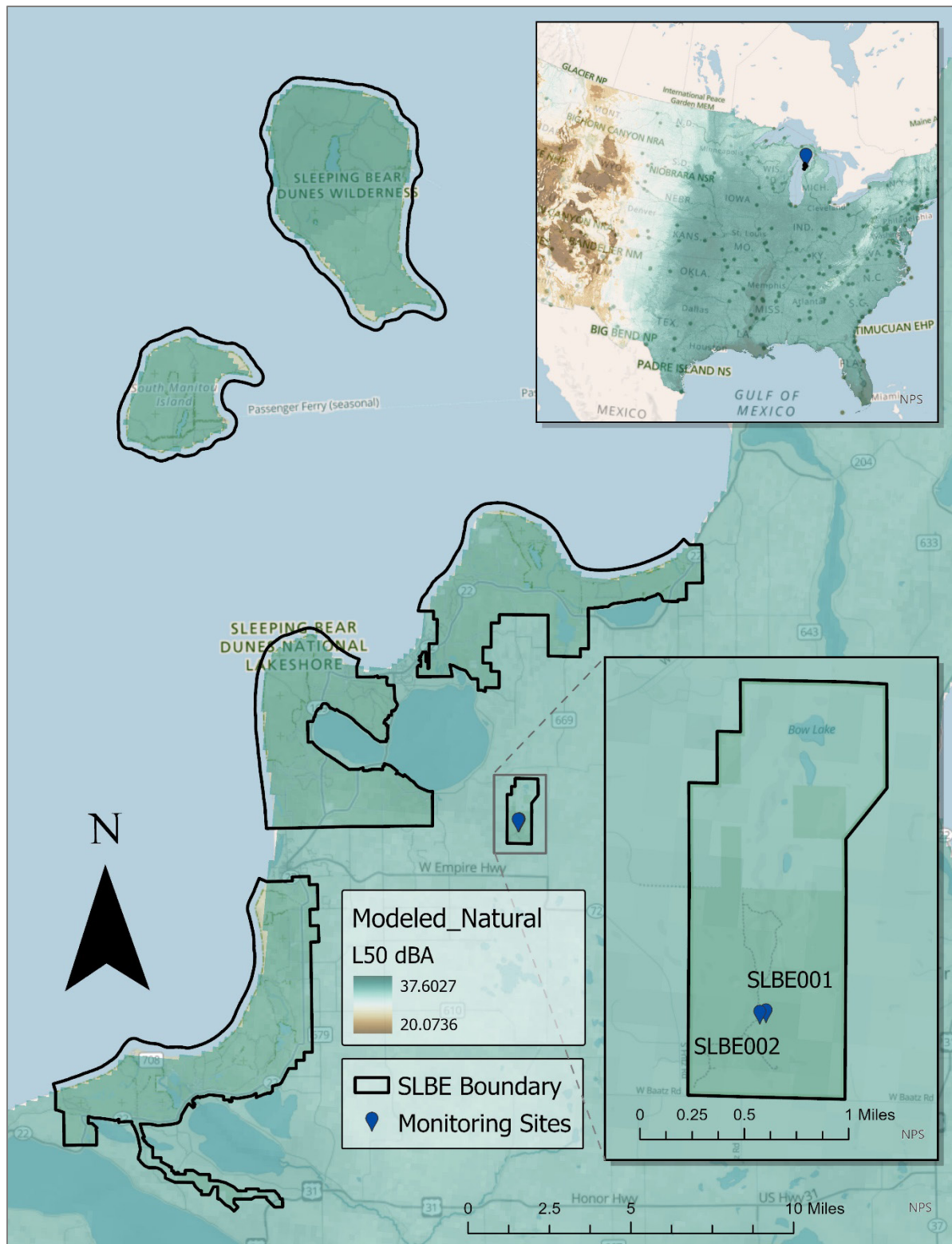


Figure 12. Map of predicted natural acoustic sound levels in SLBE for an average summer day. The color scale indicates median (L₅₀ natural) sound pressure level (in A-weighted decibels, or dBA), with 270-meter resolution. NPS / NSNSD

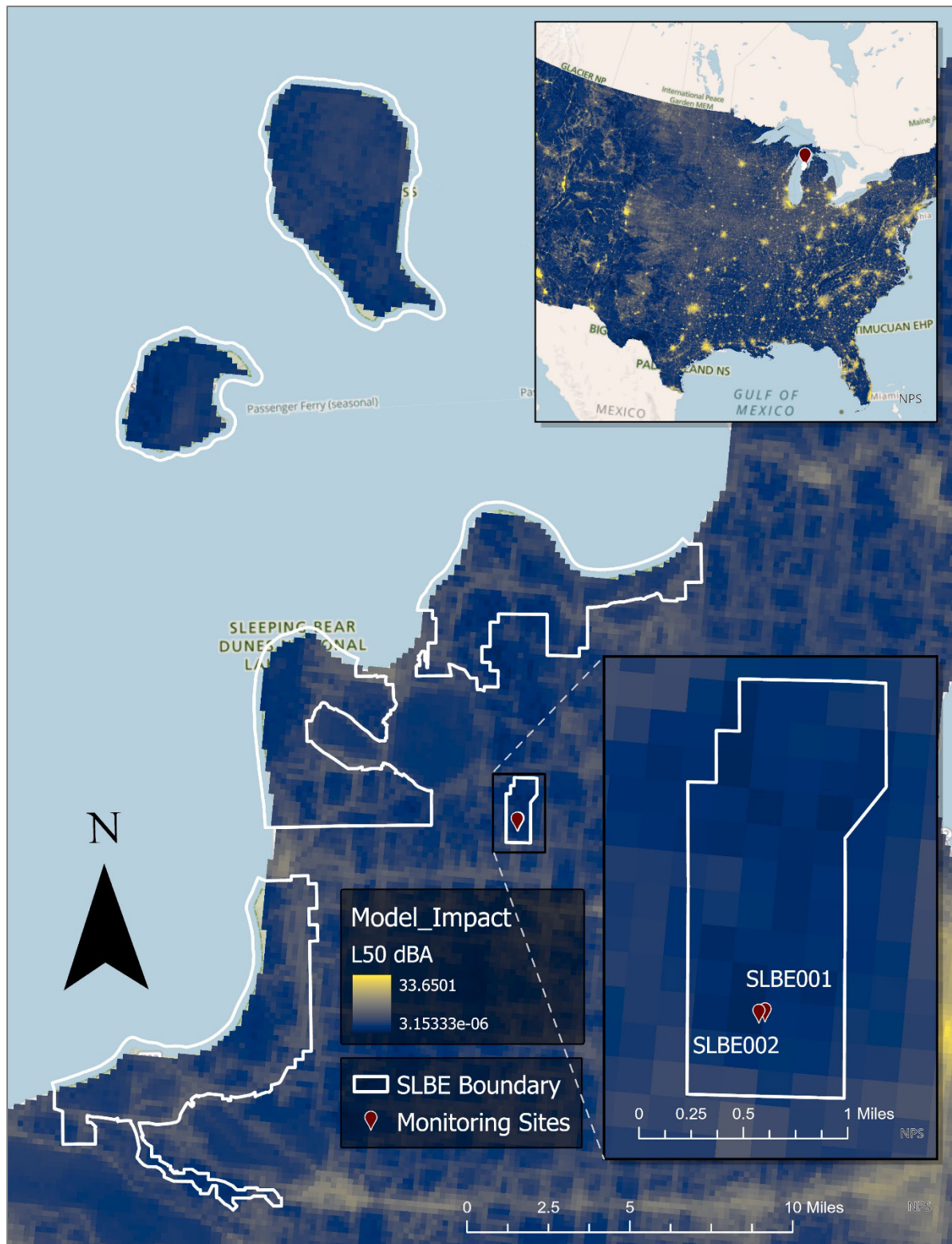


Figure 13. Map of predicted acoustic impact levels in SLBE for an average summer day. The color scale indicates how much man-made noise increases the sound level (in A-weighted decibels, or dBA), with 270-meter resolution. Dark blue indicates low impacts while yellow indicates greater impacts. The median acoustic impact level at the park is 3.5 dBA. NPS / NSNSD

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