Soundscape Mapping for Large-scale Urban Green Spaces: A Case Study of the Chengdu Outer Ring Ecological Zone

Dr Yiying Hao

Bureau Veritas UK, 2nd Floor, Atlantic House, Atlas Business Park, Wythenshawe, Manchester M22 5PR

Abstract

Soundscape quality is influenced not only by the acoustic environment but also by various physical environmental aspects, including the visual environment and their interactions. Soundscape mapping has been extensively studied to visualize and quantitatively represent soundscape quality. This tool is essential for predicting soundscape quality and optimizing urban planning/design, especially in areas impacted by intrusive noise. Given the significance of context in soundscape assessment, soundscape mapping is inherently case-based. This study introduces an approach to predict soundscape quality in large-scale urban green spaces (UGSs) in China, using the 187 km² Chengdu Outer Ring Ecological Zone as an example. The study explores the relationships between visual, aural, and functional attributes and their impact on soundscape quality. Data were collected at micro-scale measurement spots across five selected sites within the Ecological Zone through sound walks and questionnaire surveys, assessing participants' perceived soundscape satisfaction. The data were analyzed to develop a model predicting soundscape perceptions across the entire site. The soundscape qualities of the entire Ecological Zone were calculated and visualized using heat maps of soundscape quality scores generated from the model. This study identifies key environmental design features that influence soundscape quality in large-scale UGSs. The results provide a soundscape mapping technique applicable to planning and design practices in large-scale urban settings.

1. Introduction

Soundscape is a crucial indicator of environmental quality, particularly in urban green spaces (UGSs). Unlike the "acoustic environment," soundscape emphasizes the perceptual aspects of sounds and is defined as "the acoustic environment as perceived or experienced and/or understood by a person or people in context" [1]. The soundscape qualities of UGSs are closely related to human perception, often influenced by their interaction with visual perception rather than solely based on the physical environment. This subjective nature limits its practical application in providing effective planning and design guidelines for large-scale UGSs. This study aims to develop an approach to predict soundscape perceptions in large-scale UGSs through in-situ measurements, data analysis, regression model generation, and soundscape mapping, offering planning and design insights for enhancing perceptual quality in large-scale UGSs.

The perception of soundscape is multifaceted, requiring a systematic approach that considers multiple factors [2]. These factors are categorized into perceived affective quality and physical acoustic information. The perceived affective quality of soundscape was initially proposed as a two-dimensional model describing human perceptions of soundscape, including four bipolar factors: pleasantness, eventfulness, calmness, and excitement [3]. Aletta et al. [4] later proposed a three-dimensional model comprising pleasantness, eventfulness, and familiarity. Axelsson, Nilsson, and Berglund expanded the model with eight unidirectional indicators: calm, pleasant, exciting, eventful, chaotic, annoying, monotonous, and uneventful [3]. These indicators were subsequently incorporated into ISO 12913 [5] to standardize soundscape perception descriptors and guide soundscape evaluation. The perceived aural attributes of soundscapes are typically assessed using qualitative methods such as sound walks, questionnaires, semantic analysis, and interviews. Besides perceptual attributes, physical parameters related to the acoustic environment, such as noise annoyance, sound level, and the composition and significance of sound sources, also affect individual soundscape perception. Noise annoyance was measured by loudness, sharpness, fluctuation strength, and impulsiveness in early research [6]. Soundscape composition is normally used to objectively reflect the existence of different sound sources. It is another important parameter used in predicting people’s soundscape perceptions, and it is often measured together with the loudness or significance of sound sources [7]. The relationships between certain physical and psychoacoustic parameters (L_{Aeq}, L_{Ceq}, L_{A10}, and L_{A90}) and perceived soundscape composition parameters (perceived loudness of individual sound, perceived occurrences of individual sound, and soundscape diversity index) were investigated to develop a more effective way to design soundscapes in city parks [7].

In addition to aural aspects, visual environmental attributes can impact soundscape perception, including perceived naturalness, waterscape aesthetics, openness, layering and order, visibility of noise sources, crowding, and maintenance levels in various contexts (e.g., urban forests, parks, public spaces, university campuses, and neighborhoods). The interactions between visual and aural characteristics have been explored in studies, revealing that a quiet environment with low sound pressure levels does not necessarily lead to high satisfaction with soundscape perception. Visual information can supplement and enhance the meaning of the perceived sound [8, 9], and vice versa. Moreover, consistency between visual and aural attributes is crucial in shaping soundscape perceptions. When these aspects align, individuals are more likely to have favorable evaluations of environmental soundscapes [10]. Therefore, it is essential to consider both visual and aural attributes, as well as their interaction, in evaluating, modeling, and predicting individuals' soundscape perceptions. However, few studies have attempted to measure individual soundscape perceptions based on physical environmental attributes, even though the relationships between subjective human experiences and objective environmental indicators are key to delivering actionable design insights. Aletta, Kang, and Axelsson (2016) developed a conceptual framework for predictive soundscape models based on a literature review. Although this framework included physical and perceptive aural attributes, it did not account for visual indicators.

Thus, this study aims to establish a model that mathematically predicts soundscapes in large-scale UGSs based on visual, aural, and functional environmental characteristics. Using the Chengdu Outer Ring Ecological Park as a case study, this research calculates visual attributes, specifically landscape composition, using space syntax and the Quantum Geographic Information System (QGIS); aural attributes, specifically sound levels, are measured with professional acoustic equipment. Functional attributes, namely vitality, are documented through on-site observations and mapping. People's perceived soundscapes are collected via a questionnaire-based on-site survey conducted during sound walks. Environmental data are gathered at micro-scale measurement spots and used to develop a stochastic model. This model predicts perceived soundscapes across the site, which are visualized as a soundscape perception map to identify areas where planning and design improvements are needed. This model not only reveals the correlation between environmental characteristics and human-perceived soundscapes but also enables the prediction of perceived soundscapes in large-scale UGSs.

2. Methodology

2.1 Data collection

The Chengdu Outer Ring Ecological Zone (referred to as "the Zone") was selected as the research site, defined within 500 m buffers of the Chengdu Outer Ring Road. The Zone covers approximately 187.2 square kilometers and includes various land uses, such as green spaces, transportation, residences, commerce, and farmland. The southern part of the Zone, largely developed and well-received by the public, was chosen for this study. However, it faces significant noise issues, with traffic sounds from surrounding highways, railways, and Tianfu Airport severely affecting soundscape experiences. Measurement spots were selected to evaluate soundscape satisfaction, with 25 spots identified within the southern part of the site. The selection criteria included:

1. Spots should represent typical visual and acoustic features of the site and be distinct from each other.

2. Each spot should have an open view and enough space for participants to take free experiential walks without interfering with acoustic recordings.

3. The distance between measurement spots should be over 300 m to allow sufficient time for subjects to clear their heads before starting a new evaluation.

Each measurement spot was limited to a moderate size (50 m × 50 m to 100 m × 100 m) to ensure participants could fully experience the environment without losing the sense of space [11].

Visual landscape composition, sound pressure level, and functional vitality were determined as environmental indicators to explore their impact on human soundscape perceptions. QGIS and space syntax were used to calculate the landscape composition perceived at the site. Buildings and woodlands were also considered visual obstacles, with their boundaries identified using QGIS Maptiler and Google satellite images to determine visually perceived areas. These areas were then analyzed in Depthmap over a 50 m × 50 m grid, calculating the areas of buildings (B), grassland (G), waterscape (Wa), woodland (Wo), and pavement (P) within each grid. The visual landscape composition was first calculated for the entire site, with each measurement spot's composition derived from the overall results based on its location and range.

The widely used equivalent continuous A-weighted sound pressure level (LAeq) was selected to describe environmental sound levels, as it has a significant effect on soundscape perceptions. Given the workload of measuring the entire site's sound pressure level instrumentally, traffic noise was estimated using a noise prediction model. Traffic volume data for the 30 urban roads crossing the site and the penetration state of road pavement materials were obtained from the Chengdu Communication Investment Company. Additionally, the proportion of heavy vehicles and active time period (18 h/day) were estimated through on-site investigation.

Functional vitality (V), adapted from urban vitality, refers to observable people and activities in a specific space across different time schedules, representing the number and duration of various activities. This study redefined functional vitality as the diversity and intensity of activities within different site areas. The indicator was measured at the spot level through on-site observations and mapping by four groups of trained surveyors. During the site's open hours, surveyors ranked each spot's diversity (total number of activity types) and intensity (total number of people) at two-hour intervals from 8:00 to 17:00 (10:00, 12:00, 14:00, and 16:00) using a five-level Likert scale (1–5, with 1 representing "not diverse/intensified at all" and 5 representing "strongly diverse/intensified"). The mean value of the four surveyors' ratings was calculated to determine the functional vitality for each measurement spot. Given that spatial vitality can be influenced by environmental functions and landscape characteristics, the functional vitality obtained for each measurement spot was correlated with its land use and visual landscape composition. The same functional vitality value was then assigned to grids with similar land uses and visual landscape compositions using QGIS to ascertain the entire site's functional vitality.

People's satisfaction with their perceived soundscape (S) as used to describe the site's overall soundscape perception and was measured through a sound walk and questionnaire-based survey conducted at each measurement spot. The survey began with collecting subjects' background information, including gender and age, to assess potential perceptual differences, followed by a question investigating satisfaction with the perceived soundscape quality at each measurement spot using a five-level Likert scale (1–5, with 1 representing "strongly unsatisfied" and 5 representing "strongly satisfied").

At the spot level, metrics such as human-perceived soundscape satisfaction, sound pressure level, and functional vitality were collected. In July 2021, 20 local university students aged 20 to 30 years, with normal hearing and vision abilities, were recruited for the sound walk and questionnaire survey. Before the sound walk and survey, all participants underwent training and provided informed consent. The routes taken by the four groups to traverse the 25 measurement spots were predetermined, with subjects instructed to individually wander within each measurement spot for five minutes to experience the environment. Afterward, they completed the online questionnaire via a provided link. The subjects repeated this process at each of the 25 measurement spots, yielding 500 responses. The final number of valid responses was 393. Simultaneously, a group of researchers recorded the environmental sound level at each spot using a multi-channel signal analyzer positioned at the central point of each spot.

2.2 Data analysis

Before model construction, the turning point in the sound level was identified. Correlational analysis was employed to identify relevant indicators of soundscape satisfaction. These indicators were then used to formulate regression models illustrating the relationships between soundscape satisfaction and its influencing visual and aural attributes.

The internal consistency of soundscape satisfaction responses was examined using Cronbach's alpha in SPSS V26.0, with results indicating reliability consistently greater than 0.6, demonstrating data effectiveness. An independent samples t-test was conducted based on gender to investigate perceptual differences. The Levene test for variance equality showed values greater than 0.05, indicating homogeneity of variance. Additionally, t-test results for the mean equation were all greater than 0.05, suggesting gender differences did not impact perceived soundscapes. The average satisfaction with soundscape perception was rated as 3.46.

At the site level, visual landscape composition, sound pressure level, and functional vitality data were obtained and calculated. These data were then incorporated into the stochastic model to predict overall soundscape satisfaction for the site, with the results visualized using QGIS to develop planning and design implications.

3. Results

3.1 Analysis of Visual Landscape Composition

At the spot level, grassland (Mean = 55.45%) was the dominant component across the 25 measurement spots, followed by waterscape (Mean = 14.70%) and woodland (Mean = 11.70%). Pavement (Mean = 9.63%) and buildings (Mean = 1.60%) were the least prevalent components. Figure 1 shows distribution of major visual landscape elements within the site.

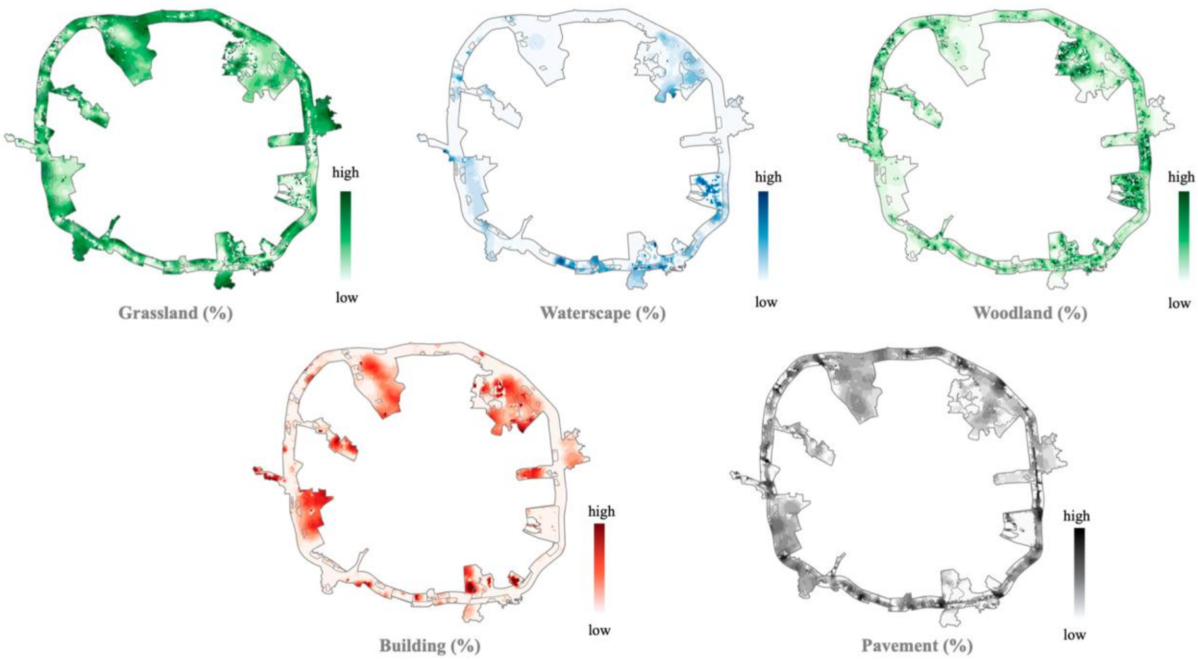

Figure 1. Distribution of major visual landscape elements within the site.

3.2 Analysis of Sound Pressure Levels

Previous studies indicate a certain range in the relationship between soundscape perception and sound level; exceeding this range may alter the relationship. Thus, sound pressure level was an indicator and mediator in this study. To ensure prediction model accuracy, the site's sound level ranges were explored.

Twenty-three spots had decibel values exceeding the 70.00 dBA limit, with sound levels at two spots surpassing 90.00 dBA. Only three spots had sound levels slightly below the 70 dBA limit. The modelling and visualization results suggested sound pressure levels above 80.00 dBA were extremely high within a 150 m range on both sides of the ring road. On the ring road itself, sound pressure levels exceeded 95.00 dBA

3.3 Analysis of Functional Vitality

Functional vitality was relatively low at the spot level, with an average of 1.91 (SD = 1.14). Most spots were rated below 3.00, except for spot 12 (4.00/5.00). The road network was manually rated 5.00 by the researcher to differentiate it from other spaces accessible to people. Functional vitality was higher in most green spaces and commercial areas, while lower levels were observed around residential areas. (see Figure 2).

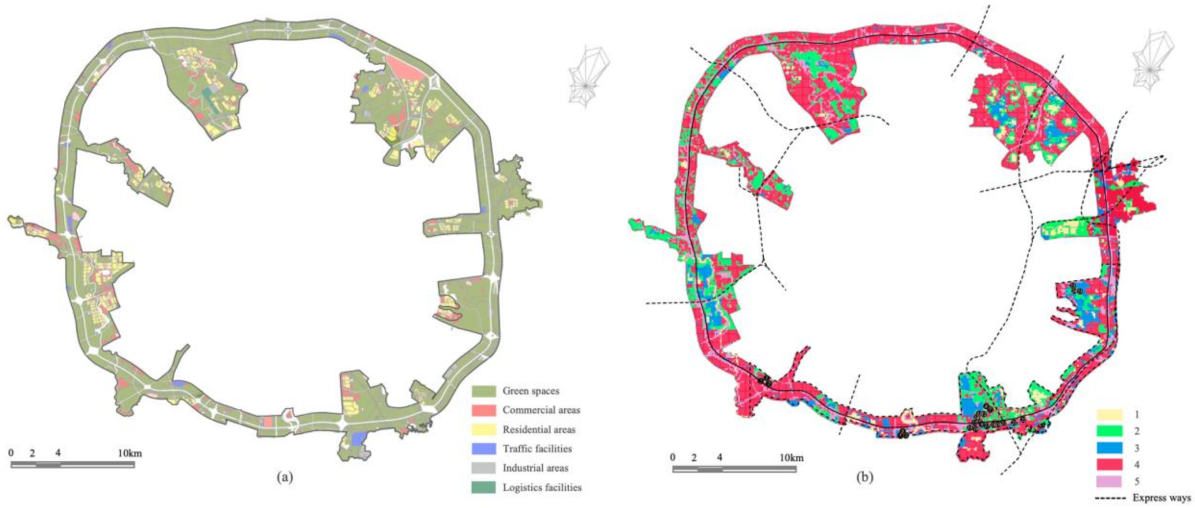

Figure 2. Land uses (**a**) and functional vitality (**b**) of the site.

3.4 Relationship between Soundscape Satisfaction and the environmental indicators

It was quite evident that a negative relationship with Soundscape Satisfaction could be observed when the sound level was lower than 75 dBA. For levels above 75 dBA, there was first a slight increase between 75 and 84 dBA, and then stability was reached when the sound level exceeded 84 dBA (see Figure 3).

Correlation analysis confirmed that at sound levels below 75 dBA, there was a significant negative correlation between sound pressure level and soundscape satisfaction ($R = -0.600$, $p < 0.01$). However, when the sound level exceeded 75 dBA, satisfaction became less correlated with sound levels ($R = 0.120$, $p = 0.062 > 0.05$). This indicated that when the sound level exceeded 75 dBA in this study, people's satisfaction with the surrounding soundscape became less relevant with sound levels. Therefore, under and above 75 dBA were identified as two sound level ranges to carry out the following model construction.

Pearson correlation analysis identified relevant visual, aural, and functional indicators for environments with sound levels above and below 75 dBA. For sound levels below 75 dBA, satisfaction was influenced by the visual proportions of waterscape, grassland, buildings, and pavement, as well as sound pressure level and functional vitality. For sound levels above 75 dBA, fewer indicators were influential, with grassland positively related and woodland, pavement, and functional vitality negatively affecting satisfaction. Only indicators with significant relationships were included in the regression analysis.

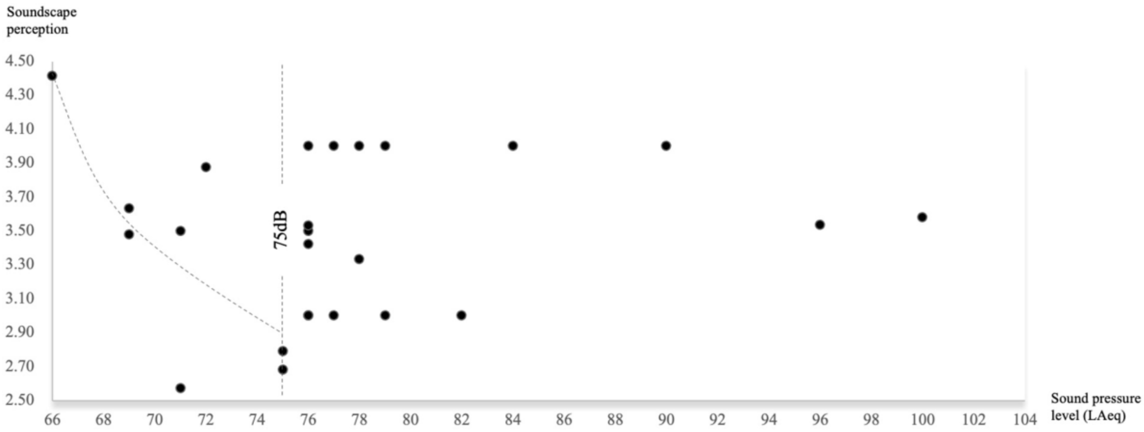

Figure 3. Scatttter plot showing the relationship between overall soundscape satisfaction and sound pressure level.

3.5 Relationship between Soundscape Satisfaction and the environmental parameters

Regression analysis was conducted separately for groups with sound levels above and below 75 dBA, resulting in two linear regression models. In the group with sound levels under 75 dBA, five environmental indicators (grassland, buildings, pavement, sound pressure level, and functional vitality) were significantly related to soundscape satisfaction ($p < 0.01$), with a model R^2 of 0.572. For sound levels above 75 dBA, woodland, grassland, pavement, and functional vitality were significant indicators ($p < 0.01$), with a model R^2 of 0.312. The model with an R^2 of 0.572 was found when sound levels are below 75 dBA:

$$S = 6.899 + 0.013 \times G - 0.079 \times B - 0.089 \times P - 0.059 \times LAeq + 0.368 \times V \qquad (1)$$

The model ($R^2 = 0.312$) when sound levels are above 75 dBA is shown as below:

$$S = 3.883 - 0.002 \times W_o + 0.003 \times G - 0.007 \times P - 0.253 \times V \qquad (2)$$

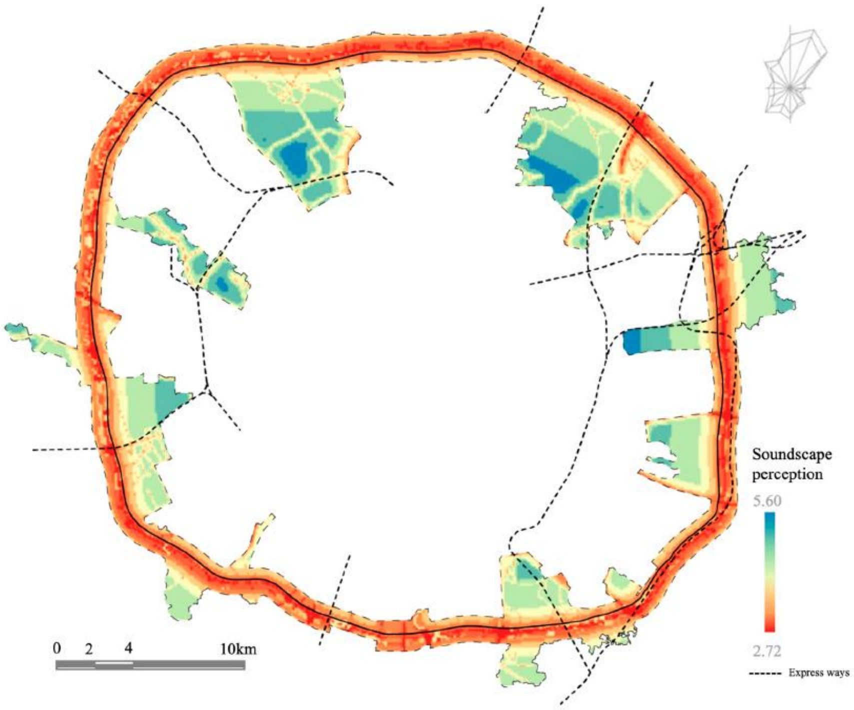

Figure 4. Soundscape perception map for the Chengdu Outer Ring Ecological Zone.

The models were employed to visually represent soundscape satisfaction across the entire site (Figure 4). The lowest satisfaction levels appeared alongside the ring road, where both sound levels and vitality were extremely high. Spaces with higher soundscape satisfaction also had high percentages of grassland, woodland, waterscape, and buildings.

4. Discussion and Conclusions

This study innovatively predicted human soundscape perception in large-scale UGSs through three major steps: (1) collecting visual, aural, and functional characteristics and soundscape satisfaction at selected measurement spots; (2) building a stochastic model describing relationships between human perceptions and environmental attributes; and (3) using site-level environmental data to predict and visualize soundscape satisfaction. This approach saves time and effort in conducting sound walks and on-site evaluations. The model, which predicts human satisfaction with soundscapes, relies on quantifiable visual, aural, and functional attributes. With advancements in big data and modeling techniques, this environmental information is increasingly accessible, improving the accuracy and feasibility of predicting perceptions in large-scale urban spaces.

Natural elements in the visual landscape have long been recognized for their positive impact on soundscape satisfaction, consistent with the distribution of grassland, waterscape, and woodland at the site. Spaces with high satisfaction also featured a significant presence of buildings, likely because high-rise buildings can obstruct views of noise sources. Moreover, controlled functional vitality should be encouraged to maintain satisfaction, modifiable through land use and visual landscape characteristics.

The findings of this study, alongside future research, are expected to introduce a more human-centered perspective into soundscape planning and design, broadening the scope of human perceptual studies in large-scale urban spaces.

5. References

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