ACTA GEOGRAPHICA LODZIENSIA
114 (2024): 111-124
https://doi.org/10.26485/AGL/2024/114/7

EXPLORING SOUNDSCAPES OF CENTRAL POLAND: A QUANTITATIVE STUDY OF MIDDLE PILICA RIVER BASIN WITHIN THE RADOMSKO AND OPOCZNO HILLS

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Abstract: The research project focuses on analyzing the acoustic environment of the middle Pilica River basin. The study aims to understand the variability of soundscapes, the structure of biotic and abiotic sounds, and the impact of human-generated noise in various spatial and temporal contexts. As part of the research, sound recording devices were deployed in three test areas: the Czarna River, the Pilica River, and the Cieszanowice Reservoir, collecting over 2,200 hours of high-quality audio recordings. The collected data was analyzed using advanced sound processing and spatial analysis techniques. The results reveal a high acoustic diversity across the studied areas, considering both natural factors and anthropogenic influences. The findings contribute to a deeper understanding of the role of soundscapes in the Central Poland ecosystems, highlighting their importance for environmental conservation and spatial planning. The methodology developed within the project, combining geomatics, data engineering, and data analysis, enables research scalability and the exploration of new research areas.

Keywords: soundscape analysis, geoinformatics, audio processing, data engineering, Pilica River

Introduction

In every ecological system, sounds, from the subtle rustling of leaves and the distinct calls of wildlife to the pervasive hum of human activity, are proof of the complexity of the interactions within it. These auditory elements, both natural and anthropogenic, weave together to shape the dynamics within a given geographical space, affecting both the habitats and the organisms that reside within them.

The term soundscape was initially introduced by Southworth (1969) to describe the perception of urban acoustic environments, including the quality and type of sounds and their arrangements in space and time. The concept of soundscapes was later popularized by Schafer (1976) to eventually find its place in various scientific fields over recent decades, particularly in the domains of environmental and geographical sciences. An in-depth analysis of the evolution of soundscape definition was carried out by Grinfeder *et al.* (2022) in the field of landscape ecology, who explicitly indicated the subject's complexity and presented a comprehensive set of diverse perspectives on understanding the phenomena that constitute a soundscape. Grinfeder *et al.* (2022) began their study by introducing a working definition of a soundscape coined by Pijanowski *et al.* (2011) as "a collection of biological, geophysical and anthropogenic sounds that emanate from a landscape and which vary over space and time reflecting important ecosystem processes and human activities." The authors highlighted that this definition leaves too much room for interpretation of a described phenomenon's components and structure. A new approach was needed to eliminate terminology ambiguity. Literature studies consequently led to the

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decision to divide the concept of soundscape into three interrelated types (Grinfeder *et al.* 2022), which are consistent with the concept of soundscapegraphy introduced by Hiramatsu (2000):

1. distal soundscape - considers a soundscape event as a collection of sound signals in a prespecified area, thus defining the phenomenon in a spatial and temporal context;
2. proximal soundscape - a collection of propagated sound signals that occur at a specific point in space, not taking into account all the potential effects of sound propagation, e.g. reflection, diffraction and interference;
3. perceptual soundscape links relevant proximal events through time and space with an internalized version of the phenomena registered by the sound recipient.

Bernat (2015) attributes a special role of geographical research in analysing soundscapes. He draws attention to the integration function of geography as a mediator between others interested in the phenomenon disciplines of science. He identifies the "emergence of a new opportunity for the development of geography, which should build bridges between expert knowledge and practice (decision-making), maintaining coherence between word and action." Bernat also postulates the use of modern technologies and citizen science initiatives to boost research on soundscape quality.

The quantitative approach to soundscape analysis has been employed for decades, providing a robust scientific framework for understanding the intricate acoustic environments in various settings. By systematically measuring sound levels, frequencies, and temporal variations, scientists have been able to characterize the acoustic properties of natural habitats, urban areas, and other environments. This resulted in many compelling initiatives in the field of soundscapes geography, including the work of Farina (2018) on the ecological role of environmental sounds and Ulloa *et al.* (2021), who prepared a high-quality programming toolbox for quantitative studies on soundscapes. The continuity and evolution of quantitative methods underscore their importance and reliability in soundscape research. Moreover, previous methods are frequently enhanced with machine learning and deep learning techniques, which have proven highly effective in extracting complex patterns, improving accuracy, and enabling real-time analysis of vast datasets (Adamiak 2021).

Geographical Information Science and geoinformatics are especially well-suited for extending contemporary quantitative approaches. Due to conceptual similarities with distal and proximal soundscapes regarding treating geographical space as a medium in which objects and events co-exist, interact, and can be georeferenced (Ney 2007; Lisowski 2014; Adamiak 2022), geoinformatics can be efficiently placed within the framework defined by Grinfeder *et al.* (2022). Such an approach allows using the full range of statistical and geoinformatics methods and techniques available for spatial analysis.

The present research aims to extend the understanding of the composition of the Central Poland soundscapes by focusing on the quantitative geospatial measures that can be used to analyze acoustic data in various environmental settings. By applying a suite of analytical techniques — including real-time, large-scale sound level measurements, bioacoustic indices, and state-of-the-art data science techniques-the author seeks to uncover the relationships between acoustic diversity and the geographical space within which it occurs.

The study targets sparsely populated settings of the middle Pilica River basin located within the Przedbórz Upland. It is grounded in a series of field recordings covering multiple biomes and phenological seasons. **Sample recordings and imagery are available online and denoted by an interactive icon**. The objectives of this research are multifold:

1. to quantify the variability and intensity of soundscapes across different spatiotemporal settings;
2. to explore the composition of soundscapes by isolating their biotic and abiotic components;
3. to assess the impact of human-induced noise on natural sound orders.

Through these objectives, the author aims to deepen the understanding of the soundscape structures found in Central Poland, thus highlighting the unique acoustic characteristics of this region and contributing to the field of soundscape studies.

Methods and Materials

Hardware

The AudioMoth audio logger is a versatile and cost-effective acoustic monitoring device for environmental and ecological research (Hill *et al.* 2019). It is a small, battery-powered recorder capable of capturing high-quality audio over extended periods. The device (Fig. 1) is equipped with a sensitive microphone, which can record sounds at various frequencies, making it suitable for monitoring various acoustic phenomena, from wildlife vocalizations to ambient noise levels. Its lightweight and durable design allows for easy deployment in diverse environments, including remote and harsh conditions.

AudioMoth is considered a reliable tool for continuous and long-term acoustic data collection. During this research, twenty AudioMoth devices with protective casings were prepared. The author adjusted each casing to match and resemble each targeted area's biotop by introducing customized painting and texture. The devices were equipped with a 32GB microSD card and configured to capture single-channel audio with a 48kHz sampling rate, medium gain (25 dB), -18 dB/V microphone sensitivity, and no initial filtering applied. Various recording schedules were defined depending on the deployment date and predicted weather conditions.

Research Area

The Pilica River, the longest Vistula River left tributary, is an ecologically significant area characterized by a curved fluvial system, extensive palustrine environments, and a heterogenous landscape comprising deciduous and coniferous forests, grasslands, and agricultural zones.

The research was conducted in the subsection of the middle river basin located within two mesoregions: Radomsko and Opoczno Hills. The Opoczyńskie Hills are located in the northernmost part of the Przedbórz Upland macroregion[1]. From the northwest and north, the border with the subprovince of the Central Polish Lowlands runs along the Pilica Valley and the eastern shore of the Sulejowski Reservoir. The natural vegetation is spatially diverse. Luminous oak forests dominate the northern part, and the southern part is dominated by continental mixed pine and oak forests (Krysiak *et al.*, 2021a). The Radomsko Hill mesoregion is located in the north-western part of the Przedbórz Upland macroregion[2]. Towards the north, it passes into the Bełchatów Upland and the Piotrkowska Plain, southwards into the Niecka Przyrowska and Niecka Włoszczowska. From the east, it borders the Opoczyńskie Hills and the Przedborsko-Małogoskie Range. This mesoregion is characterized by flat and gently rolling highlands locally varied by wind-blown sands forming dunes up to several meters high. Similarly, the landscape features hills and knolls that are part of terminal moraines. The predominating vegetation is mainly mixed pine-oak forests, with significant areas of continental swamp forests and patches of highland fir forests (Krysiak *et al.*, 2021b). The fauna of the Radomsko and Opoczno Hills is notably diverse, reflecting the varied habitats and relatively low levels of urbanization in this region.

The waters of the Pilica and Czarna rivers are rich in biodiversity. Numerous freshwater fish species have been confirmed, contributing to the ecological balance of the area. The avifauna is particularly well represented, with many bird species regularly nesting in the region, highlighting the area's importance as a breeding ground for many animals. In addition to the birdlife, the insect population is abundant, with various species thriving within the plant communities that characterize the area. Mammal populations are also robust, with many species typical of the Polish lowlands inhabiting the region.

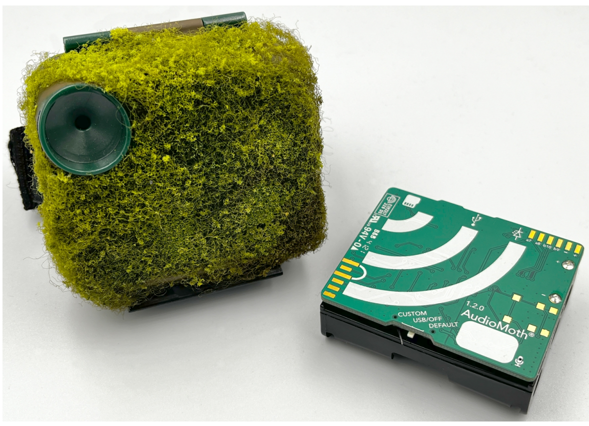

Fig. 1. AudioMoth deployment package in a customized protective casing (*photo by M. Adamiak 2024*)

1. 51.5277°N, 19.8619°E to 51.0292°N, 20.4557°E
2. 51.2572°N, 19.2865°E to 50.9239°N, 19.9385°E

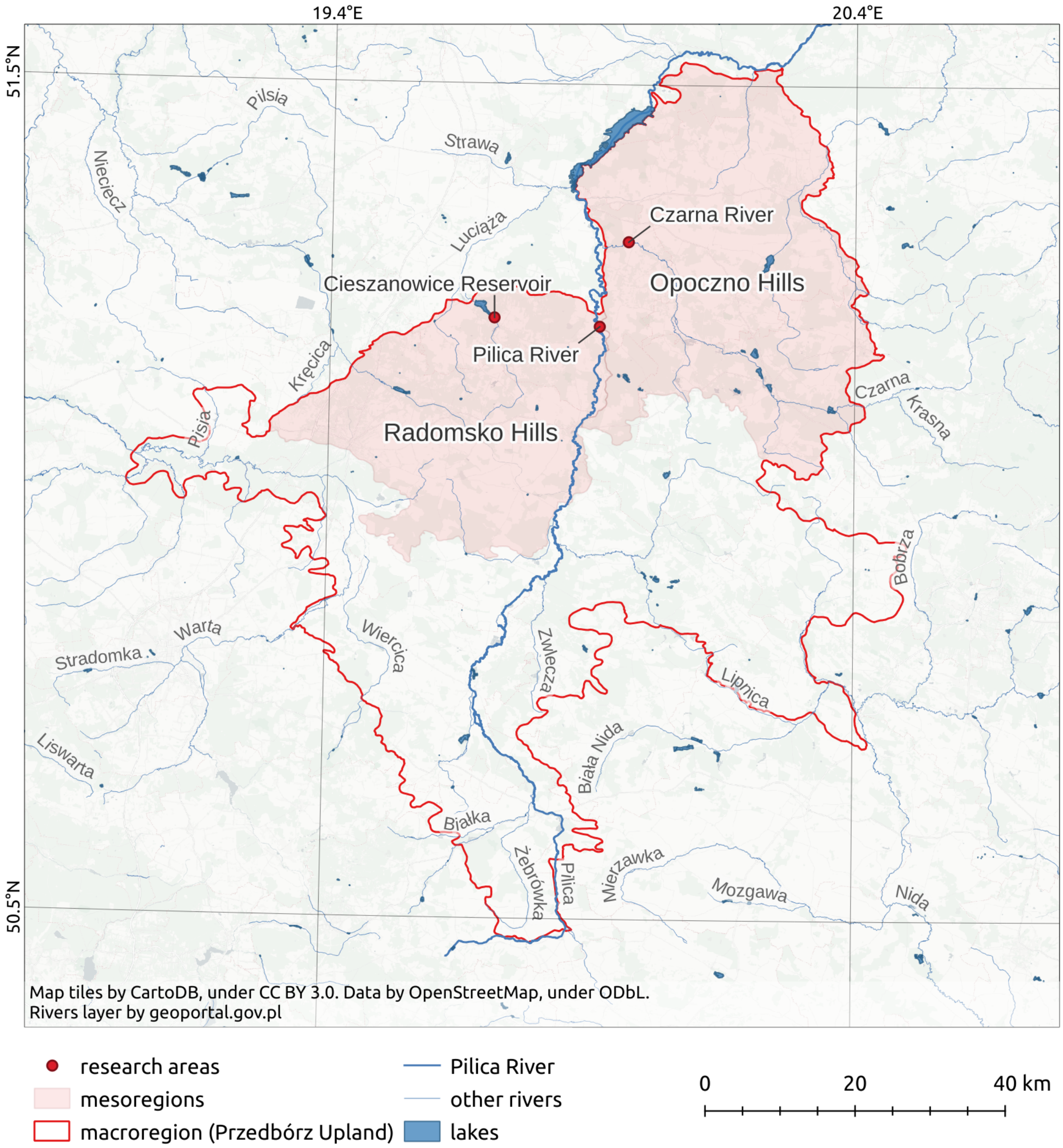

Fig. 2. Research areas in relation to physico-geographical mesoregions of Poland (Solon *et al.* 2018)

The soundscape data acquisition research was conducted across three distinct research locations within the Middle Pilica River basin, each characterized by unique sensor deployment patterns to capture comprehensive acoustic profiles (Fig. 2). After preliminary tests, the author assumed a 250m effective sensor range. In the Czarna River area (Fig. 3), sensors were deployed in a linear pattern of 750m-1000m segments parallel to the riverbed, enabling detailed monitoring of the acoustic characteristics along approximately 10km of the river's flow. The second area featured a curved deployment pattern following approximately 1.5km of the Cieszanowice Reservoir shore (Fig. 4), reflecting the interactions between aquatic and terrestrial acoustic environments in a homogenous 0.5km^2) geographical space. In the last case, a 0.5km^2 areal deployment covered the Pilica riverbed and adjacent terrestrial regions (Fig. 5), providing a holistic view of the soundscape, including aquatic and nearby land-based sources. This multifaceted approach allowed a nuanced understanding of each soundscapes' spatial and temporal dynamics across different geocomplexes.

Fig. 3. Czarna River research area

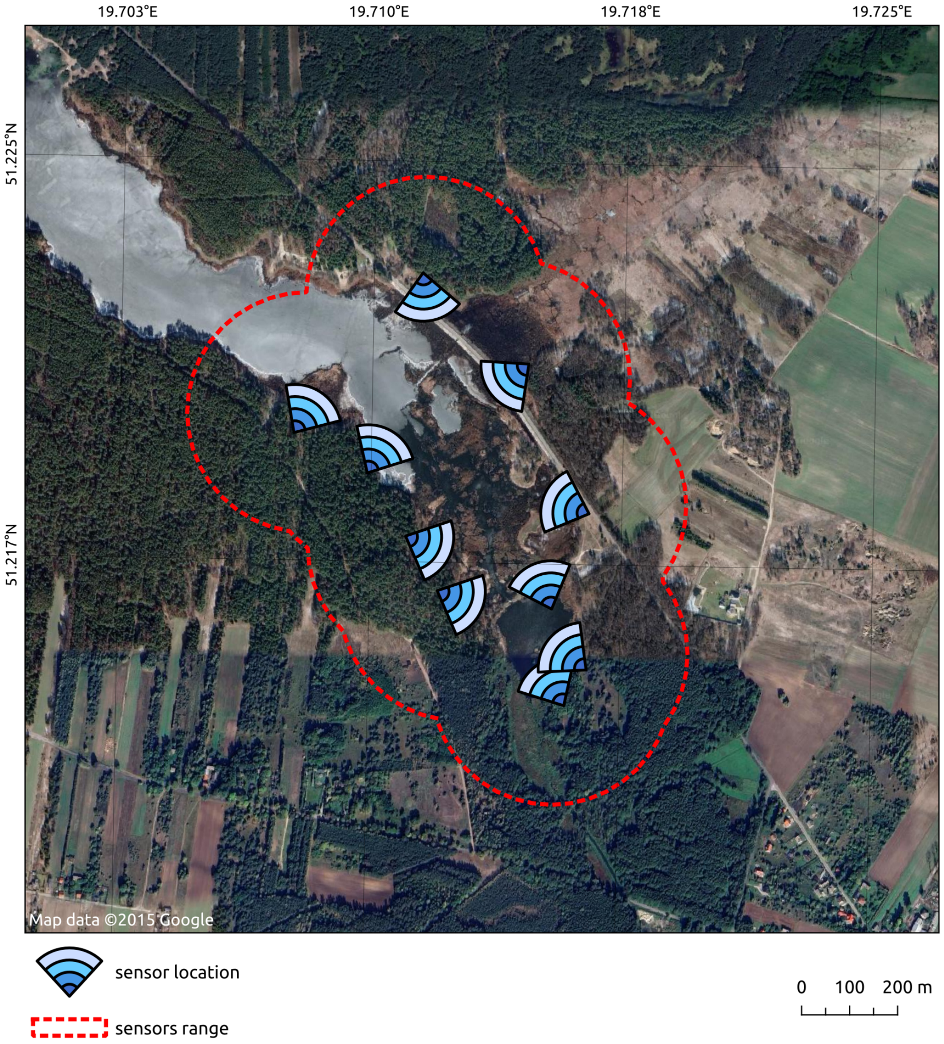

Fig. 4. Cieszanowice Reservoir research area

Fig. 5. Pilica riverbed research area

Sound Data Analysis

A systematic data collection approach ensures the quality of sound data. Thus, the study's data acquisition protocol begins with carefully selecting the sensor target locations within the chosen research area. The sensor placement points were selected based on the most recent SentinelHub (Sentinel Hub 2024) and Planet Scope (Planet Satellite Imaging 2024) remote sensing imagery to ensure the presence of appropriate device reading conditions. The fastest and safest deployment path was determined based on the defined sensor locations. One of the designed routes can been visualized as an online spherical imagery tour ().

Next, protective casing maskings were prepared according to the conditions identified in the target research locations. Each casing was carefully checked for possible leakages and then painted with a colour pattern and covered with a texture corresponding to the vegetation of the potential location. Finally, the audio loggers were programmed using official AudioMoth (Open Acoustic Devices 2024) onboard time setting and configuration applications. Such an approach ensures all devices are in sync and set to the appropriate recording schedules and parameters chosen for the specified area.

During a field study, each logger was placed at a predetermined point 1-3m above the ground facing the river bed or water reservoir shore (Fig. 6). After deployment, the device's coordinates and bearing, as well as a description of its location and a spherical photo, have been recorded. This process requires careful attention to the environment and potential disturbances to secure the sensors, avoiding displacement or damage, and reducing noise in the recording.

Fig. 6. AudioMoth mounted in one of the designated points (51.3009°N, 20.0021°E) (*photo by M. Adamiak*)

The recording starts the day after deployment to avoid capturing the sounds of the sensor being mounted at the target location. The biggest challenge was positioning the device in a location free from repetitive sounds from nearby leaves and reeds. Their impact would negatively affect the results by introducing an overwhelming amount of interference ().

After three to seven days of monitoring, the loggers automatically stopped recording to be retrieved the next day. The audio data collected in WAV format was uploaded to the Google Cloud Platform (GCP 2024) for storage and processing. Data has been stored in the standard storage class to enable rapid access during the analysis.

To process audio data efficiently, the author developed an advanced data processing pipeline based on a combination of Ray Data (ray-project/ray 2024), scikit-maad (Ulloa *et al.* 2021), librosa (McFee *et al.* 2024), geopandas (Bossche *et al.* 2024) and torch audio (Yang *et al.* 2022).

The Ray Data framework, a scalable computing library, combined with scikit-maad, a package dedicated to audio analysis, offers a robust solution for handling large-scale audio datasets. Ray Data facilitates distributed data processing, enabling the parallelization of tasks and efficient utilization of computational resources. By leveraging specialized audio processing libraries, the vast amount of data (approx. 1.2 TB) gathered from all devices could be processed more quickly and accurately. This approach enabled multiple experiments to be conducted in a shorter time frame.

The analysis focuses on calculating various acoustic indices that summarize a chosen aspect of the distribution of acoustic energy and information in a recording (Towsey *et al.* 2014), thus facilitating the quantification of acoustic patterns and biodiversity.

Additionally, the approach incorporates sound pressure level measurements to evaluate the intensity of sound energy in the environment, and a region of interest (ROI) detection procedure carried out on the processed audio spectrograms. Calculating various values is crucial because no single acoustic index can fully represent the entire soundscape. Multiple indices are necessary to capture the differences between habitats because a particular index value often has multiple possible explanations (Villanueva-Rivera *et al.* 2011). Table 1 describes acoustic indices computed during the study.

The analysis is inherently spatiotemporal, focusing on sound dynamics over time in a given geographical space. Each audio file was split and processed in ten-minute chunks. The output for each chunk is then matched against the sensor deployment location, georeferenced and processed using geographical information system (GIS) techniques. Integrating the spatiotemporal aspect with quantitative acoustic metrics, the author aims to achieve a multifaceted understanding of the acoustic environment and provide a more nuanced understanding of the ecological and environmental factors that characterize the soundscape.

Table 1

Audio analysis indices

Id	Index Name	Description	Unit
LEQt	Equivalent Continuous Sound Level	Represents the constant sound level that, over a given period, contains the same amount of acoustic energy as the varying levels during the same period (Ulloa *et al.* 2021). Provides a single number that summarizes fluctuating noise levels over time, making it easier to compare different noise environments or to assess compliance with noise regulations.	dB
NBPEAKS	Number of Peaks	Introduced by Gasc *et al.* (2013) counts the number of major frequency peaks obtained on a mean spectrum scaled between 0 and 1.	scalar
ACI	Acoustic Complexity Index	Computes the variability of the intensities registered in audio recordings, despite the presence of constant human-generated-noise (Pieretti *et al.* 2011). The index is a positive number.	scalar
NDSI	Normalized Difference Soundscape Index	NDSI aims at estimating the level of anthropogenic disturbance on the soundscape by computing the ratio of human-generated (anthropophony) to biological (biophony) acoustic components (Seewave 2024). NDSI varies between -1 and +1, where +1 indicates a signal containing no anthropophony.	scalar

Results

Sensor measurement indicated a high variation of LEQt values among research areas and over time (Fig. 7). The primary differentiation is visible between the Czarna River and Pilica River areas and is related to the season of data collection. The complete dataset (areas combined) median reached a value of 60.56dB. The minimum LEQt value of 51.77dB was registered in the Pilica area in the early morning. Generally, the tendency to observe LEQt low values during the night between 01:00 and 06:00 is prevalent. The highest values of the indicator occurred in the morning. They were recorded in the Czarna and Cieszanowice areas during an extended period of pronounced bird song recording. Sensors closer to human settlements or animal habitats generally recorded higher LEQt values during noon and afternoon (11:00 and 14:00). The most prominent sound pressure peaks, exceeding 95dB, didn't correspond to periods of high continuous sound levels. This is mainly due to the episodic nature of sound-generating events, the strongest of which were related to cars speeding on nearby asphalt roads and direct interactions with the sensor housing, e.g., during heavy rain, tampering with the device by a third party or animal activity (woodpecker pecking).

The NBPEAKS index analysis indicates high-value variability over time. The influence of seasons and time of day is evident: fewer near-maximal values were recorded during the night or winter hours than in spring, mornings, and afternoons. Multiple high values of the indicator were observed in the area of the Czarna river and corresponded to a melodic bird song (). The state of the NBPEAKS variable is related to the daily cycle of animal life and human activity. It is worth adding that the analyzed frequency of 48kHz didn't allow for reading ultrasound emitted by bats, which would need at least 192 kHz according to Nyquist's Theorem, influencing the final NBPEAKS index analysis. Table 2 presents statistics of the NBPEAKS index for the research areas.

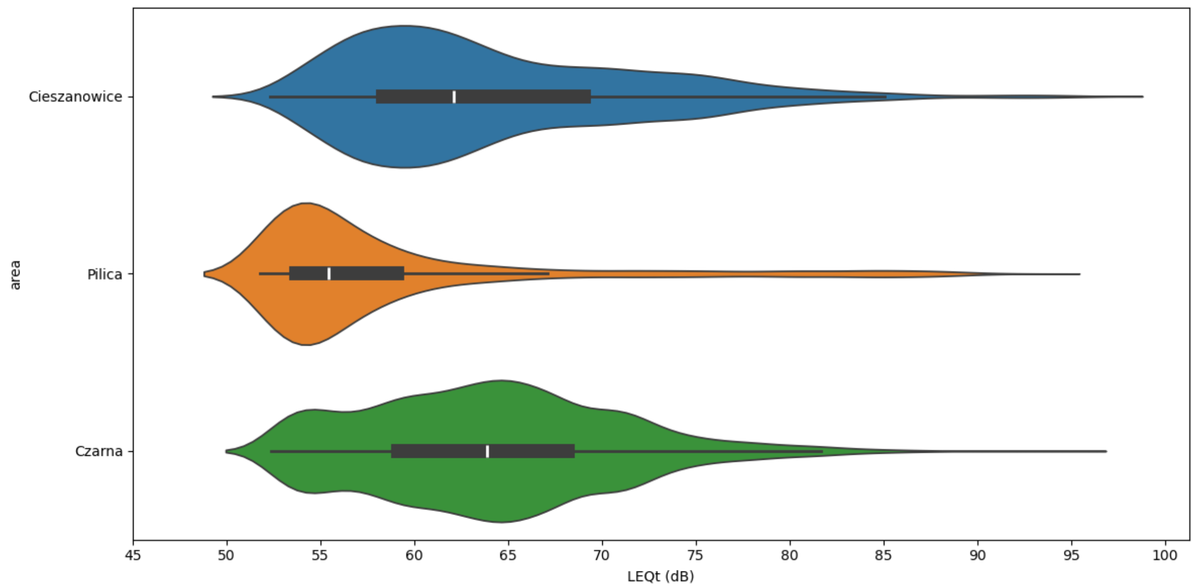

Fig. 7. Violin plot of LEQt calculated for three research areas, showing each area's values distribution, median, and interquartile range. An internal boxplot has been placed to mark the median value and outliers, thus highlighting variability in sound levels across the different locations.

The Acoustic Complexity Index (ACI) heatmap (Fig. 8) reveals distinct patterns of acoustic activity across the three research areas. In the Cieszanowice area, readings indicate a pronounced increase in acoustic complexity between 7:00 and 14:00, with an additional spike around 21:00 on several devices. The Czarna area exhibits constantly occurring peaks in multiple devices, showing significant complexity throughout the day and during night hours (). The Pilica area shows the highest complexity from 08:00 to 14:00 while maintaining relatively low complexity at other times.

The box plots (Fig. 9) illustrate how the soundscapes, as captured by the NDSI, vary between research locations and sensors, with Czarna showing the most variability and the potential for more positive (natural) soundscapes samples (). Conversely, the Cieszanowice and Pilica research areas show predominantly negative NDSI values, indicating that anthropogenic noise negatively impacts NDSI and is likely more prevalent.

Table 2

NBPEAKS statistics for the research areas

Area	Mean	Std	Min	25%	50%	75%	Max
Cieszanowice	6.37	3.9	2	4	5	8	47
Czarna	10.07	6.11	2	6	9	12	54
Pilica	3.21	2.17	1	2	3	3	56

The lack of readings with high positive NDSI values is not surprising because these selected areas, and a significant part of Central Poland, cannot be considered natural areas devoid of signs of human activity.

Discussion

Soundscape Quantitaive Analysis

The data revealed significant spatial and temporal sound-level variations, which can be attributed to both natural and anthropogenic factors. For instance, the observed high LEQt values in the Pilica River area during winter highlight the impact of human-induced noise and natural events like heavy rain over animal activity (). Although LEQt output doesn't show signs of abnormal sound levels in this research area, this does not mean it can be considered a healthy soundscape that exhibits moderate sound levels, balanced frequency distribution, temporal coherence, minimizes excessive noise pollution and maintains auditory diversity. On the contrary, the persistent, distant human-produced hum is present and noticeable, especially during winter and early spring ().

Additionally, the analysis of NBPEAKS demonstrated how daily and seasonal cycles influence sound complexity, with melodic bird songs

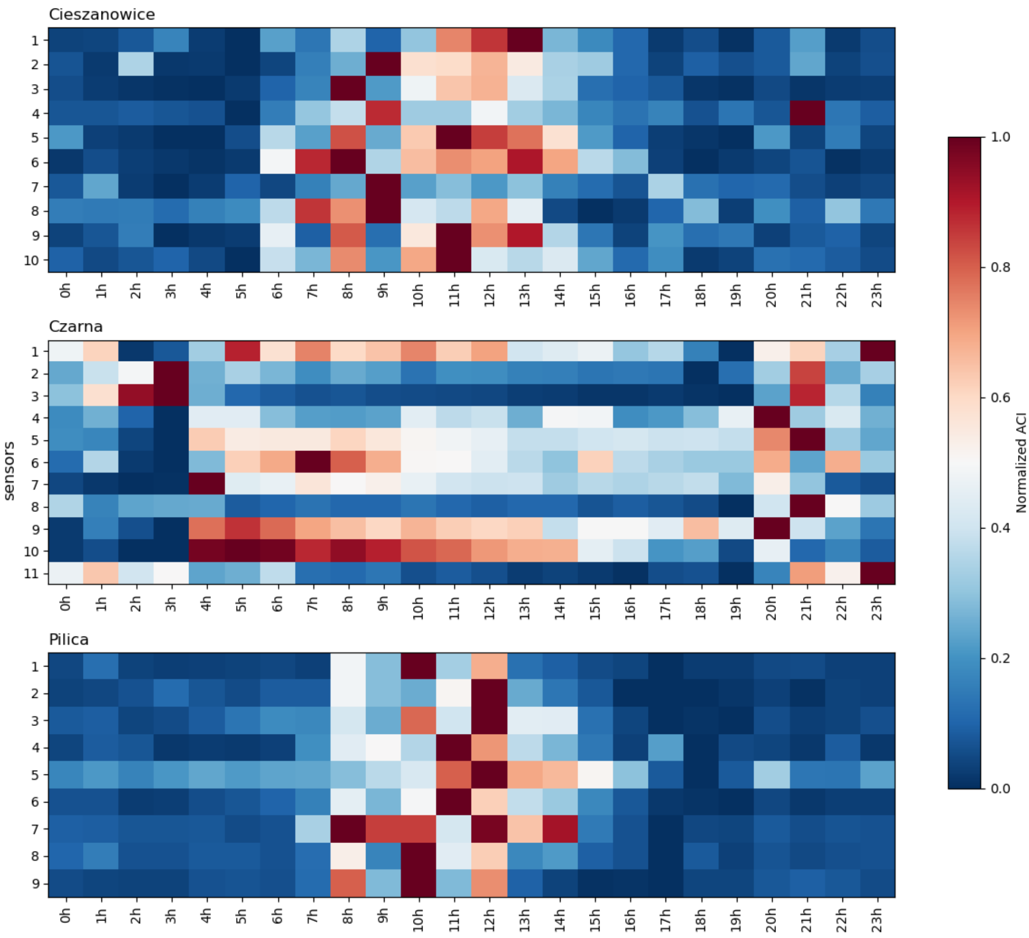

Fig. 8. Normalized ACI heatmap calculated for all deployed devices in the scope of specific research areas

contributing to high values in the Czarna River area during mornings and spring. These findings align with previous studies that emphasize the cyclical nature of soundscapes concerning biological and human activities, especially phenological seasons (Fleming *et al.* 2023).

The influence of human activity on natural soundscapes is apparent in the NDSI results. The predominantly negative NDSI values in the Cieszanowice and Pilica areas suggest a higher prevalence of anthropogenic noise, particularly near roads (). Human impacts are most pronounced during winter when animal activity is significantly lower. The influence of anthropophony, even in sparsely populated areas, could be potent enough to mask biological signals, leading to a distorted understanding of the natural acoustic environment. This finding is consistent with the research objective of assessing the impact of human-induced noise on natural sound.

Due to the linear pattern with which the sensors were deployed, further analysis of the Czarna River area presents valuable insights (). Correlating the values of the acoustic indices with distances between deployed sensors and the nearest occurring human-made structures can reveal several highly localised spatial characteristics (Fig. 10). Weak-negative ACI correlations for built-up areas and roads dominate. This indicates that more complex sounds are less frequent in urbanized areas, particularly in the evening and early night. Moderate-positive correlations exist between NDSI and built-up areas, particularly in the evening. This suggests that anthropogenic sounds (linked to built-up areas and roads) may dominate during these times, potentially reducing the natural soundscape. Moderate-negative NBPEAKS correlations could reflect a decline in bioacoustic peaks during the afternoon near human settlements. Moderate-negative LEQt correlations are seen for both built-up areas and roads, particularly in the morning and night. In conclusion, although highly local, the analysis shows that urbanization has a strong negative impact on the natural acoustic environment, reducing sound complexity and bioacoustic presence and increasing noise levels.

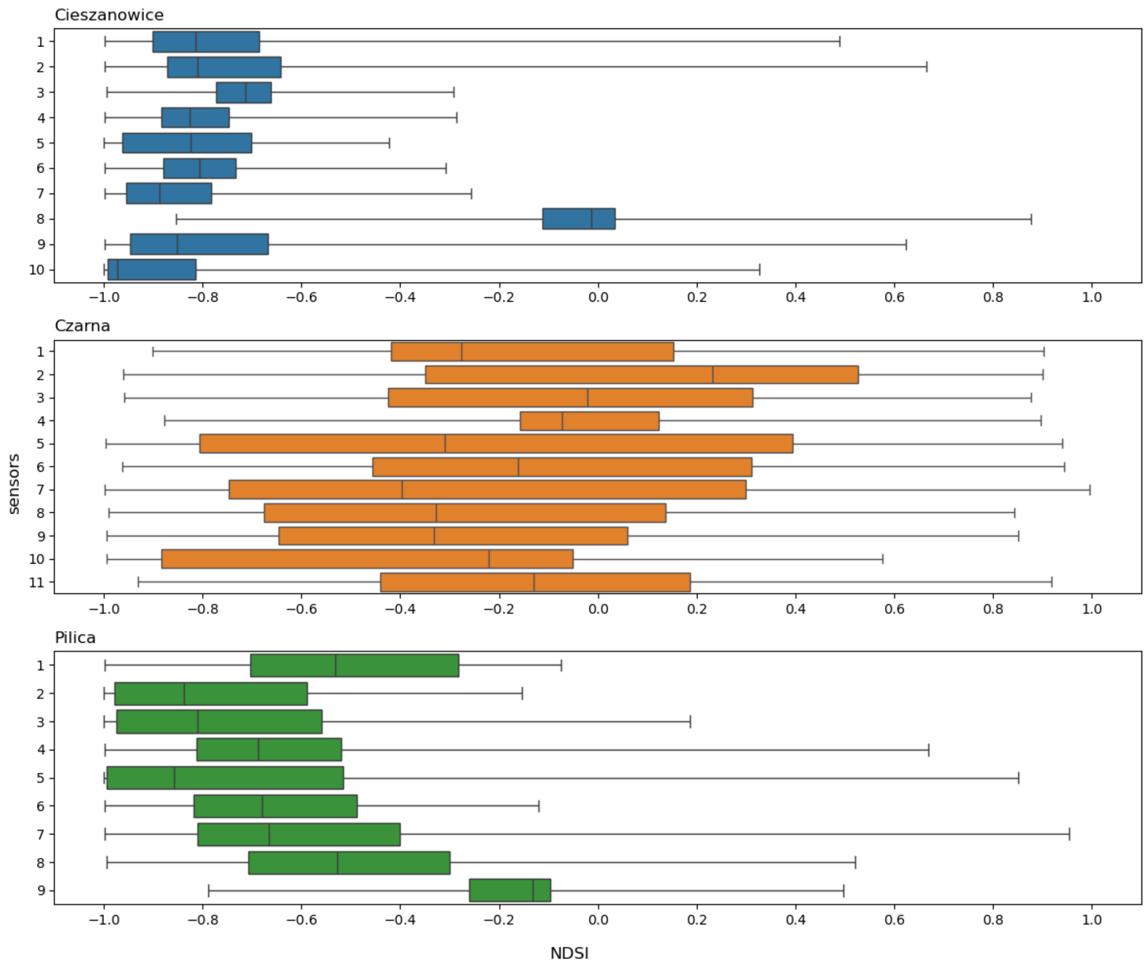

Fig. 9. NDSI boxplot calculated for all deployed devices in the scope of a specific research area

Methodological contributions and limitations

One of this study's key methodological contributions is the integration of modern data science techniques and geoinformatics with traditional soundscape analysis methods. By leveraging tools like Ray Data, scikit-maad, and torchaudio, the research was able to process large-scale datasets efficiently, enabling detailed acoustic analyses across multiple research sites. Furthermore, this approach facilitated a more nuanced understanding of soundscapes by integrating spatiotemporal dimensions with acoustic metrics. The combination of real-time sound data collection with advanced data processing offers a robust and reproducible model for future soundscape research in various environmental settings. Enriching the methodological approach through future collaboration with ecologists and biologists is the next desired research step.

Despite the study's contributions, some limitations should be acknowledged. First, the study's exclusion of ultrasound frequencies, such as those emitted by bats, may have resulted in an incomplete analysis of the region's acoustic diversity. Future research could address this gap by including ultrasonic sensors to capture a broader range of frequencies. Additionally, while the study provides a detailed analysis of specific soundscapes in Central Poland, its findings may not be generalizable to other regions with different ecological and environmental conditions. Expanding this research framework to other geographical areas would provide a more comprehensive understanding of soundscape dynamics across diverse landscapes. Lastly, while integrating geoinformatics and data engineering to enhance the study's data processing capabilities, there is still room for improvement regarding real-time sound source analysis. Future studies will explore deep learning techniques to predict soundscape changes based on environmental and anthropogenic factors or precisely classify sound sources, thus providing valuable landscape management and conservation tools.

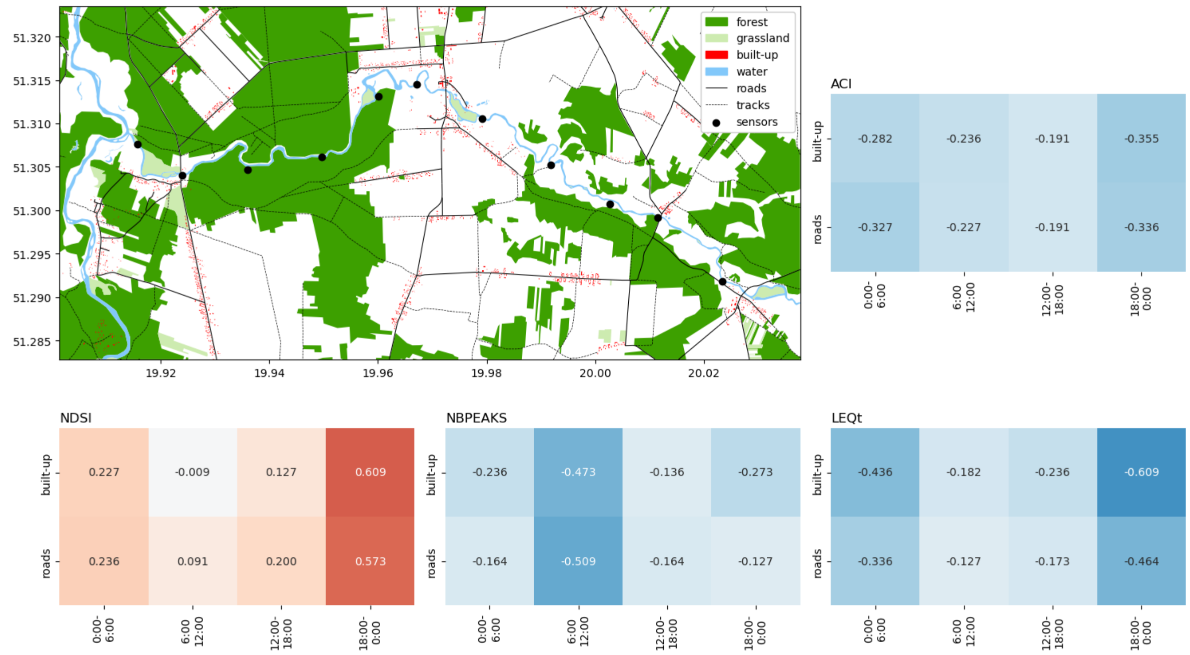

Fig. 10. Correlation matrices between analysed acoustic indices (mean value; temporal buckets) and distances between nearest buildings and roads (map data source: Raifer *et al.* (2023))

Conclusions

The research in the middle Pilica River basin provided valuable insights into spatial and temporal dynamics of soundscapes across three distinct research locations. By employing a comprehensive quantitative approach, this study contributes to understanding soundscapes in Central Poland, especially concerning human and natural influences on acoustic environments. The study demonstrated quantitatively that natural soundscapes exhibit higher acoustic complexity and biotic richness, especially in areas with minimal human interference. Areas showing higher acoustic diversity likely support more complex ecosystems. Conversely, areas with dominant anthropology, such as the Pilica and Cieszanowice locations, may experience disruptions in natural sound orders, potentially affecting wildlife communication and behaviour. These findings align with previous studies that emphasize the ecological role of soundscapes in maintaining ecosystem integrity. Furthermore, the study's findings have significant methodological implications concerning biodiversity conservation and noise pollution mitigation. The analytical procedure is relatively simple when combined with modern data engineering and data science approaches. The results confirm that soundscape indicators can serve as an important ecological indicator of habitat health.

Acknowledgements

I sincerely thank Stanisław Krysiak, Joanna Adamiak, Karolina Adamiak, and Jagoda Adamiak for their invaluable support throughout this research, particularly during fieldwork and data collection. I also want to express my gratitude to my colleagues and reviewers for their constructive feedback, which greatly enhanced this work.

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