Research Article

Chia-Jung Lin, Jia-Hong Tang, Chih-Chung Fan and Ta-Chien Chan*

Measuring and managing urban quietness: refining the quietness suitability index (QSI) model for Asia's densely populated cities

https://doi.org/10.1515/noise-2025-0025
Received August 8, 2025; accepted December 24, 2025;
published online February 2, 2026

Abstract: Noise pollution is a growing threat to public health in dense cities yet widely used quietness indices were calibrated in European contexts and transfer poorly to Asian megacities. This study proposed the Adaptive Quietness Suitability Index (AQSI), a refined, validated framework that enhances sensitivity, accuracy, and transferability in mixed-use urban environments. The AQSI advances three elements: (i) dynamic impact-zone delineation via physics-based sound propagation rather than fixed buffers, (ii) alignment with locally regulated noise limits and control zones, and (iii) explicit temporal stratification (daytime, evening, nighttime, all-day) to capture diurnal variability. We validated the AQSI using monitoring data from 1997 to 2024 in New Taipei City, Taiwan, and compared it to the original QSI through regression and spatial analyses. The AQSI showed stronger agreement with measured sound levels than the original QSI (Pearson's $r = -0.238$ vs. -0.202), representing a 39 % improvement in explained variance ($R^2 = 0.057$ vs. 0.041). It eliminated extreme-value saturation (0 or 1 in 86.2 % of cells) and reduced it to 0 %, yielding continuous gradients that better resolved intermediate environments. Nighttime emerged as the critical period, with the steepest negative coefficient (-0.0142, $p < 0.001$) and the highest adjusted R^2 (0.16), highlighting the need for nocturnal noise management. By integrating operational mapping with soundscape-aware considerations at a 50 m resolution, the AQSI provides a transparent, context-sensitive tool for urban planning, regulatory compliance, and targeted mitigation in diverse metropolitan settings.

Keywords: quietness suitability index (QSI); environmental noise; noise control zones; sound propagation modeling; sustainable development

1 Introduction

Acoustic comfort is a key determinant of urban quality of life across public spaces, buildings, and transport settings. Beyond energy-based indicators, evidence shows that perception matters: background levels, temporal dynamics, spectral content, source dominance, shape comfort, and natural sounds can enhance relaxation, even at comparatively high levels. Accordingly, "quietness" is more than low decibels; it includes perceptual, cultural, and restorative dimensions such as vibrancy, appropriateness, and contextual fit [1]. These insights support assessment frameworks that pair exposure metrics with context-sensitive soundscape characteristics [2].

Simultaneously, noise management is advancing from mapping to action planning and mitigation, enabled by smart-city monitoring, real-time analytics, AI-based source identification, and new levers such as electric vehicles and low-noise pavements [3]. While rail, airports, industry, and ports remain relevant, road traffic dominates many urban soundscapes and requires continuous monitoring and prevention [4]. Corridor acoustics depend on flow composition, surface texture, and aging, underscoring the need for spatially resolved, context-aware indicators to guide interventions [5]. Health evidence across sources links noise to annoyance, sleep disruption, and cardiometabolic risks, with complaints revealing socio-spatial disparities in exposure, while complaint data reveal socio-spatial disparities and source predominance in practice [6].

Within this evolving landscape, the European Environment Agency's (EEA) Quietness Suitability Index (QSI) provided an early interpretable spatial indicator that combined

***Corresponding author: Ta-Chien Chan**, Research Center for Humanities and Social Sciences, Academia Sinica, 128 Academia Road, Section 2, Nankang 115, Taipei, Taiwan, E-mail: tachien@sinica.edu.tw. https://orcid.org/0000-0002-1685-783X
Chia-Jung Lin, Department of Land Economics, National Chengchi University, Taipei 116, Taiwan. https://orcid.org/0009-0003-3987-1276
Jia-Hong Tang, Research Center for Humanities and Social Sciences, Academia Sinica, Taipei 115, Taiwan; and Department of Statistics and Data Science, Tamkang University, New Taipei City 251301, Taiwan
Chih-Chung Fan, Research Center for Humanities and Social Sciences, Academia Sinica, Taipei 115, Taiwan

distances to major noise sources with land-cover-based naturalness [7, 8]. Initially developed to identify and protect quiet areas in an open country, the QSI emphasized areas that are relatively undisturbed by environmental noise, such as those far from traffic, industry, or recreational activities. Its strengths include its transparency, ease of interpretation, and multiscale applicability. However, the original QSI methodology primarily targeted rural contexts and exhibited limitations when applied to semi-rural and urban environments. Recognizing these constraints, the EEA introduced complementary frameworks to address the specific challenges of managing quiet areas within urban agglomerations. This distinction highlights the need for context-specific tools for both urban and rural settings.

Several limitations constrain performance in dense, mixed-use urban contexts. Fixed-threshold buffers can fail to capture environmental and temporal variability in propagation and tolerance across land uses. Multiplicative combination rules may underestimate cumulative impacts when any single source yields zero suitability. Reclassifying urban land covers into low "naturalness" can oversimplify heterogeneous fabrics, obscuring quieter urban pockets. These issues are particularly salient in Asian cities, where higher densities and mixed land uses complicate the transferability of fixed-threshold, land-cover-only approaches calibrated primarily for European conditions [9].

To address these challenges, we propose the Adaptive Quietness Suitability Index (AQSI), a refined, transferable framework that preserves the interpretability of the QSI while introducing three advances: (i) dynamic impact-zone delineation via sound-propagation and attenuation modeling rather than static distance thresholds; (ii) integration of locally regulated noise limits and noise-control zones to respect context-specific tolerance and land-use sensitivity; and (iii) explicit temporal stratification into daytime, evening, nighttime, and all-day evaluations to reflect diurnal variability. We validated the AQSI against observed monitoring data to assess accuracy and practical utility. Although the approach is demonstrated using a representative high-density Asian city, the methodology is designed to be adaptable and replicable in other urban settings with similar characteristics. By bridging soundscape-aware considerations with operational mapping needs, the AQSI provides a robust, validated, and context-sensitive tool for assessing and managing urban quietness, supporting targeted actions that advance sustainable development and urban well-being.

Finally, to orient the reader, Section 2 reviews the original QSI methodology and details the key refinements introduced in the AQSI. Section 3 describes the AQSI's development and reports validation results based on empirical data. Section 4 examines transferability, outlines limitations, and considers implications for urban-noise policy. Section 5 concludes with actionable recommendations for extending the AQSI to diverse urban contexts and identifies priorities for future research.

2 Materials and methods

2.1 Study area

The study area was New Taipei City, Taiwan, as shown in Figure 1. The city had a population of over 4 million as of June 2024 [10]. Notably, five districts within the city had population densities exceeding 20,000 people per square kilometer (Figure 1), exemplifying characteristics of densely populated urban areas commonly found across Asia. The city also featured diverse traffic types and mixed land use (Figure 1), representing typical complexities of Asian metropolitan regions. These characteristics made New Taipei City a suitable testbed for validating the transferability and applicability of the AQSI in high-density, mixed-use urban contexts across Asia.

2.2 Modeling quietness

2.2.1 Original QSI methodology

The European Environment Agency (EEA) proposed the Quietness Suitability Index (QSI) in 2014, and refined it in 2016 as Europe's first spatial assessment of environmental noise to identify and protect noise-free areas [7, 8]. The index ranges from 0 (noisiest) to 1 (quietest) and is applied at the national and local scales. The QSI integrates traffic, urban, and industrial noises with land cover data.

The QSI operates on a 100 m × 100 m raster in five steps. It compiles Environmental Noise Directive (END) sources – major roads, railways, airports, urban agglomerations, and industries – and 2006 CORINE Land Cover data [11]. It derives source-specific thresholds from noise contour maps, typically the 55 dB contour. It applies a fuzzy distance transform: QSI = 1 beyond the maximum threshold and QSI = 0 within the minimum threshold, with a linear interpolation between. It reclassifies CORINE using the Hemeroby scale (levels 1–7) and rescales to 0–1 for naturalness [12–14]. It multiplies the combined distance layers with the naturalness layer to produce the QSI.

The calibrations used were European noise maps. For major roads, the mean maximum and mean minimum distances were 1,119 m and 257 m, respectively; for railways, they were 662 m and 151 m. For airports, the 55 dB contour

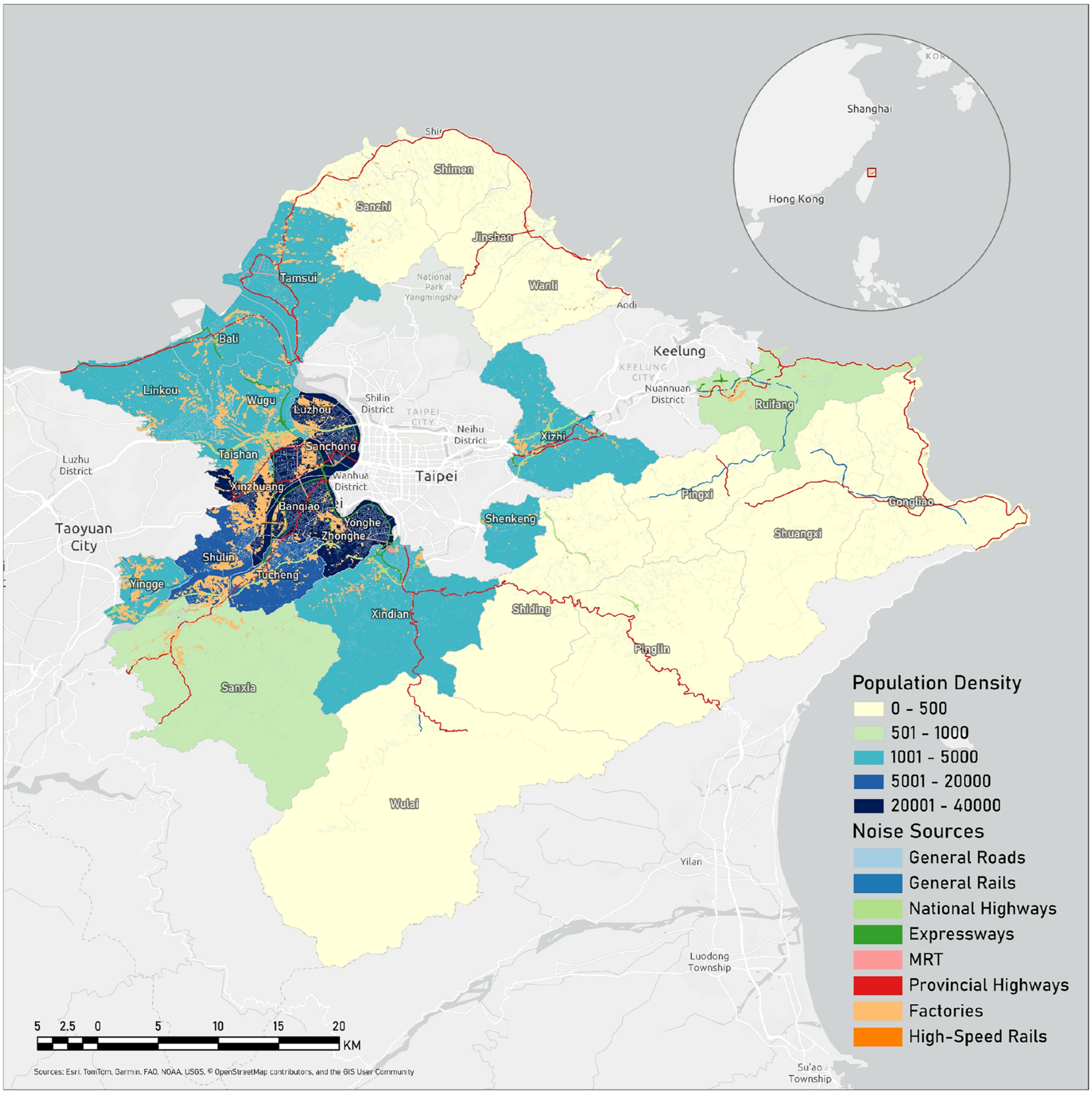

Figure 1: Population density map of new Taipei city as of June 2024.

was used, where available; otherwise, buffers of 1,500 m for major and 900 m for other airports [15]. For industrial sites, distances <500 m received QSI = 0 and >1,100 m QSI = 1 [15]. For urban agglomerations (>50,000 inhabitants), distances <1,000 m map to QSI = 0 and >1,500 m to QSI = 1.

The model multiplies five source-specific distance layers to form the potential quietness, and any zero sets the composite to zero. This composite was then multiplied with the naturalness to yield the final QSI.

The QSI performs well in Europe but poorly in dense Asian cities. A 100 m grid can miss fine-scale urban noise. Data may omit sources beyond the major infrastructure. European thresholds may not match the local conditions. The naturalness proxy can oversimplify mixed-use urban land.

2.2.2 AQSI: methodological refinements

To mitigate these limitations and improve applicability in dense, mixed-use urban areas, this study introduced the Adaptive Quietness Suitability Index (AQSI) with several key refinements. Figure 2 provided a flowchart of the methodology, showing how the calculation was partitioned into distinct stages.

First, the AQSI enhanced spatial resolution. The resolution was increased from 100 m to 50 m and, rather than raster-based calculations, a 50 m × 50 m vector grid was employed. Each cell's value was assigned based on the modeled noise level at its centroid, enabling a more detailed representation of spatial variation.

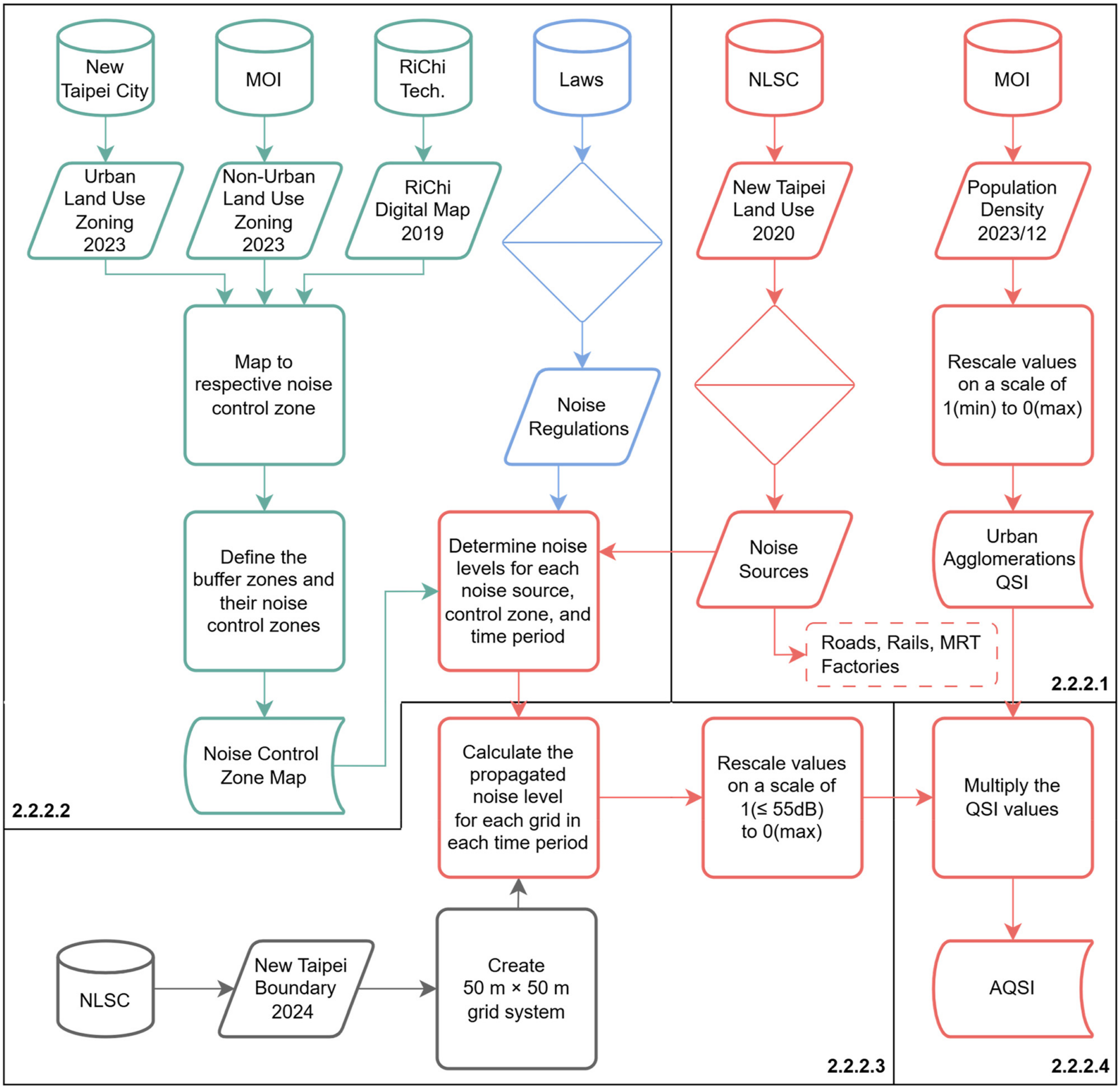

Figure 2: AQSI methodology flowchart. Abbreviations represent: MOI (Ministry of the Interior), NLSC (national land surveying and mapping center), RiChi Tech. (RiChi technology), laws (laws & regulations database of the Republic of China [Taiwan]).

Second, the AQSI broadened noise-source coverage beyond the original methodology. Whereas the QSI primarily considered major roads, railways, and airports, the AQSI included all road classes, rail infrastructure, airports, urban agglomerations (derived from population density), and industrial areas, supporting a more comprehensive assessment of urban noise.

Third, the framework integrated Taiwan's regulatory context to better parameterize source levels. Relevant laws and standards – including the Noise Control Act (Laws & Regulations Database of the Republic of China (Taiwan), [16]), the Environmental Sound Standard (Laws & Regulations Database of the Republic of China (Taiwan), [17]), the Amendment to Noise Control Standards (Laws & Regulations Database of the Republic of China (Taiwan), [18]), the Noise Control Standards for Land Transportation Systems (Laws & Regulations Database of the Republic of China (Taiwan), [19]), and the Regulations for Aircraft Noise Prevention Around Airports (Laws & Regulations Database of the Republic of China (Taiwan), [20]) – were used to assign initial source levels by noise-control zone and time period (daytime, evening, nighttime).

Fourth, the AQSI improved sound-propagation modeling. Source-specific attenuation formulas were applied to dynamically estimate impacts across space, distinguishing line sources (roads, railways) from point sources (airports, factories). Setting the reference distance (R_1) to 1 m minimized zero-valued cells, yielded smoother spatial gradients, and produced more realistic estimates.

Finally, the AQSI simplified land-use treatment. Given the complexity of mixed land use in dense Asian cities and the explicit inclusion of major noise-generating land uses (urban agglomerations and industries) in the modeling, the AQSI did not reintroduce the land-cover "naturalness" scale. Consistent with the original multiplicative structure, the final index was computed as the product of component scores from roads, rails, airports, urban agglomerations, and industries.

2.2.2.1 Noise sources

This study considered all types of roads, railways, airports, urban agglomerations, and industrial areas. Traffic sources and industrial areas were identified from the 2020 land-use investigation data in New Taipei City provided by the National Land Surveying and Mapping Center, Ministry of the Interior, Taiwan, and delivered as polygon shapefiles [21]. Urban agglomerations were delineated using population density data from basic statistical areas (December 2023) provided by the Ministry of the Interior Socioeconomic Data Service Platform, Taiwan [22]. Departing from the original QSI methodology, which used Urban Morphological Zones (UMZ) with a threshold of 50,000 inhabitants [8], we adopt a continuous population density approach to capture fine-scale variation in dense Asian cities.

Traffic sources and industrial areas were evaluated using source-specific procedures described below. For urban agglomerations, the AQSI values were obtained by rescaling the population density to [0, 1], with 0 being assigned to the maximum observed density and 1 to the minimum.

2.2.2.2 Noise control zones and standards

The AQSI derived the sound level for each noise source during specific time periods from the relevant noise-control zones and their associated standards; identifying these zones and regulations was therefore a prerequisite.

In Taiwan, counties designated noise-control zones. The Environmental Protection Department of the New Taipei City Government provided criteria for zoning [23]. Four levels were defined: Level 1 denoted the quietest areas (for example, national parks); Level 2 covered residential areas and schools; Level 4 covered industrial and high-traffic areas; and Level 3 encompassed all other areas. The guidelines also prescribed transitional buffers between levels. When adjacent levels differed by two (for example, Levels 1 and 3), each boundary receded 15 m to create an intermediate zone of the middle level (Level 2). Likewise, at Level 1–Level 4 boundaries, each boundary retreated 15 m, yielding Level 2 and Level 3, respectively. Rather than relying solely on land use, zones were determined using land-use zoning data from both urban and non-urban planned districts.

Accordingly, we obtained urban zoning data from the Urban Development Department of the New Taipei City Government [24] and non-urban zoning data from the National Land Management Agency, Ministry of the Interior [25]. Because the zoning datasets lacked road features, we integrated the 2019 RiChi Digital Map road network [26].

Given the heterogeneity and unstructured nature of the zoning-attribute texts, we applied natural language processing (NLP) with CkipTagger [27] from Academia Sinica's Chinese Knowledge and Information Processing (CKIP) group to segment and extract keywords, enabling systematic mapping to zone categories. We then implemented the official buffering rules to assign transitional levels, producing a noise-control zone map for New Taipei City.

With sources and zones identified, maximum allowable sound levels by periods were assigned according to the applicable regulations (Table 1). Airport zones and limits followed the Regulations for Aircraft Noise Prevention Around Airports (Laws & Regulations Database of the Republic of China (Taiwan), 2009). Within New Taipei City, Level 1 and Level 2 aircraft noise-control zones were identified, with maximum noise levels of 65 and 75 dB, respectively, for all day periods.

Because the regulations specified period-specific limits, the all-day AQSI used the day–evening–night noise level, L_{den}, the 2002 European metric that applied penalties for evening and night. L_{den} was computed as follows [28]:

$$L_{\text{den}} = 10\log_{10}\left(\frac{1}{24}\left(T_{\text{day}} \times 10^{\frac{L_{\text{day}}}{10}} + T_{\text{evening}} \times 10^{\frac{L_{\text{evening}}+5}{10}} + T_{\text{night}} \times 10^{\frac{L_{\text{night}}+10}{10}}\right)\right) \quad (1)$$

Day-evening-night noise levelwhere T denoted the duration of each period and L represented the corresponding sound level.

Under the Amendment to Noise Control Standards (Laws & Regulations Database of the Republic of China (Taiwan), [18]), daytime was defined as 7:00 AM to 7:00 PM.

Table 1: Noise control standards and sound levels (dB) by zone and source (daytime/evening/nighttime).

Control zone (source type)	General roads[b] (line)	Expressways[c] (line)	Provincial highways[b] (line)	National highways[c] (line)
1	71/69/63	74/70/67	74/70/67	74/70/67
2	71/69/63	74/70/67	74/70/67	74/70/67
3	74/73/69	76/75/72	76/75/72	76/75/73
4	74/73/69	76/75/72	76/75/72	76/75/73

Control zone (source type)	General rails[c] (line)	High-speed rails[c] (line)	MRT[c] (line)	Factories[a] (point)
1	73/73/70	70/65/60	70/65/60	50/45/40
2	73/73/70	70/65/60	70/65/60	57/52/47
3	75/75/70	75/70/65	75/70/65	67/57/52
4	75/75/70	75/70/65	75/70/65	80/70/65

[a]Amendment to noise control standards. [b]Environmental sound standard. [c]Noise control standards for land transportation system.

For Level 1 and Level 2 noise-control zones, evening time was 7:00 PM to 10:00 PM and night was 10:00 PM to 7:00 AM the next morning; for Level 3 and Level 4, evening was 7:00 PM to 11:00 PM and night was 11:00 PM to 7:00 AM the next morning.

2.2.2.3 Impact area identification

For each source and time period, we modeled propagation using sound attenuation formulas [29], replacing the original QSI's empirically derived threshold distances from the noise contour maps [8]. This physics-based approach better represents the propagation across heterogeneous urban settings. Because propagation differs by source geometry, we distinguished line sources (roads and railways) and point sources (airports and factories); airports that were not otherwise categorized were treated as point sources. The attenuation equations are as follows:

$$L_{\text{line}} = L_{\text{line}}(R_1) - 10\log_{10}\frac{R_2}{R_1};\ L_{\text{point}} = L_{\text{point}}(R_1) - 20\log_{10}\frac{R_2}{R_1} \quad (2)$$

Sound attenuation formulas where L is the source-type level, R_1 is the distance to a location with known level, and R_2 is the distance from the source to the centroid of each grid cell. Consistent with the Amendments to Noise Control Standards (Laws & Regulations Database of the Republic of China (Taiwan), [18]), Noise Control Standards for Land Transportation System (Laws & Regulations Database of the Republic of China (Taiwan), [19]), and Environmental Sound Standard (Laws & Regulations Database of the Republic of China (Taiwan), [17]), we set R_1 = 1 m. If R_2 < 1 m, we replaced it with 1 m to avoid unrealistically high levels.

For each grid centroid, we computed the minimum distance to each source, retrieved the corresponding control zone, and assigned a period-specific source noise level. Subsequently, we computed the propagation levels using attenuation. Following the original QSI convention that 55 dB L_{den} marks quiet conditions [8], propagated levels below 55 dB are floored at 55 dB, yielding AQSI = 1 for those cells. After computing the noise levels for all sources, the values were min–max rescaled to [0, 1] to obtain the per-source AQSI layers.

2.2.2.4 Integration of the AQSI values

Given mixed land use and the oversimplification inherent in the original "naturalness" layer based on the Hemeroby scale applied to CORINE Land Cover [8], and because major noise-generating land uses were explicitly modeled, the AQSI did not re-integrate land-cover naturalness. This was a substantive departure from the original QSI, which multiplied the composite distance layer by the naturalness layer.

Instead, the AQSI aggregated physics-based source layers derived with R_1 = 1 m. In contrast, the original QSI used fixed thresholds of 257–1,119 m for roads, 151–662 m for railways, and up to 1,500 m for airports [8]. The small reference distance prevented widespread zeros, avoided overly linearized contours, and produced smooth spatial gradients while retaining contributions from all sources. Accounting for distinct time periods yielded separate AQSI maps for daytime, evening, nighttime, and L_{den}.

By incorporating a fuller set of sources and periods, increasing spatial resolution to 50 m (vs. the original 100 m), and employing realistic attenuation, the AQSI provided a more robust and policy-relevant basis for assessing and mitigating urban noise.

2.3 Quantifying the relationship between QSI and noise measurement

This study validated the AQSI using historical noise-monitoring records. The Environmental Protection Department of the New Taipei City Government provided measurements from 14 manual traffic-noise stations, 14 manual environmental-noise stations, and five automatic traffic-noise stations, spanning 1997 through July 2024. Station locations were supplied by the Ministry of the Environment. Unlike the original QSI, which was developed primarily through spatial analysis without direct validation against observed sound levels, this study incorporated empirical measurements to evaluate the AQSI's predictive accuracy.

Monitoring sites were spatially joined to retrieve the corresponding AQSI values. We then compared temporal trends in the equivalent continuous sound level (L_{eq}) at each station by time period and season with the calculated AQSI values. L_{eq} summarized environmental noise as a single noise level over a specified duration [30].

To quantify the association, we fit time-series regression models relating the AQSI to monitored L_{eq}, including year and season as covariates. Consistent, directionally plausible relationships between the AQSI and L_{eq} supported the validity of the AQSI as an indicator of quietness and provided empirical evidence of its improved performance in dense, mixed-use urban environments.

3 Results

3.1 AQSI mapping results

Figure 3 displayed spatial and temporal patterns of quietness across New Taipei City at 50 m resolution, revealing finer gradients than the original QSI. The higher-resolution, physics-based attenuation modeling produced smoothly varying surfaces that captured intra-neighborhood transitions otherwise masked at coarser scales.

3.1.1 Spatial distribution patterns

High AQSI values (>0.7) concentrated in mountainous terrain, large parks, and low-density residential areas distant from major transport corridors, while low values (<0.3) clustered along national and provincial highways, arterial streets, and dense commercial districts. The 50 m grid resolved short-range gradients, delineating sharp transitions from quieter residential interiors to noisier street frontages.

3.1.2 Temporal variations

The AQSI increased from day to night in line with diurnal activity cycles, with mean values rising from 0.8658 (daytime) to 0.8788 (evening) and 0.9202 (nighttime). Nighttime maps showed the broadest extent of high-AQSI areas, particularly within residential zones, whereas 24-h commercial centers and multimodal hubs remained persistently low across periods. The all-day surface applied the L_{den} weighting, emphasizing evening and nighttime sensitivity.

3.1.3 Distribution characteristics

The AQSI yielded a continuous distribution of values, avoiding the bimodality of the original QSI that produced heavy clustering at 0 and 1. The share of extreme cells fell from 86.2 % to 0 %, improving interpretability at boundaries between quiet and noisy areas and enabling more granular comparisons within mixed-use settings.

3.2 Validation of the AQSI against measured noise levels

3.2.1 Correlation analysis

Figure 4 showed that the AQSI was negatively associated with measured sound levels across all periods, with the steepest slope at night. The continuous spread of AQSI values strengthened the monotonic relationship, reducing saturation effects that limited sensitivity in the original QSI.

3.2.2 Regression models

Multiple linear regressions using log(QSI + 1) as the outcome and including year and measured noise level as predictors confirmed that noise was a significant negative covariate in all periods ($p < 0.001$) (Table 2). Seasonal indicators were excluded due to non-significance (F-tests $p > 0.24$) and worse information criteria. Coefficients ranged from −0.0075 (all-day) to −0.0142 (nighttime), indicating the strongest decrement in quietness under nighttime noise. The year term suggested a modest daytime increase in the AQSI and small but significant declines in

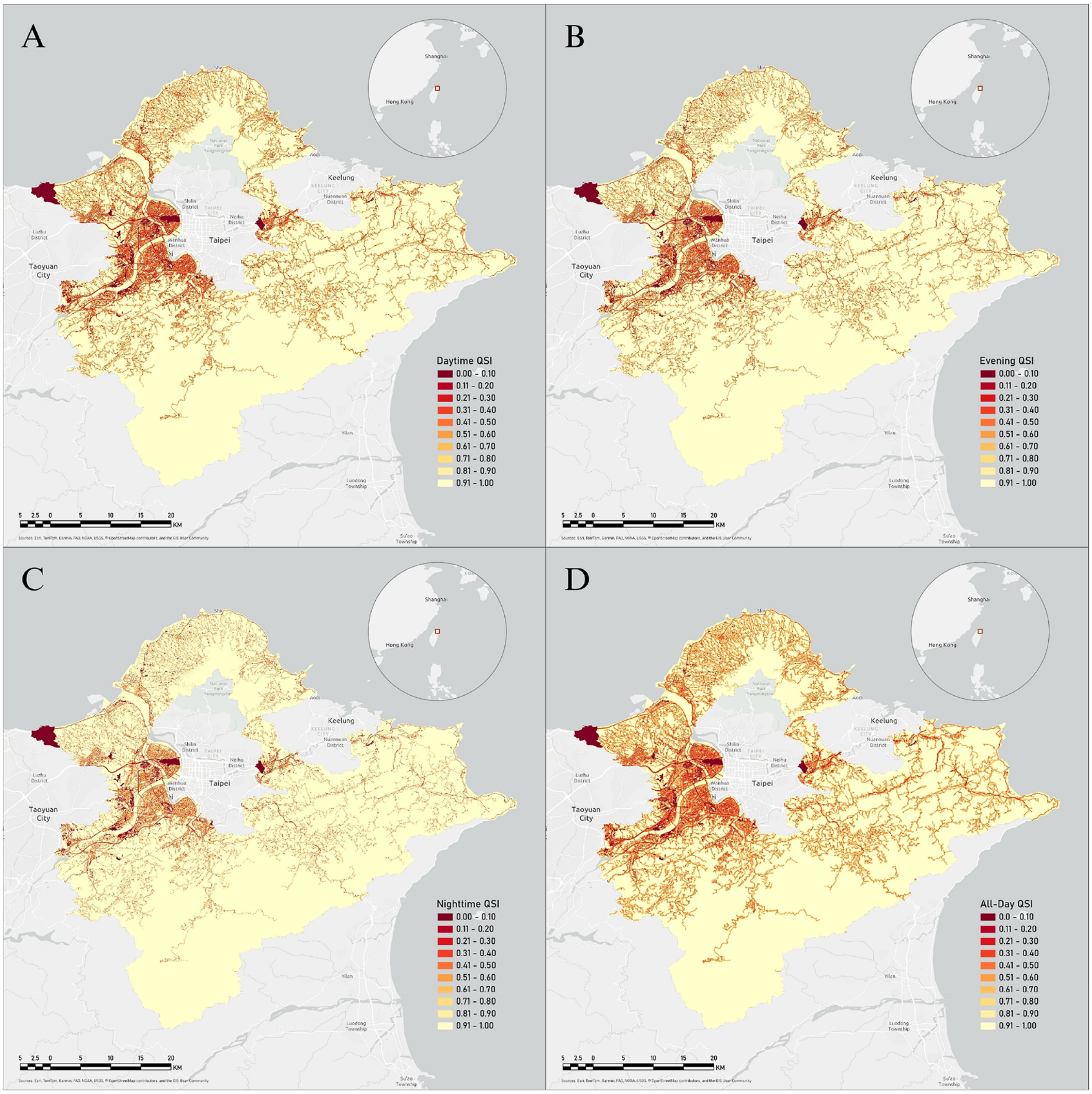

Figure 3: AQSI maps across different time periods (A) daytime QSI (B) evening QSI (C) nighttime QSI (D) all-day QSI.

evening and nighttime AQSI over the study window (1997/1–2024/7).

3.2.3 Model performance and interpretation

The adjusted R^2 values were modest, from 0.06 (all-day) to 0.16 (nighttime), reflecting the variability intrinsic to urban noise monitoring. Stations were situated near busy corridors and activity centers, and short-lived events introduced additional variance that is not captured by period averages. Despite the log transformation, the dispersion in the observed sound pressure levels remained high. Even so, the AQSI models outperformed those based on the original QSI, exhibiting a higher adjusted R^2 and more stable coefficients across periods.

3.2.4 Implications

The validation confirmed a robust, directionally consistent link between higher measured noise and lower AQSI, particularly at night. The moderate R^2 values implied contributions from unmodeled dynamics such as localized activities, micro-environmental conditions, and site selection. Period-specific

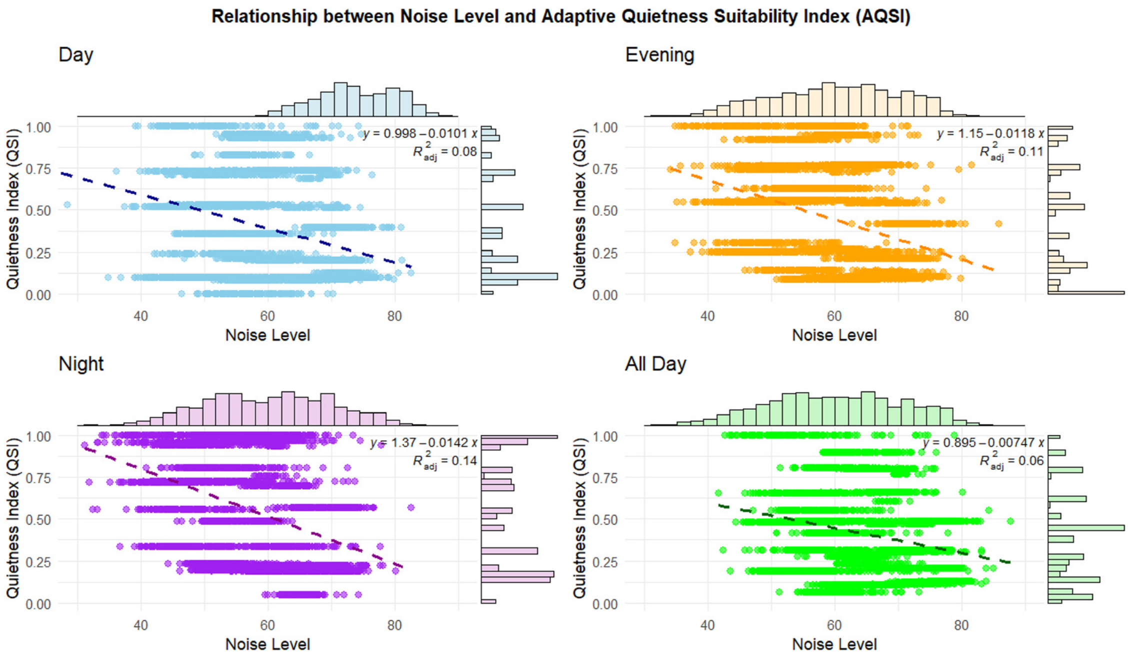

Figure 4: Relationship between noise level (dB) and AQSI across different time periods.

Table 2: Regression results for the AQSI versus noise level (dB) across time periods from 1997/1–2024/7.

Predictors	Daytime AQSI Estimates	Evening AQSI Estimates	Nighttime AQSI Estimates	All-day AQSI Estimates	Original QSI Estimates
(Intercept)	0.2942***	0.4014***	0.4691***	0.3537***	−0.0029
Year (1997 = 1)	0.0025***	−0.0010*	−0.0015***	−0.0003	0.0008***
Noise level categories (ref: -0.5σto 0.5σ)					
Very low (<−σ)	0.0269**	0.0325***	0.0716***	0.0206**	0.0161***
Low (<−0.5σ)	0.0321***	0.0249**	0.0525***	0.0152*	0.0159***
High (>0.5σ)	−0.0968***	−0.1314***	−0.0977***	−0.0539***	−0.0093***
Very high (>σ)	−0.1347***	−0.1605***	−0.1654***	−0.0941***	−0.0098***
Observations	4,721	4,721	4,721	4,721	4,721
R^2/R^2 adjusted	0.087/0.086	0.138/0.137	0.161/0.160	0.061/0.060	0.055/0.054

*$p < 0.05$ **$p < 0.01$ ***$p < 0.001$.

differences indicated that nighttime management warranted particular attention when prioritizing mitigation.

3.3 Performance comparison: original QSI versus AQSI

3.3.1 Visual and statistical assessment

Figure 5 contrasts L_{den}–index relationships for the two approaches. The original QSI exhibited clumping at the extremes (0 and 1), limiting discrimination across intermediate exposure levels. The AQSI distributed values continuously, yielding a steeper regression slope and a higher adjusted R^2 (0.06 vs. 0.04). The box plot reinforced these differences. The original QSI produced tightly centered residuals with minimal spread, indicating a limited sensitivity to variations in the measured noise. The AQSI generated a broader residual distribution, with a median near zero, reflecting greater responsiveness across the exposure range and improved explanatory power.

3.3.2 Quantitative metrics

Table 3 indicates a stronger negative correlation for the AQSI (Pearson's r −0.238 vs. −0.202) and a 39.0 % gain in R^2 (0.057 vs. 0.041). Error metrics were comparable or slightly

Table 3: Performance comparison of original QSI and AQSI against measured noise levels (L_{den}).

Metric	Original QSI	AQSI	Amount of improvement
Sample Size (*n*)	4,721	4,721	
Pearson's *r*[a]	−0.202	−0.238	−17.8 %
R^2	0.041	0.057	39.0 %
RMSE (dB)[b]	7.9	7.83	−0.9 %
MAE (dB)	6.59	6.58	−0.2 %
% Extreme values (0 or 1)[c]	86.2	0	−100.0 %

[a]Pearson's *r*: correlation coefficient between QSI and measured noise levels. [b]RMSE, root mean square error; MAE, mean absolute error. [c]Extreme values refer to QSI = 0 or QSI = 1, indicating over-simplification.

improved for the AQSI (RMSE 7.83 dB vs. 7.90 dB; MAE 6.58 dB vs. 6.59 dB). Crucially, the proportion of extreme values decreased from 86.2 % to 0 % under the AQSI, eliminating threshold-driven saturation.

3.3.3 Spatial patterns

Figures 6 and 7 show that the original QSI produced large zones of maximal quietness or noisiness with abrupt edges, whereas the AQSI resolved smoother transitions and broader mid-range values. This continuous structure better differentiates neighborhood-scale variations and mixed-use mosaics typical of dense Asian cities.

3.3.4 Interpretation and implications

The AQSI improves both sensitivity to measured noise and spatial realism, offering a more discriminating and policy-

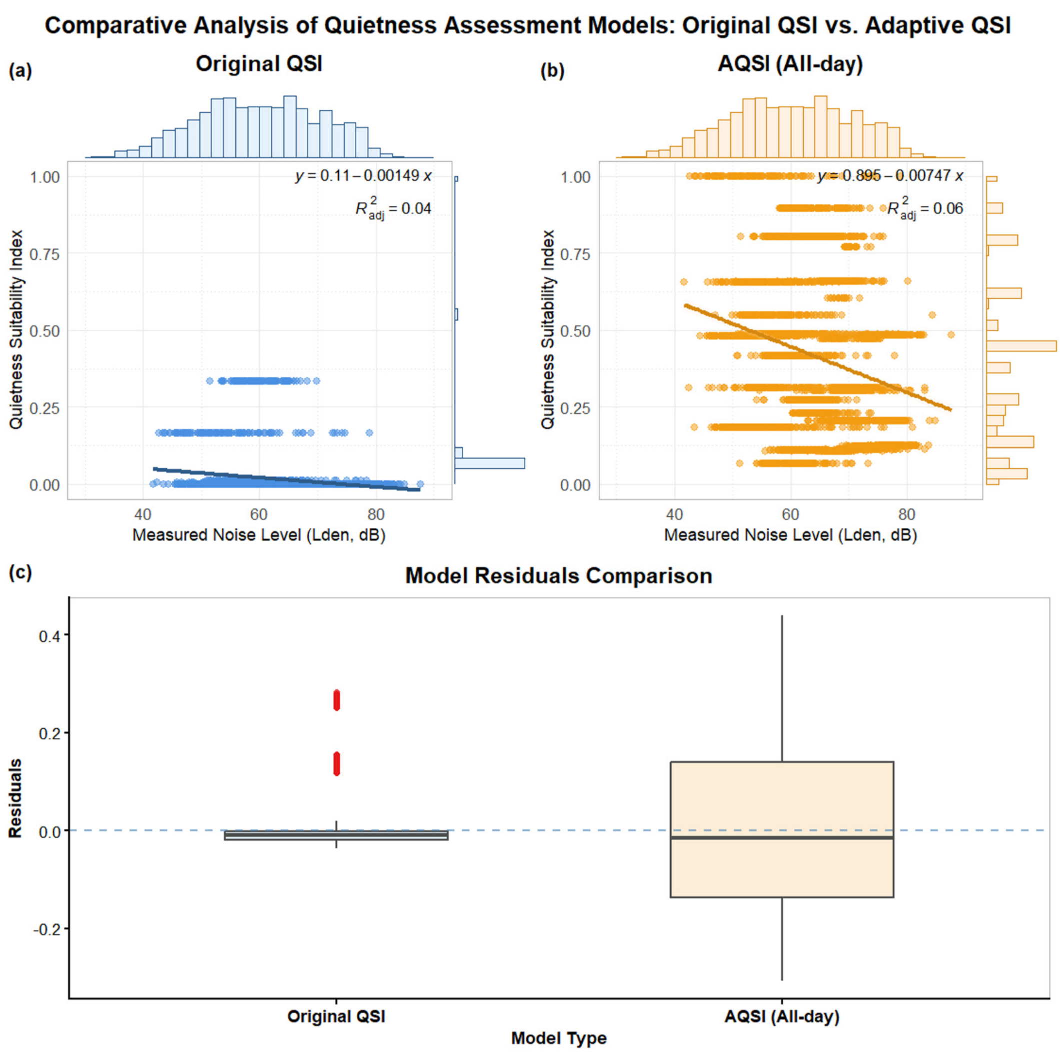

Figure 5: Comparative analysis of QSI & AQSI.

relevant depiction of the acoustic environment. Although the overall explanatory power remains modest due to the monitoring context and stochastic events, the enhanced continuity and reduced extremity enable clearer identification of candidate quiet areas and more precise targeting for mitigation, setting up a deeper discussion on operational use, limitations, and transferability.

4 Discussion

4.1 Bridging noise metrics and soundscape quality

Validation results indicated that the AQSI translated physics-based propagation into a policy-relevant indicator of quietness. The consistent negative association with measured noise levels (Pearson's $r = -0.238$, $p < 0.001$) showed that the AQSI reflected observed acoustic conditions rather than theoretical exposure alone. At the same time, the modest adjusted R^2 values (0.06–0.16) reinforced a central point: quietness cannot be reduced to decibels. Contemporary soundscape research shows that acoustic comfort depends on background levels, temporal variability, spectral composition, source dominance, and the presence of natural sounds, which can enhance restoration even at relatively high levels [31, 32]. Conceptually, quietness encompasses perceptual, cultural, and restorative dimensions – vibrancy, appropriateness, and contextual fit [1]. The AQSI's explanatory power was therefore appropriate to its scope: it robustly recovered exposure gradients while leaving room for perceptual and contextual factors

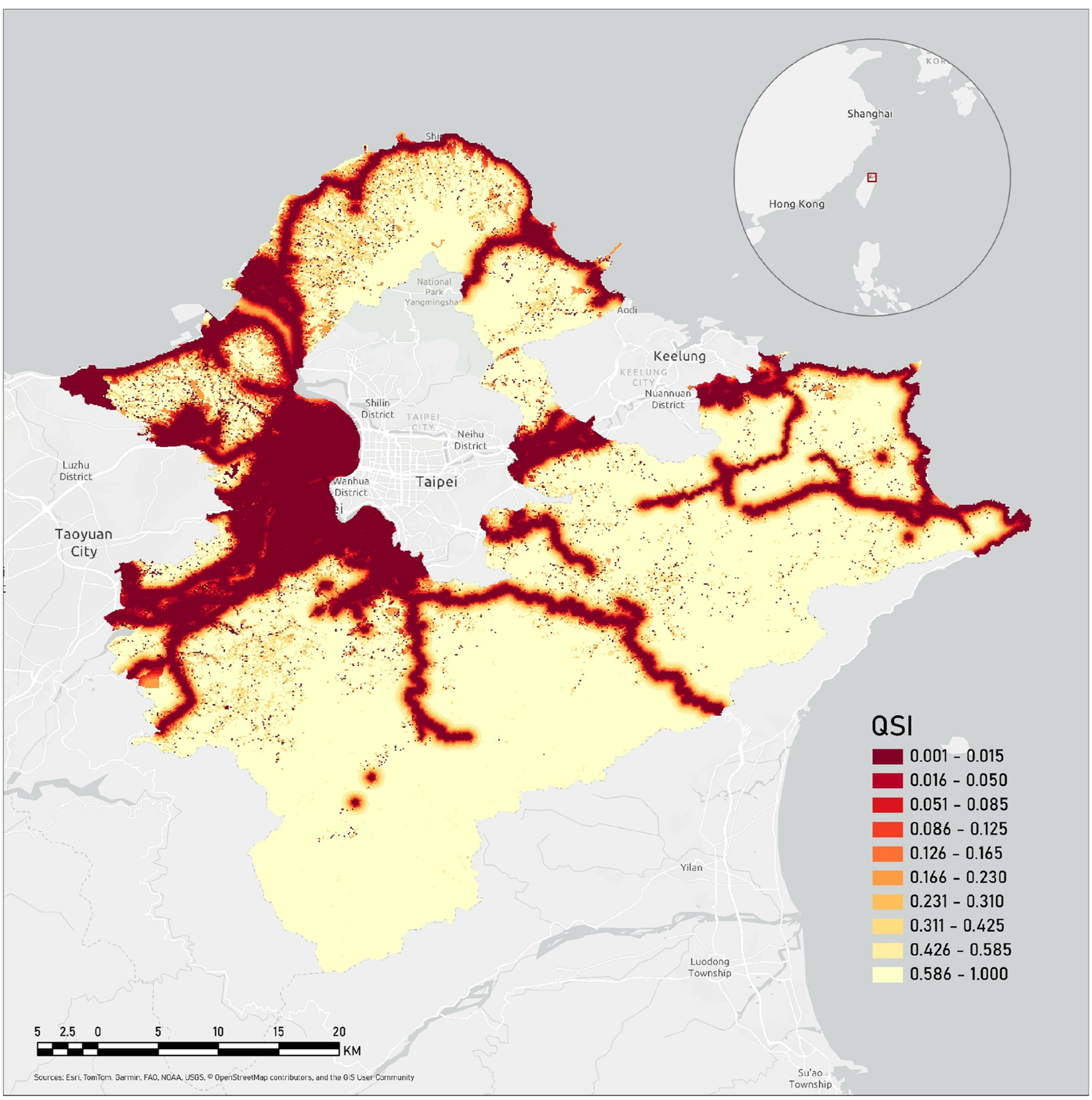

Figure 6: QSI map by the original QSI approach.

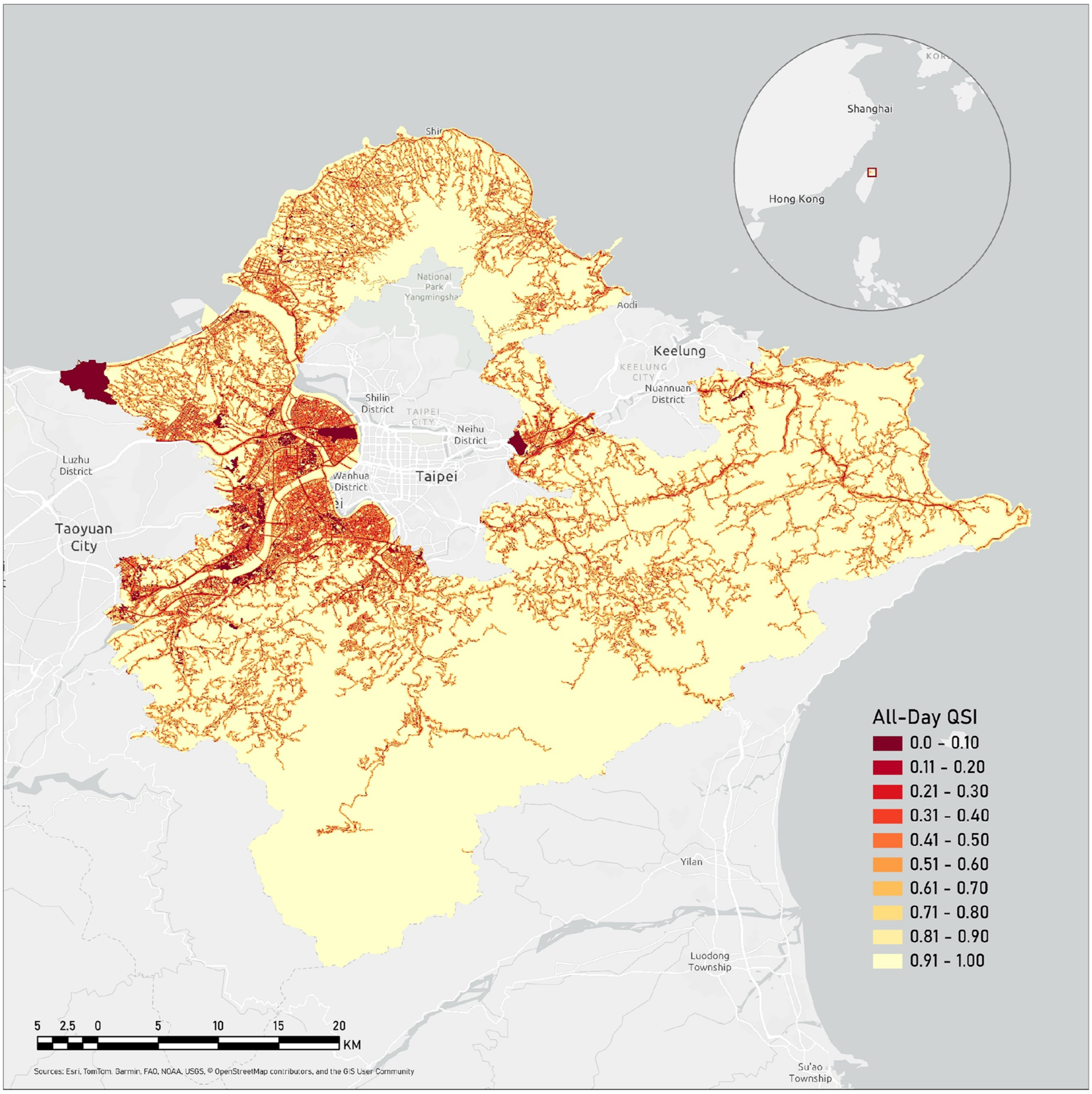

Figure 7: All-day QSI map by the AQSI approach.

that physical models do not capture. These findings motivate future extensions that incorporate psychoacoustic attributes and community-specific tolerance thresholds to link quantitative exposure mapping with qualitative soundscape assessment.

4.2 Temporal asymmetry: nighttime as the critical window

Model performance peaked at nighttime (adjusted R^2 = 0.16; coefficient = −0.0142), suggesting that nocturnal noise was more stable, predictable, and health-relevant than daytime or evening conditions. This accords with evidence that night time sources are more consistent (road traffic, industrial background), whereas daytime soundscapes fluctuate with human activities [33]. The heightened health salience of nighttime exposure – including sleep disruption, annoyance, and cardiometabolic risks – is well established [34–36]. Long-term trends further pointed to a temporal divergence: daytime AQSI rose modestly (+0.0025 per year, $p < 0.001$), while evening and nighttime AQSI declined (−0.0010 and −0.0015 per year, $p < 0.05$ and $p < 0.001$), indicating increasing nocturnal noise. These shifts likely reflect extended operating hours, late-night commercial activities, and expanded transport operations. Accordingly, while daytime policies appear to have yielded progress, managing nighttime noise now requires urgent regulatory priority, focusing on sources active after hours to support a more sustainable and health-protective urban soundscape.

4.3 Overcoming the urban transferability gap

Originally designed to identify rural quiet areas, the QSI framework has limited utility in dense, mixed-use urban contexts [7]. Fixed-threshold buffers, multiplicative zero-forcing, and low “naturalness” ratings for urban land covers oversimplify heterogeneous city fabrics and obscure quieter micro-areas within dense districts [9]. The AQSI addressed these constraints through three adaptations: dynamic impact-zone delineation via sound propagation rather than static distances; alignment with locally regulated limits and control zones; and explicit temporal stratification (daytime, evening, nighttime, all-day). Empirically, the elimination of extreme-value saturation (from 86.2 % to 0 %) and the 39 % improvement in R^2 indicated finer discrimination and more realistic spatial gradients in high-density, mixed-use settings. Validation in New Taipei City – where several districts exceed 20,000 people per km^2 – demonstrated adaptability under Asian megacity conditions. More broadly, the AQSI offers a standardized yet flexible framework that can be calibrated to diverse regulatory regimes and monitoring infrastructures, thereby bridging exposure modeling, compliance, and soundscape-oriented planning.

4.4 Limitations and the path forward

This study had three limitations. First, data availability and siting introduce bias: monitoring stations are often located in noisy places, and short-lived events (construction, festivals, and incidents) inflate variance that period averages cannot capture, helping to explain modest R^2 values. Integrating crowdsourced observations and distributed sensors, complemented by AI-based prediction, can expand the coverage and temporal resolution [37]. Second, the AQSI currently omits meteorological influences (wind, temperature gradients, and humidity) and fine-grained seasonal activity patterns, both of which modulate propagation and perception [38]. Explicitly modeling these factors may improve predictive accuracy and reveal seasonal dynamics not detected here. Third, removing the land-cover “naturalness” layer avoids urban misclassification but risks overlooking restorative contributions from green and blue infrastructure and natural soundmarks [1, 31]. Hybrid approaches retain physics-based propagation while adding context-sensitive soundscape indicators to reflect positive acoustic qualities. Finally, although the AQSI uses recent land use data, historical shifts in sources were only partially captured. Incorporating past land-use and traffic records would improve decadal trend analyses and strengthen retrospective policy evaluations.

4.5 Policy implications: from mapping to action

The AQSI provided a validated, spatially explicit basis for three tasks: identifying candidate quiet areas, prioritizing high-noise zones, and screening the acoustic impacts of proposed developments. Its continuous values and 50 m resolution supported targeted measures – such as traffic calming, low-noise pavements, electrification, and zoning refinements – enabling parcel-scale decisions aligned with the ISO 12913 emphasis on context and WHO guidance [39, 40].

Designation, planning, and compliance can be operationalized through simple tiers and period-specific targets. For example, “Priority Quiet Zones” (AQSI ≥ 0.8 across all periods) and “Nighttime Quiet Zones” (AQSI ≥ 0.7 at night) can trigger stricter limits, buffers, and design standards; development control can buffer sensitive uses from noisy corridors; and regulators can set AQSI-based targets by control zone and period, with adaptive responses when thresholds are not met. Given the stronger nighttime model performance and the downward nighttime trend, nocturnal management should be prioritized via tighter enforcement in residential areas, incentives for quieter business operations, urban-design shielding, and dynamic traffic management, consistent with WHO recommendations to protect sleep and cardiometabolic health.

Looking ahead, the AQSI’s calibration capability facilitates broader international adoption across diverse regulatory frameworks and monitoring infrastructures. Integrating perceptual descriptors from the ISO 12913 soundscape framework and linking them with smart-city capabilities – real-time sensing, AI-assisted source identification, and predictive mapping – would enable adaptive governance that advances public health and urban livability while maintaining a clear, transferable decision framework.

5 Conclusions

This study introduced the Adaptive Quietness Suitability Index (AQSI), a physics-informed, temporally stratified, and regulation-aware framework tailored to dense, mixed-use urban environments. By replacing fixed-distance thresholds with sound-propagation modeling, aligning source levels with local noise-control zones, and differentiating daytime, evening, nighttime, and all-day periods, the AQSI improved the accuracy, sensitivity, and policy relevance of urban quietness mapping.

Validation in New Taipei City (1997–2024) demonstrated stronger concordance with measured sound levels than the original QSI (Pearson's r −0.238 vs. −0.202) and a 39 % gain in explained variance (R^2 0.057 vs. 0.041). The AQSI eliminated extreme-value saturation (0 or 1 in 86.2 % of cells reduced to 0 %), yielding a continuous value distribution that better discriminated intermediate noise environments. Nighttime emerged as the critical window, with the steepest negative coefficient (−0.0142, $p < 0.001$) and the highest adjusted R^2 (0.16), underscoring the need for targeted nocturnal noise management.

Spatially, the AQSI's 50 m resolution and attenuation-based modeling captured short-range gradients and intra-neighborhood transitions, enabling clearer identification of candidate quiet areas and more precise mitigation targeting. These advances addressed the transferability gap of threshold-based approaches calibrated for European contexts and strengthened applicability to high-density Asian cities.

The AQSI's design is standardized yet adaptable. By integrating locally regulated limits and control zones while dynamically delineating impact areas, it supports context-sensitive planning, compliance assessment, and prioritization of investments. Limitations remain: modest adjusted R^2 values reflect monitoring-site bias and event-driven variability. Additionally, quietness is shaped by perceptual and cultural factors beyond decibels. Future work should incorporate soundscape descriptors, participatory data, meteorology, and emerging sources, and it should also leverage real-time sensing and AI-assisted modeling to enhance temporal coverage and source attribution.

Overall, the AQSI provides a transparent, validated indicator that bridges operational mapping and soundscape-aware considerations. It equips policymakers and planners to preserve quiet areas, target mitigation, and evaluate development impacts, advancing healthier and more sustainable urban environments – particularly in high-density, mixed-use contexts where traditional indices fall short.

Acknowledgments: We would like to thank Mr. Min-Ching Tsai from the Environmental Protection Department, New Taipei City Government, Taiwan, for supporting the historical noise measurement data in New Taipei City.

Declaration of interests: The authors declare that they that have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Author contributions: Chia-Jung Lin: Conceptualization, Formal analysis, Methodology, Writing – original draft. Jia-Hong Tang: Conceptualization, Methodology, Validation, Supervision. Chih-Chung Fan: Data curation, Project administration. Ta-Chien Chan: Conceptualization, Methodology, Resources, Supervision, Validation, Writing – review and editing.

Funding: This study was supported by a grant from the National Science and Technology Council of Taiwan (grant number: NSTC 113-2121-M-001). The funder played no role in the study design, data collection and analysis, decision to publish, or manuscript preparation.

References

1. Aletta F, Kang J. Promoting healthy and supportive acoustic environments: going beyond the quietness. Int J Environ Res Publ Health 2019;16:4988.
2. Chen P, Dai Y, Zhen M. Effects of thermal and acoustic environments on human comfort in urban and suburban campuses in the cold region of China. Environ Sci Pollut Res Int 2024;31:30735–49.
3. Liu Y, Ma X, Shu L, Yang Q, Zhang Y, Huo Z, et al. Internet of things for noise mapping in smart cities: state of the art and future directions. IEEE Network 2020;34:112–18.
4. Ascari E, Cerchiai M, Fredianelli L, Licitra G. Statistical pass-by for unattended road traffic noise measurement in an urban environment. Sensors 2022;22:8767.
5. Praticò FG. On the dependence of acoustic performance on pavement characteristics. Transp Res Part D Transp Environ 2014;29:79–87.
6. Tong H, Kang J. Relationships between noise complaints and socio-economic factors in England. Sustainable Cities Soc 2021;65:102573.
7. European Environment Agency. *Good practice guide on quiet areas (EEA Technical Report No. 4/2014).*; 2014.
8. European Environment Agency. *Quiet areas in Europe — The environment unaffected by noise pollution (EEA Report No. 14/2016)*; 2016.
9. Chen T-L, Chiu H-W, Lin Y-F. How do east and southeast Asian cities differ from Western cities? A systematic review of the urban form characteristics. Sustainability 2020;12:2423.
10. Department of Civil Affairs, New Taipei City Government. *Population statistics*; 2024 Retrieved 2025-02-19 from https://www.ca.ntpc.gov.tw/home.jsp?id=bfd4abbcdb3ce7a3.
11. Copernicus Land Monitoring Service; European Environment Agency. *CORINE Land Cover 2006 (raster 100 m), Europe, 6-yearly - version 2020_20u1, May 2020* Version 2020_20u1) [Raster, GeoTIFF]. European Environment Agency; 2020. https://doi.org/10.2909/08560441-2fd5-4eb9-bf4c-9ef16725726a.
12. Paracchini ML, Capitani C. Implementation of a EU wide indicator for the rural-agrarian landscape. Water 2011;10:25137.
13. Steinhardt U, Herzog F, Lausch A, Müller E, Lehmann S. Hemeroby index for landscape monitoring and evaluation. Environ Indices, Syst Anal Approach 1999:237–54.
14. Zebisch M, Wechsung F, Kenneweg H. Landscape response functions for biodiversity—assessing the impact of land-use changes at the county level. Landscape Urban Plann 2004;67:157–72.
15. Votsi NE, Mazaris A, Kallimanis A, Zomeni M, Vogiatzakis I, Sgardelis S, et al. Road effects on habitat richness of the Greek Natura 2000 network. Nat Conserv 2012;1:53–71.

16. Noise Control Act, (2021). https://law.moj.gov.tw/ENG/LawClass/LawAll.aspx?pcode=O0030001.
17. Environmental Sound Standard, (2010). https://law.moj.gov.tw/LawClass/LawAll.aspx?pcode=O0030014.
18. Amendment to Noise Control Standards, (2013a). Laws & Regulations Database of the Republic of China (Taiwan).
19. Noise Control Standards for Land Transportation System, (2013b). https://law.moj.gov.tw/LawClass/LawAll.aspx?pcode=O0030018&kw=%e9%99%b8%e4%b8%8a%e9%81%8b%e8%bc%b8%e7%b3%bb%e7%b5%b1%e5%99%aa%e9%9f%b3%e7%ae%a1%e5%88%b6%e6%a8%99%e6%ba%96.
20. Regulations for Aircraft Noise Prevention Around Airports, (2009). https://law.moj.gov.tw/LawClass/LawAll.aspx?pcode=O0030010&kw=%e9%9f%b3.
21. National Land Surveying and Mapping Center, Ministry of the Interior, Taiwan. (2020). *2020 Land Use Investigation Data in New Taipei City, Taiwan* Version 2020) [GIS spatial data (vector, raster)]. National Land Surveying and Mapping Center, Ministry of the Interior, Taiwan. https://www.nlsc.gov.tw/cl.aspx?n=13705.
22. Ministry of the Interior, Department of Statistics, Taiwan. (2023). *Basic Statistical Area Population Density Data (December 2023), New Taipei City, Taiwan* Version December 2023) [CSV (Statistical Area Data)]. Ministry of the Interior, Department of Statistics, Taiwan. https://segis.moi.gov.tw/STATCloud/.
23. Environmental Protection Department of the New Taipei City Government. *Amendments to prohibited activities, control areas, and time periods in noise control zones of New Taipei City, effective from July 18, 2023*; 2023. Retrieved 19 February 2025 from https://www.epd.ntpc.gov.tw/Article/Info?ID=350.
24. New Taipei City Government, Urban and Rural Development Department. (2023). *Urban District Land Use Zoning Data, New Taipei City* Version 2023) [GIS spatial data (CSV, ZIP, JSON, XML)]. New Taipei City Government, Urban and Rural Development Department. https://data.ntpc.gov.tw/datasets/fe26e0a5-54c2-4876-bbc7-150243c048f5.
25. National Land Management Agency, Ministry of the Interior, Taiwan. (2023). *Non-urban Planned District Land Use Zoning Data (2023), Taiwan* Version 2023) [GIS spatial data (file, CSV, SHP)]. National Land Management Agency, Ministry of the Interior, Taiwan. https://data.gov.tw/dataset/169538.
26. RiChi Technology Co., Ltd. *RiChi Digital Map: Street Map Data, Taiwan* Version Standard and Premium editions) [GIS spatial data (ESRI Shp, TWD97/WGS84)]. RiChi Technology Co., Ltd; 2019. https://www.richitech.com.tw/streetmap.
27. Li P-H, Fu T-J, Ma W-Y. Why attention? Analyze BiLSTM deficiency and its remedies in the case of NER. In: Proceedings of the AAAI conference on artificial intelligence. Washington, DC, USA: Association for the Advancement of Artificial Intelligence; 2020, vol 34:8236–44 pp.
28. Directive 2002/49/EC of the European Parliament and of the Council of 25 June 2002 relating to the assessment and management of environmental noise: Declaration by the Commission in the Conciliation Committee on the Directive relating to the assessment and management of environmental noise, 12–25 §L 189 12 (2002).
29. Kurze UJ, Anderson GS. Sound attenuation by barriers. Appl Acoust 1971;4:35–53.
30. The Engineering ToolBox. *Sound - Leq - Equivalent Level*. The Engineering ToolBox. Retrieved 2025-01-09 from; 2004. https://www.engineeringtoolbox.com/equivalent-sound-level-d_721.html.
31. Yang W, Kang J. Acoustic comfort evaluation in urban open public spaces. Appl Acoust 2005;66:211–29.
32. Zhang X, Ba M, Kang J, Meng Q. Effect of soundscape dimensions on acoustic comfort in urban open public spaces. Appl Acoust 2018;133:73–81.
33. Basner M, Babisch W, Davis A, Brink M, Clark C, Janssen S, et al. Auditory and non-auditory effects of noise on health. Lancet 2014;383:1325–32.
34. Dratva J, Phuleria HC, Foraster M, Gaspoz JM, Keidel D, Künzli N, et al. Transportation noise and blood pressure in a population-based sample of adults. Environ Health Perspect 2012;120:50–5.
35. Muzet A. Environmental noise, sleep and health. Sleep Med Rev 2007;11:135–42.
36. van Kempen E, Babisch W. The quantitative relationship between road traffic noise and hypertension: a meta-analysis. J Hypertens 2012;30:1075–86.
37. Ascari E, Cerchiai M, Fredianelli L, Melluso D, Licitra G. Tuning user-defined pavements in CNOSSOS-EU towards reliable estimates of road noise exposure. Transp Res Part D Transp Environ 2024;130:104195.
38. Guski R, Schreckenberg D, Schuemer R. WHO Environmental noise guidelines for the European region: a systematic review on environmental noise and annoyance. Int J Environ Res Publ Health 2017;14:1539.
39. International Organization for Standardization. ISO 12913-1:2014 Acoustics — Soundscape — Part 1: Definition and conceptual framework. In: ISO; 2014.
40. World Health Organization. Environmental Noise Guidelines for the European Region; 2018. https://www.who.int/publications/i/item/9789289053563.