FACULTY OF ENGINEERING AND SUSTAINABLE DEVELOPMENT
Department of Computer and Geospatial Sciences

Mapping Noise Pollution with Open-source GIS

Faustina Lina Yeboah

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Preface

I give thanks to my God, the Almighty in whom I move, live and have my being and without whom I would not have made it this far. I am grateful to the University of Gävle for awarding me with the scholarship that has funded my education.

I must thank the staff of the Swedish Transport Administration and the Municipality of Gävle for providing me with the data used in this study.

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Abstract

In a time when urban areas continue to expand, environmental noise pollution especially from road traffic remains a big challenge. This study was aimed at using open-source GIS tools to predict road traffic noise pollution using the mid-sized city of Gävle as a case study. The noise indicators measured were the equivalent day (L_{day}), evening ($L_{evening}$), nighttime (L_{night}), and the equivalent daily average (L_{den}). Traffic data (composition and flow of vehicles on selected roads), traffic source characteristics (road gradient, road surface type), and buildings (geometry) were integrated into Quantum GIS (QGIS) using the CNOSSOS-EU prediction method packaged in OpeNoise, a QGIS plug-in. The resultant noise levels at receiver points were interpolated using the Inverse Distance Weighting method to create noise maps for the city.

The results showed the maximum equivalent day, evening, nighttime predicted noise levels at 85 dB (A), 80 dB (A), 75 dB (A) respectively while the maximum for overall daily average noise level predicted was 85 dB (A). These limits far exceed population exposure threshold limits for the onset of annoyance (55 dB (A)) and sleep disturbance (40 dB (A)). This result is indicative of a poor sound acoustic environment. The pattern of noise level across the city was found to follow street connectivity and traffic intensity. The maximum noise levels were clustered around the highway. Within the city, areas with the highest noise levels were found close to main roads. Residential areas served by service roads were areas with the lowest noise levels.

Predicted daytime noise levels (L_{day}) were compared with 60-second measurements of equivalent noise levels measured at 85 locations during the day in residential and mixed land use areas in the city. The mean of differences between predicted and observed noise levels was found at +1 dB for both residential and areas of mixed land use respectively. Correlation and regression analyses performed for observed and predicted values showed an initial weak positive association with a correlation coefficient of 0.21. However, when outliers were excluded, a correlation coefficient of 0.69 was observed indicating a strong association and linear relationship between the observed and predicted noise levels. Most outliers were underestimations recorded in residential areas at hidden facades. These were attributed to local effects at the measuring locations and assumptions made for building diffraction.

The application of the CNOSSOS-EU method in this study did not consider attenuation from ground reflection and terrain effects. Despite these limitations, the results show that the CNOSSOS-EU has good predictive power. However, this study has only been exploratory in nature. It is recommended

that further studies be performed with this model as well as in comparison with other models to find the one that best reflects the acoustic environment of the city. A wide application of the CNOSSOS-EU method across several cities will be integral in increasing our understanding of its strengths and weaknesses.

Keywords: Road traffic noise, CNOSSOS-EU, noise exposure, L_{day}, $L_{evening}$, L_{night}, L_{den}

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1 Introduction

Pollution is a term that has fast become attached to urban environments. While there is no consensus for a definition of urban pollution, some authors have explained it as the presence of harmful substances in cities (Martínez-Bravo & Martínez-del-Río, 2019). Pollution of air, water, and land resources continually increase as a result of the ever-increasing human population and ensuing human activities. Goel (2006) asserts that there is a positive relationship between population densities and pollution in cities. With this comes dense transport infrastructure and amenities that are characteristic of urban environments. There are significant environmental health risks from various forms of pollution. The World Bank asserts that pollution is the largest environmental cause of disease and death globally (World Bank Group, 2016). Air and noise pollution are among the leading causes of illness and death from human exposure to the environment. Noise, especially traffic-related noise is responsible for the loss of one million healthy life years in Western Europe, second only to air pollution in terms of its burden of disease (World Health Organization and Joint Research Council, 2011).

Environmental noise pollution is an age-old problem plaguing societies for centuries. For instance, it is reported that in ancient Rome, Julius Caesar banned the use of chariots on streets to help citizens sleep. History also credits the first noise abatement ordinance to Greece when potters, tinsmiths, and roosters were prohibited from operating in residential areas in cities (Goldsmith, 2012). Unlike air pollution which may in some circumstances be attributed to natural events such as volcanic eruptions, the sources of environmental noise pollution especially in urban areas are largely anthropogenic. The WHO in its Guidelines for Community Noise report defined environmental noise as noise emitted from all sources except for the noise from industrial workplaces (Berglund et al., 1995). The European Union (EU) Directive 2002/49/EC on environmental noise management on the other hand defines environmental noise as all unwanted or harmful outdoor sound that is created by human activities with the inclusion of road, rail, air, and industrial noise sources (European Parliament and Council of the European Union, 2002). Of these, road traffic noise is the most pervasive affecting numerous people each day because of its large areal coverage and popularity as a preferred transport, especially for commuting over relatively short distances (European Environment Agency, 2014). This is true in all European countries in and out of cities. The European Environmental Agency (2020) reports that there are about 82 million people exposed to road traffic noise 55dB(A) and above for day-evening-night times within cities.

Environmental noise is an issue of global concern affecting all societies and countries, developed and developing alike. It must be stated, however, that research, as well as governmental and institutional efforts at managing noise pollution, vary significantly

between developed and developing countries and even among developed countries and regions of the world. For instance, Schwela (2021) asserts that although legislation on environmental noise pollution exists in many low and middle-income countries, noise levels continue to rise because of the lack of enforcement by authorities. In comparing North American cities to European cities, Murphy and King (2014) mention that European cities are perceived to be quieter compared to North American cities. They affirm that Europe is a forerunner in the management and control of environmental noise. Following the WHO Guidelines for Community Noise report (Berglund et al., 1995), the European Union published its Position paper on noise indicators which recommended some physical indicators for the description of outdoor noise sources for the management of environmental noise (Directorate-General for Environment in the European Commission, 2000).

A follow-on to this was the European Commission's Environmental Noise Directive (European Parliament and Council of the European Union, 2002), the policy instrument to guide the management of environmental noise through actionable measures to be taken by EU member states and at the regional level. A major requirement in the directive is the mandate of member states to produce and publish strategic noise maps and noise management action plans for all agglomerations with populations exceeding 100,000 inhabitants as well as for major roads, highways, and airports (European Parliament and Council of the European Union, 2002). Also, Environmental Action Programmes (EAP) rolled out over the years have included noise management objectives and regional targets to promote sustainability. The efforts made in this regard have made significant contributions to noise management practices even outside of the European region.

Despite the advances made, environmental noise continues to be a major health concern in Europe. The WHO in its Burden of Disease from Environmental Noise report states that population exposure to noise is increasing in comparison to other environmental stressors such as exposure to benzene, dioxins, and secondhand smoke which have seen a decline (World Health Organization & Joint Research Council, 2011). The European Environment Agency reports that environmental noise, specifically road traffic noise, continues to be a public health concern. Population exposure to high noise levels has not reduced despite the 7th EAP objective to reduce noise levels bringing them closer to WHO recommended levels by the end of 2020. The number of people exposed to high levels of road traffic noise is also expected to increase in the future (European Environment Agency, 2020).

A prominent recommendation in the Environmental Noise Directive was the development of a common noise assessment method to be used in the European region. Noise modeling is a complex process and very often, the human impact, and understanding that must be conveyed to stakeholders is lost as a result of the many

technicalities to be considered. Seong et al. (2011) describe environmental noise assessment and mapping as the presentation of predicted or measured noise data, indicating breached thresholds together with an estimation of people exposed. There are several noise prediction models designed for assessing environmental noise whose application is largely dependent on the country in question as well as the traffic and environmental characteristics. For instance, the NMPB-Routes-2008 is the preferred prediction method in France, Calculation of Road Traffic Noise (CoRTN) is used in the UK, whiles the Nord2000 is popular in the Nordic countries (Dutilleux et al., 2010; Gulliver et al., 2015; Khan et al., 2018). These methods differ significantly in their assumptions and thus, results. Consequently, comparing noise pollution levels across countries is difficult. Qualities of the environment such as pollution are however not confined to man-made boundaries. Roads and rivers run across several countries. The need for a uniform method for predicting environmental noise is paramount. The Common Noise Assessment Methods in Europe (CNOSSOS-EU) was therefore developed for the effective implementation of the END (Kephalopoulos et al., 2012). Since then, the method has been used in an exploratory fashion because of its novelty relative to other older methods to evaluate its strengths and weaknesses.

The method has frequently been implemented using open-source Geographic Information Systems (GIS) such as PostGIS, and Quantum GIS (Larsson, 2016; Morley et al., 2015). Geographic Information Systems have gained popularity in many disciplines because of their versatility, and their general applicability to problem-solving. Bolstad (2002) describes a GIS as a computer-based system that supports the collection, maintenance, storage, analysis, output, and distribution of spatial data and information. From this perspective, a GIS allows for the integration and management of large and multiple datasets which in the context of noise prediction will include building information, exposure levels from noise sources, demographic information, etc. GISs are also powerful visual communication tools. They help present complex datasets in the most effective ways helping to reveal underlying patterns hidden in data. GIS-based maps and datasets are often the foundation of many other analyses in diverse disciplines. While many GISs are commercial, open-source GISs have fast increased in popularity. Ibrahim and Ludin (2015) assert that open-source GISs are capable of extending the functionality of GIS analysis through the optimized handling of datasets.

The direct impact of environmental noise on humans, as well as on ecological heath, is severe. In the short term, noise presents itself as an annoyance, which prolonged, disrupts sleep, affects the cognitive ability of children, and causes extreme cardiovascular complications (Babisch et al., 2013; Sørensen et al., 2012). Studies have identified thresholds at or above which these health effects are evident. For instance, Berglund et al. (1995) report that noise levels of sound 55 dB(A) trigger annoyance. Night-time environmental noise levels exceeding 40 dB result in sleep

disturbance, and environmental insomnia causing an increase in the use of sedatives (World Health Organization, 2009). Environmental noise is also known to be a threat to wildlife by reducing reproductive success, increase mortality, increase emigration among terrestrial and marine animals (European Environment Agency, 2020). With due consideration of present efforts on the mitigation of environmental noise in Europe, this study is aimed at predicting environmental noise from road traffic in the medium-sized city of Gävle in Sweden using the CNOSSOS-EU method through an open-source GIS approach.

1.1   Problem Statement

Environmental noise remains a major threat to human and ecological health worldwide and is particularly associated with areas of rapid urbanization. In Europe, despite the many directives guiding limits on most roads and noise management strategies for cities, human exposure to road traffic noise is increasing in comparison to other stressors (World Health Organization & Joint Research Council, 2011). A significant number of studies on environmental noise have focused on the modeling of noise from noise sources and their propagation. More recently in Europe, the CNOSSOS-EU method is being explored. Despite the efforts made in this regard, a lot remains to be understood on its predictive power and associated strengths and weaknesses. For instance, Khan et al. (2021) compared the performance of three noise prediction models: the CNOSSOS-EU, Nord2000, and Traffic Noise Exposure (TRANEX) using test-cases in place of measured traffic data. This proved to be a significant limitation in evaluating the performance of the models. Another area that is widely investigated where environmental noise is concerned is exposure effects on a given population. Epidemiological studies often reveal noise exposure effects such as annoyance and cardiovascular diseases (Bodin et al., 2016; Babisch et al., 2013). Despite the advances made, noise modelling remains a complex process. On a local scale, it is largely ignored because of the absence of the relevant data as well as computational power. This study was thus aimed at assessing levels of road traffic noise using open-source GIS.

1.2 Objectives and Research Questions

Focusing on modelling road traffic noise pollution in Gävle, the study had two main objectives: to review current road traffic noise prediction methods and to test one model to predict the spatial pattern of road traffic noise in Gävle. The research was guided by the following questions:

a. What are the levels of day-evening-nighttime noise from road traffic in Gävle?

b. What is the performance of the CNOSSOS-EU method in predicting road traffic noise?

2 Theory

Environmental noise is a complex and multi-faceted issue. The scope of environmental noise and its assessment in the context of this study can be aggregated into technical considerations (sound properties and propagation methods), population exposure and health risks (exposure assessment and epidemiological studies), and the communication of noise levels using maps. These are further explained in the sections below.

2.1 Sound Properties

Sound, as perceived by the ear is interpreted primarily according to the human experience and thus labeled as laughter, speech, noise, etc. Murphy and King (2014) more technically describe sound as the result of pressure variations in a medium and perceived by the ear when fluctuations cross prevailing atmospheric pressure limits. A sound wave typically describes the movement of a single air molecule (back and forth motion) through which the sound propagates. It is characterized by its period and frequency, amplitude, and wavelength. Of the three, frequency, and amplitude are most significant where sound measurements are concerned. Typically, an air molecule is in equilibrium until it is displaced through a series of oscillations by a propagating sound. The maximum displacement of the air molecule from its equilibrium (undisturbed position) is the amplitude of the wave. It, therefore, describes the maximum pressure value of a wave in a horizontal direction. Sound pressure level is a measure of the vibrations of air that make up sound. It is measured on a logarithmic scale in decibels (dB) instead of Pascals (Pa) by comparing each record of pressure level to a reference level. This reference level is 20 μPa corresponding to 0 dB. The time taken for the air molecule to move back and forth is the period of the wave. Closely related to the period is frequency. It is the inverse of the period. So while period is the number of seconds per oscillation, frequency is the number of oscillations a sound wave makes every second and is expressed in Hertz (Hz). The frequency of a sound is heard as its pitch. High-frequency sounds such as a fire alarm are perceived to have a high pitch. Fig. 1 below is a diagrammatic representation of sound as it travels as a wave while Tab. 1 describes some environmental sound pressure levels expressed on the decibel scale.
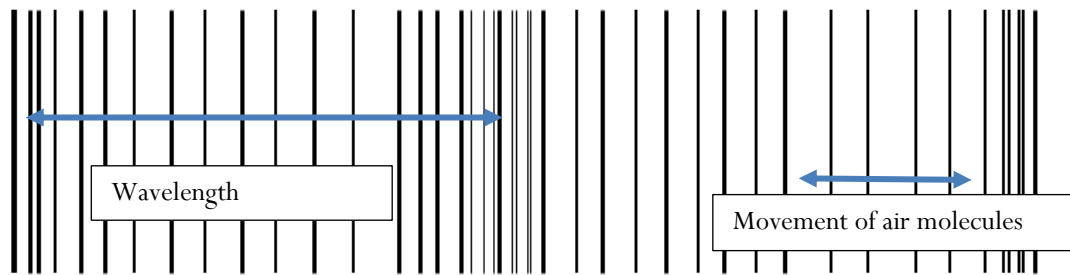
Wavelength

Movement of air molecules

Figure1. Sound as a wave

Table 1. Some environmental sound pressure levels in decibels

Sound description	Decibel Value
Hearing threshold	0
Whisper	30–40
Quiet conversation	40–50
Ordinary conversation	50–60
Heavy Traffic	70–80
Opera concert	80–90
World series	90–100
Wood work shop	100–110
Jet aircraft	130–140
Threshold of pain	140 and over

Source: Adapted from Murphy and King (2014)

Furthermore, it is important to mention that environmental sound levels cover a wide range of different frequencies and human perception differs from person to person. To account for such variations in perception, a weighting method is applied to sound level meters to determine the relative strength of frequencies. The A-weighting is used for adaptation to the human ear (Berglund et al., 1995).   In noise exposure modeling, the frequency content of individual noise sources is often of more importance than the overall noise level. The frequency range of a sound is therefore grouped into smaller manageable frequency bands. These frequency bands are grouped into single octave and third-octave frequency bands. Characteristic of octave bands are their center frequencies, lower and upper limits.

2.2   Noise indicators

Choosing a noise indicator should be guided by the purpose for which it is to be used. According to (Naish et al., 2011), road traffic noise indicators can be categorized into objective indicators and subjective indicators. Objective indicators assess the change of ambiance, energy levels as well as peak levels. Subjective indicators on the other

hand assess noise impact on sleep disturbance, health, and annoyance. Regardless of this difference, objective indicators are used to determine human response to noise levels. These objective indicators can be described more generally as energetic indicators and statistical indicators. Other indicators are the Number of Noise Events (NNE) and mask indices (MI) indicators, noise rhythm indicators, and specific urban noise indicators (Can et al., 2016; Naish et al., 2011).

Energetic indicators measure the same quantity of sound energy over a defined time. Statistical noise indicators on the other hand assess the percentage of time above which specific noise thresholds are exceeded. NNE's and MI's are used to assess noise levels in emergencies. Noise rhythm indicators assess the roughness of sound and specific urban noise indicators are adapted to traffic signals. The number of noise indicators is many and maybe somewhat confusing, especially to the layman. The Position Paper on EU noise indicators (Directorate-General for Environment in the European Commission, 2000) categorizes noise indicators into three broad categories that are easy to understand. These are basic indicators, composite indicators, and complex indicators. Basic indicators are physical quantities with little indication of the effects they may reflect. Composite indicators are obtained by combining basic indicators and are applicable to land use planning, noise control, and general policies on population exposure to noise levels. Complex indicators measure exposure from different noise sources and favour inter-country or state comparison.

2.2.1 Energy Indicators

Energy equivalence is the averaging method that describes the equivalent continuous sound level (L_{eq}). Sound levels recorded must also consider the sensitivity of the human ear to different sound pressure levels. This is called the A-weighting applied to decibel (dB) measurements giving the L_{Aeq} of which some commonly used timeframes are the $L_{Aeq(1\ hour)}$ and the $L_{Aeq(24\ hours)}$(Naish et al., 2011). Other energy-based indicators are the SEL, L_{day}, L_{eveing}, L_{night}, $L_{24hr,}$ and the composite L_{den}. SEL stands for sound exposure level and it is a single event descriptor for measuring for instance exposure to aircraft noise. They are considered to show a weak correlation to the long-term effects of noise exposure (Directorate-General for Environment in the European Commission, 2000). This makes it suitable for predicting the short-term or instantaneous effect of noise. L_{day} is the average sound level pressure recorded over a day (often 12 hours from 7:00 am to 7:00 pm according to European practice). L_{night} is the average sound level pressure recorded for a night (8 hours from 11:00 pm to 7:00 am European practice). It is the choice indicator for assessing the impact of night-time noise especially for studying the long-term effects of nighttime exposure on health for example in the occurrence of cardiovascular diseases (World Health Organization, 2009).

L_{den} is the average sound pressure level for all days, evenings, and nights recorded over a year. The indicator has two penalties; 5dB for evening recordings and 10dB for night recordings. It is the general-purpose indicator and is used in assessing population exposure for cities with populations exceeding 100,000. It is defined as follows:

$$L_{DEN} = 10 \times \log\left[\frac{12}{24}10^{L_{day}/10} + \frac{4}{24}10^{(L_{evening}+5)/10} + \frac{8}{24}10^{(L_{night}+10)/10}\right] \quad (1)$$

2.2.2   Statistical Indicators

A popular statistical noise indicator is the L_{10} which is strong in measuring the peaks in noise levels. It is a measure for the sound level that is exceeded 10% of the entire measuring period. It is also the adopted indicator for road traffic noise mapping in the UK in the Calculation of Road Traffic Noise Method (CoTRN). The method uses the $L_{10(18hour)}$ which is the arithmetic average of the $L_{10(1hour)}$ measurements from 6 am to midnight (18 hours). It is expressed as follows:

$$L_{A10(18hour)} = \frac{1}{18}\sum_{6\,am}^{midnight} L_{A10(1hour)} \quad (2)$$

For measuring background noise, the L_{90} is the noise indicator for calculating the sound level that is exceeded 90% of the measurement period. L_{Amax} is the highest sound pressure level that is recorded in an interval where the interval may be described as the passing of each vehicle. Like the SEL, it measures specific noise events.

2.3   EU Legislation on environmental noise

The European Commission's Position Paper (Directorate-General for Environment in the European Commission, 2000) on noise indicators for the European region reports that steps towards the management of environmental noise begun in 1996 with a Green Paper on Future Noise Policy (European Commission, 1997). Following this, a conference for the harmonization of noise metrics was held in 1997. With a good foundation from efforts made in these years, the Position Paper recommended physical (noise) indicators suitable for describing environmental noise for all assessment, planning, mapping, and control purposes. These noise indicators refer to the measure of sound pressure levels at distinct time intervals such that they can be meaningfully interpreted in their possible effects on an exposed population. In 2002, the Environmental Noise Directive (European Parliament and Council of the European Union, 2002) was issued on the assessment and management of environmental noise. Among other things, the Directive emphasizes the need for a common method for assessing environmental noise. It focuses on three main actionable areas. These are noise exposure, the communication of noise effects to the

public, and strategies to prevent and reduce high noise levels while preserving areas with low noise levels.

More specifically, the Directive requires all Member States to prepare and publish noise maps and noise management action plans on a five-year basis for agglomerations with populations exceeding 100,000 inhabitants, roads accommodating more than 3 million vehicles per year, railways accommodating more than 300,000 trains per year as well as for airports experiencing more than 50,000 movements per year. According to the directive, the reports from noise monitoring campaigns were to start from 2005 with data on population exposure reported in 2007, 2012, and 2017. The Environmental Noise in Europe 2020 report describes the trend in population exposure to noise levels across Europe (33 European Economic Area countries excluding Turkey) from the latest reporting year (2017). An estimated 133 million people are exposed to day-evening-night noise levels of 55 dB or higher from road traffic noise, 22 million from railway noise, 4 million from aircraft noise, and 1 million from industrial noise sources (European Environment Agency, 2020). The report outlines though, that the reporting of noise mapping data has not been timely. Many datasets are incomplete which contributes to uncertainties in the assessment. On the issue of uncertainty, the lack of a unified method of calculation is perhaps the biggest problem. After 2017, the CNOSSOS-EU method is the mandatory method for environmental noise assessment and reporting for all member states.

2.4   Noise prediction methods

Noise modeling is a rigorous process to characterize sound levels from various noise sources and their propagation. It involves a description of the noise source and the collection of relevant data together with the description of the receiver environment as well as all intervening elements between the source and receiving regions. This translates into heavy computation and numerous assumptions for the description of the noise, propagating, and receiver regions. Several noise modelling methods exist and are applied depending on the county of focus. The process of noise modeling and some commonly applied methods in Europe are described below.

Until a common noise prediction method to be used across Europe was realized, many countries had employed different methods well adapted to their environment. For the 2017 phase of noise mapping, as many as 10 different methods were used by the various countries for reporting environmental noise levels. They are RVS 4.02, NMPB-Routes-96, NMPB-Routes-2008, RMW 2002(SRM II), CNOSSOS-EU 2015, sonROAD, VBUS, Nord2000, CRTN, RTN 1996, and SKM2. Of these, the Nord200, CNOSSOS-EU, and CoRTN (together with a recent modification; Traffic Noise Exposure TRANEX) are explained below.

2.4.1   Nord2000

The Nord2000 is the Nordic environmental noise prediction method. It was originally developed from 1996 to 2001 in a collaborative manner with the Nordic countries to create models for sound propagation for all environmental noise sources. The model was however revised from 2005 to 2006. This was to make road traffic noise calculation easier by avoiding the use of empirical propagation models by adapting theoretical algorithms in frequency band calculations (Kragh et al., 2002).   The assumptions of the model will be discussed below.

Sound pressure level from the receiver is predicted in one-third octave bands from 25 Hz to 10kHz.   The model works for point source predictions and the pressure recorded by the receiver (L_R) is predicted for each frequency expressed by:

$$L_R = L_W + \Delta L_d + \Delta L_a + \Delta L_t + \Delta L_s + \Delta L_r \tag{3}$$

where L_w is the sound power level in a frequency band, ΔL_d is the propagation effect for spherical divergence, ΔL_a is the propagation effect of air absorption, ΔL_t is the propagation effect from the terrain, ΔL_s is the propagation effect from scattering zones, and ΔL_r is the propagation effect from reflections by obstacles. Most of the propagation effects can be assessed independently and are assessed along the path from the source to the receiver. The model is designed to assume sound propagation in an atmosphere with moderate refraction. This is a modification from the initial model that assumes a homogeneous atmosphere hence the use of straight rays for propagation. The present model incorporates curved rays where, as the basic condition, the speed of sound varies linearly with height above ground. Where prevailing winds move from the source to the receiver (downward propagation) or with increasing temperature with increasing height (positive temperature gradient) downward refraction will occur. The opposite is true for upward refractions, that is, wind movement from receiver to source and decreasing temperature with height.

Propagation effects for spherical divergence are however modelled for a homogeneous atmosphere. Propagation methods from ground and screen effects are made of three base models for considerations for flat terrain, valley-shaped terrain, and hill-shaped terrain. Additional computations must be made for significant refraction from weather conditions.

Scattering zone computations for the urban environment and vegetation are made based on the length of the sound path from the source to the receiver. Generally, the computation for scattering is complex because there will be several interactions between the sound and the natural and built environment. For example, reflection, absorption, and scattering by the various parts of trees as well as diffraction from building corners. This translates to heavy deterministic modelling. As such, statistical

modelling is used and based on average sound pressure and the distance from the source (Kragh et al., 2002). In the event of obstacles, the sound path is measured along the top of the obstacles. Where there is refraction, it is measured in circular arcs. Reflection from the ground is assessed to capture the changes in propagation path before and after reflection in relation to wind direction(Plovsing, 2006).

2.4.2   CNOSSOS-EU

The CNOSSOS-EU method is a framework for strategic noise mapping following the Environmental Noise Directive (2002/49/EC). Its prime objective is to prescribe a common approach for assessing environmental noise exposure for the member states of the EU to serve as a template for noise exposure mapping mandatory for all agglomerations with populations exceeding 100,000 inhabitants every 5 years.

The method is based on the NMPB-Routes 2008 noise prediction method and is valid for noise emissions from point sources which refer to noise emitted from a single point in space. In the case of a moving noise source, a source line composed of continuous point sources must be aggregated into segments and then singular point sources.

The model is used for determining road traffic noise from 125Hz to 4KHz for road traffic and railway noise, from 63Hz to 4KHz for aircraft noise, and from 50Hz to 10KHz for industrial noise. Octave bands are used for road traffic, railway, and industrial noise with A-weighting sound pressure level computed through a summation of the frequencies as expressed below:

$$L_{eq,T} = 10 \times lg \sum_{i=1} 10^{(L_{eq,T,i}+A_j)/10} \tag{4}$$

where A_j is the A-weighting correction and i is the index of the frequency band. The noise indicator applied is the L_{den}. The sound energy emitted from all possible noise sources is described as the directional sound power measured for each frequency band. Sound power is measured according to vehicle model parameters such as vehicle category, the number and position of equivalent sound sources, and traffic model parameters such as traffic flow. It includes computations for rolling noise with corrections for the influence of studded tires and air temperature and propulsion noise with computations for noise steady speed conditions and the effect of road gradient. Vehicle acceleration and deceleration, as well as road surface type, are considered. Similar conditions are modelled for railway noise as well with significant differences in the types of noise.

The propagation path of sound in the model is based on modelling the geometric properties of the environment in a partial 3d (2.5d). Road surfaces, terrain, and

building roofs are modelled as horizontal surfaces while barriers and building facades are modelled as vertical surfaces. Ray paths are modelled as direct, reflected, and diffracted paths. Sound propagation is valid for two atmospheric conditions. These are propagations in an atmosphere where downward refraction occurs and for homogenous conditions. The recorded sound pressure at the receiver is modelled as a function of sound power level in various attenuation conditions (geometric divergence, atmospheric absorption, ground effects, diffraction from buildings) for homogeneous and favourable conditions. Homogeneous conditions refer to when the speed of sound waves may be considered constant and sound rays are straight segments. Favourable conditions refer to downward refraction conditions.

Ground effects in the model first assume equivalent height (z) for the terrain instead of real heights (h). A mean ground plane is created to replace the original terrain so that the equivalent height for the noise source and the equivalent height for the receiver is their orthogonal heights to the mean plane. Ground properties are also considered as compact surfaces reflect sound energy whiles porous surfaces absorb sound energy. A co-efficient (G) ranging from 0 to 1 signifies the absorbent properties for all ground surfaces and is valid for all frequency bands. Between a source and a receiver, several ground surfaces may exist. The G_{path} must thus be computed taking into account the ground surface description and the distance it covers.

Diffraction is measured overhead obstacles along the propagation path. If ray paths are well above an obstacle, attenuation is negligible (set to 0). Where the ray path intersects the obstacle, diffraction is calculated by splitting the propagation path into a source side and a receiver side. The calculating ground effects together with three diffraction parameters. If this method is applied, attenuation from ground effects in the overall attenuation equation must be set to 0 since it is included in the diffraction measures.

2.4.3 CoRTN and Tranex

The CoTRN method is the model of choice for road traffic noise exposure in the UK and was developed by the Department of Transport (1988). While some authors (de Lisle, 2016) suggest that the method is old and designed for hand computation thereby lacking the approaches of relatively more recent methods, the method is simple and less confusing which can be considered as a strength especially when considering the acceptance of the approach and its understanding by stakeholders such as policymakers and community members.

The method is valid for measuring noise levels from 63Hz to 5KHz. The noise indicator of choice is the $L_{A10\ (18hour)}$ derived from the arithmetic average of the $L_{A10(1hour)}$. It is given by:

$$L_{A10(1hour)} = L_0 + \Delta_f + \Delta_g + \Delta_p + \Delta_d + \Delta_s + \Delta_c + \Delta_a + A_r \qquad (7)$$

where L_0++ is the basic sound level, Δ_f is the correction applied for traffic speed and the percentage of heavy vehicles in traffic, Δ_g is the correction for road gradient, Δ_p is road surface correction, Δ_d is the slant distance between the road and the receiver, Δ_s is the correction for shielding or barriers along the propagation path, Δ_c is attenuation due to ground cover, Δ_a is the correction for angle view, and Δ_r is the correction for building reflection. The model does not consider atmospheric conditions (upward and downward refraction), thus the bending of rays. Gulliver et al. (2015) successfully applied the method in open-source GIS where it showed good results. It is known as the Traffic Noise Exposure method (TRANEX). While the authors generally follow the CoRTN, they make significant changes to the creation of source geometry, the calculation of propagation path distance, the volume of traffic on minor roads, tunnels, the nature of road surfaces, and road gradients. More importantly, the method includes the noise metrics prescribed by the END such as the L_{night}.

2.5 Overview of studies on environmental noise

Where the choice of noise indicators is concerned, no singular indicator fits all. For instance, composite indicators (L_{day}, L_{eve}, L_{night}, L_{den}) are often the choice indicators in recent times because they are known to better reveal the long-term health impact of noise. The weightings applied to L_{den} allow for better prediction of annoyance among an exposed population while L_{night} is better suited for assessing sleep disturbance (World Health Organization, 2009; European Environment Agency, 2010). L_{den}, in particular, overcomes some limitations of other indicators which cover relatively shorter time frames (Naish et al., 2011). Statistical noise indicators such as the L_{A10}(1hr and 18hrs) and the L_{A90} are also popular methods for assessing average maximum noise levels and background noise respectively. Can et al. (2016) give a tabular overview of the predictive and perceptive power of the various noise indicators.

In assessing population exposure to aircraft noise in Ataturk Airport Turkey, Ozkurt, Sari, Akdag, Kutukoglu, and Gurarslan (2014) used the L_{den} and L_{night} as pollution indicators. Site measurements were taken at four locations in the airport. Their results were noise maps showing the exceeded thresholds of 55, 65, and 75 dB(A). From the study, 1.5% of the land area of Istanbul has noise levels exceeding 55dB with 1.3% of the population exposed to nighttime noise exceeding 55dB with 1% exposed to noise levels greater than 65 dB(A).

The implementation of TRANEX by Gulliver et al. (2015), in London saw the measurement of A-weighted $L_{A10\ (1hour)}$ and the $L_{A10(18hour)}$ for the hours 6:00 pm to 12:00 am from 189531 address locations from 2003 to 2010. Their results indicated that about 1.03 million (12%) people are exposed to daytime road traffic noise levels

above 65dB(A) while 1.63 million people are exposed to night-time road traffic noise levels above 55 dB(A).

Other epidemiological studies have focused on exposure to noise levels and human cardiovascular health. Babisch et al. (2013) assessed the influence on annoyance in the relationship between aircraft and road traffic noise level and the prevalence of hypertension in 4861 subjects. The Integrated Noise model was used to assess aircraft noise exposure whiles road traffic noise assessment was based on the national noise assessment methods for participant countries (UK, Germany, Italy, Greece, Netherlands, and Sweden). Their results point to significant annoyance modification in respect to aircraft noise and hypertension with a stronger association found in more annoyed subjects.

Bodin et al. (2016) explored the association between current and medium-term exposure to road traffic noise, air pollution, and myocardial infarction. The cohort study was carried out in 1999/2000, 2005, and 2010. The Nordic prediction method was used to calculate the A-weighted road traffic noise levels in SoundPLAN. Their results revealed mean exposure levels to road traffic noise as 51 dB(A) in 2005. They concluded that the study did not provide evidence to support an increased risk of Myocardial Infarction because of moderate exposure to road traffic noise or air pollution.

Some studies have been dedicated to the sampling of noise sources. Noise sampling is needed to guide the prediction process. Two main methods are generally used in obtaining data for in noise studies. These are the grid method and the categorization method. The grid method, much older, makes use of a grid overlay on the study area to guide sample selection which is done for each grid. For instance, Zannin et al. (2002) successfully applied a non-uniform grid to guide sample point distribution for measuring noise levels in the city of Curitiba in Brazil. The categorization method is relatively new and thought to be less time-consuming and effective. For this method, the area of study is divided into categories based on a specific theme (land use, streets function, etc). Most studies employ street categorization because of the dominance of road traffic noise on the overall urban environment. For instance, Barrigón Morillas et al. (2005) and Gómez Escobar and Pérez (2018) employed street-based classifications using street function and Average Daily Traffic (ADT) respectively.

Some studies have focused on simplifying the noise modelling process by incorporating mobile phones as monitoring devices. The appeal for mobile phone devices and their associated applications is their widespread use. Mobile phones have shown potential in environmental quality modelling (Milošević et al., 2011; Sagawe et al., 2016). Concerning environmental noise modelling, in particular, Kanjo (2010) developed a mobile platform that allows for real-time monitoring of environmental noise levels using sound level apps. Similarly, D'Hondt et al. (2013) studied the

possibility of a participatory noise mapping tool as a citizen science initiative. More recently, Murphy and King (2016) conducted a study to integrate smartphone-based noise data collected with sound level meters with traditional noise mapping methods. Accuracy remains a major concern where mobile phone usage is concerned.

2.6 GIS in noise modelling

It is nearly impossible to exclude geographic information workflows, methods, and analysis, particularly in environmental monitoring and assessment. GISs provide powerful tools for the integration of diverse datasets, their manipulation, analysis, and visualization. Khan et al. (2018) reviewed the tools and techniques that have been employed in road traffic noise and air pollution studies. They assert that GIS tools have been used extensively in numerous studies. More specifically, terrain properties in the area and road segments of the propagating sound are well handled in a GIS. Landcover and Land use maps needed to identify the absorptive properties of the sound and propagating environment can efficiently be generated using GIS. Another extension of GIS capabilities that are particularly useful in noise mapping is the generation of noise contour maps using interpolation methods in GIS, thereby creating a spatially continuous model of noise levels (Hadzi-Nikolova et al., 2012).

Open source-GIS tools have in recent years increased in popularity. A contributing factor to this development is the optimized handling of datasets which in the case of environmental impact and assessment studies is often of large spatial and temporal extents. The automation of workflows and relatively faster processing time for various analyses may give open-source GIS tools an edge over proprietary software as well as more freedom to analysts. For instance, Gulliver et al. (2015) employed open-source GIS to develop their Traffic Noise Exposure Model (TRANEX) to optimize model performance given their large study area and need for intensive computing. Open-source GISs such as QGIS, PostgreSQL/PostGIS, and Geospatial Data Abstraction Library (GDAL) have been employed in some noise exposure studies. A unique strength of open-source methods is the ease of replication through the sharing of methods used. Through this, their capability and functionality are quickly enhanced because of their crowd-sourced nature.

3 Methods

This chapter describes the geographic coverage of the study together with the data used, their sources, and how they are prepared and used. The chapter also describes how the CNOSSOS-EU method is implemented in QGIS.

3.1 Study area

The study was conducted in the municipality of Gävle in Sweden. It is the capital of the Gävleborg region. Traditionally, it is a part of the Swedish northern lands although it is situated fairly south. By 2017 the population of the municipality had exceeded 100,000; the threshold above which the EU requires the strategic mapping of environmental noise for major roads, railways, and airports. At the end of 2020, the municipality had a population of 102,904 (SCB, 2021). In the municipality, Gävle is the municipal seat and the largest town by population and land area. The municipality lies within longitudes 60°2'9.6''E and 61°5'42''E and latitudes 16°41'49.2''N and 17°48'54''N and has an areal coverage of about 1613.37 square kilometres. The municipality is bordered by the Baltic sea to the east to which the Gavle River empties into. It is also drained by the Testebo river. To the west, it is bordered by Sandviken municipality, which is an industrial hub for mining, metal, and construction companies. In the south, it is bordered by Heby and Tierp municipalities and in the north by Söderhamn municipality. The municipality shares the climate of central Sweden experiencing an average temperature of −5°C in January and 17°C in July. The land is generally low-lying extending eastward with forests and lakes which are characteristic of central Sweden.
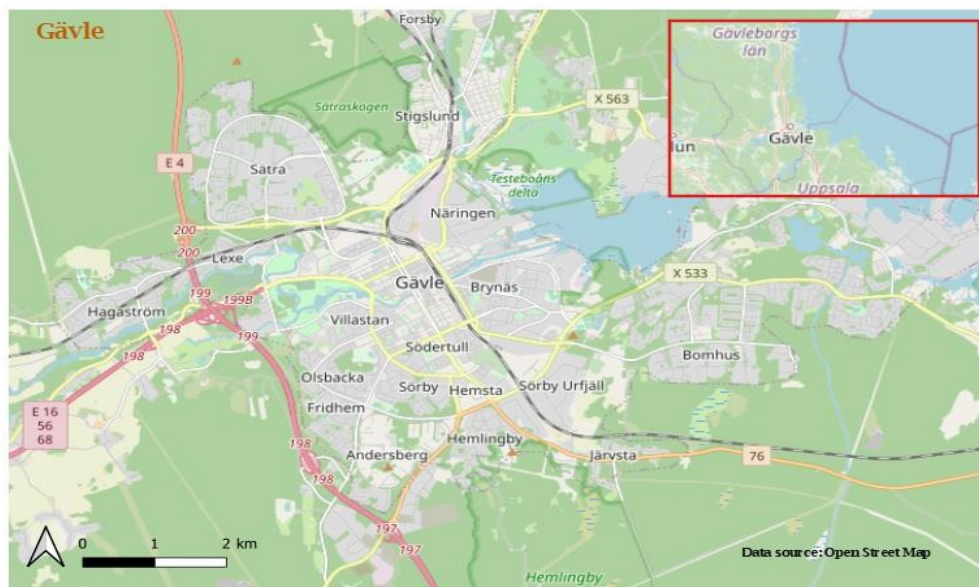

Figure 2. Map of the study area

3.2   Data, data sources, and data preparation

Data for the study was mainly obtained from the Municipality's Traffic Planning Department as well as from government agencies, namely the Swedish Transport Administration and Lantmäteriet (the Swedish national mapping and cadastral agency). From the Traffic Planning Department, 450 measure points of traffic composition and traffic flow for some select road segments in the city were obtained. Traffic composition highlighted the various vehicle categories and their sighting in number per hour per observation period (12-hour day, 4-hour evening, and 8-hour night) for the observed road segments as well as average vehicle speeds. The vehicle categories were further aggregated into the vehicle classes for use in the CNOSSOS-EU method (see appendix). A shapefile of road segments disaggregated into highways, major roads, and streets was obtained from the Lastkajen, the Swedish Transport Administration's data portal accessible at (https://lastkajen.trafikverket.se/). These roads were further reclassified into main roads, small main roads, collecting, and service roads according to the Good Practice Guide (European Commission Working Group Assessment of Exposure to Noise (WG-AEN), 2006). Highways were excluded as there were no traffic measure points available for them. Following the Good Practice Guide, extrapolation is not advised for these roads.

The traffic data from the measured points were used as attribute data for their representative road link and applied to all adjoining links of the same road segment. For roads with no measured data, the average of traffic flow values and vehicle speeds for roads of the same category was used as suggested in the Good Practice Guide. A Digital Elevation Model (DEM) with a 2 m accuracy was obtained from the Geodata portal of Lantmäteriet (accessible from maps.slu.se for Swedish university students and researchers). This was used to calculate the average slope for all road segments. Finally, a road surface attribute information was added for all roads set at a default value of 0 corresponding to the reference road surface in the CNOSSOS-EU method (dense asphalt concrete 0/11 and stone mastic asphalt 0/11). A building shapefile was also obtained from the Geodata portal. This was made up of all buildings in the study area placed in different categories according to function. All irrelevant geometries were excluded.

3.3   Execution of CNOSSOS-EU method

OpeNoise, a plug-in for use in QGIS was used to estimate sound levels from roads to receptor points at building facades. It was created by Arpa Piemonte of the Environmental Protection Agency of Piedmont. The steps below explain how the plugin works to generate noise levels.

3.3.1   Generating receiver points

For every building, a receptor point is generated in the middle of every façade at a distance of 0.1 meters from the side of the building at a height of 4 meters. Receiver points created at building facades in the study area are shown in Fig 3. This method deviates from the CNNOSSOS-EU guideline which creates receptor points at a distance of 2 m from buildings taking into consideration the length of the façade. A building façade is considered exposed if it is the side of a building directly facing a road. A façade is also considered quiet if its noise level is 20 dB lower than that of the exposed façade of the same building.
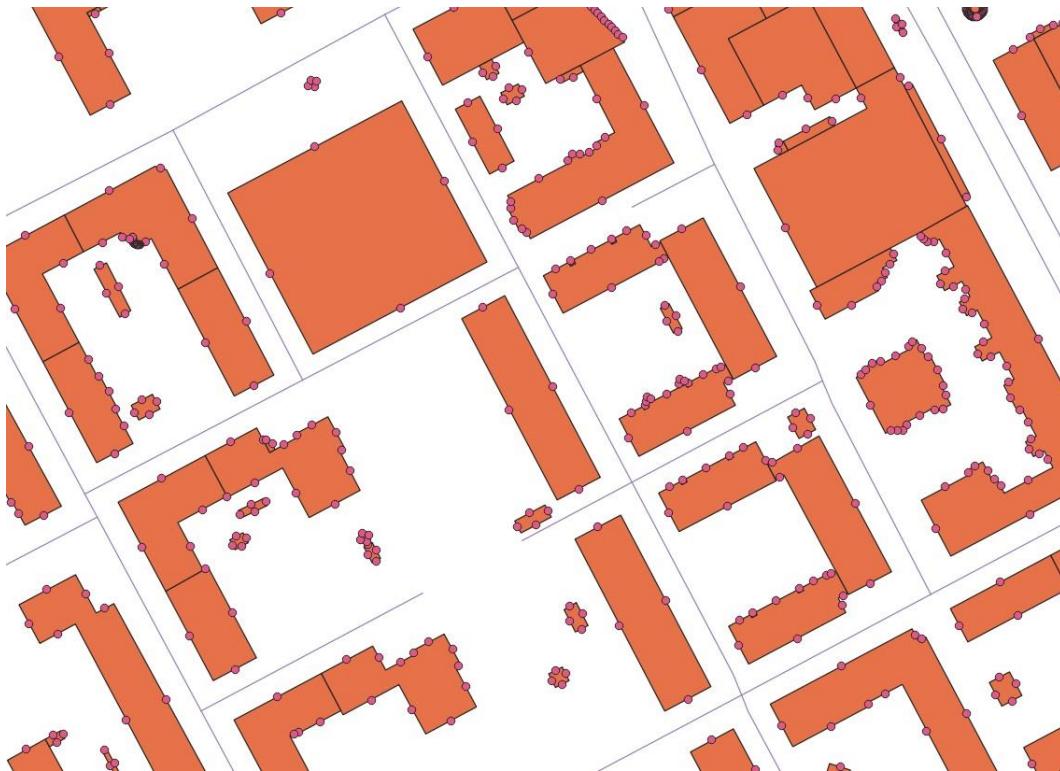

Figure 3. Receiver points at building facades

3.3.2   Sound Power level calculation

Sound power level which quantifies the acoustic energy emitted by a noise source is then calculated for all noise sources. Using a traffic flow model, sound pressure level

is expressed as a function of the number of vehicles per hour per vehicle category and vehicle speed given by:

$$L_{W'eq,line,i,m} = L_{W,i,m} + 10 \times log\left(\frac{Q_m}{V_m}\right) \qquad (19)$$

where $L_{W,i,m}$ is the reference sound power level of 0 dB equivalent to $10^{-12}W/m$, Q_m is the number of vehicles per hour per vehicle category, V_m is the average speed, calculated for each frequency band i of the source line.

3.3.3 Emission points and propagation

The CNOSSOS-EU method is a point-to-point model. As such, road sources must be represented by equivalent point sources. The plug-in creates emission points at intervals of half the minimum distance between receptor points and roads. After this, a ray is traced between the point sources and receptor points. The length of the ray path determines the number of noise-receptor points traced. Longer ray paths increase the number of rays leading to longer computational time but higher predictive power. In this study, the search distance for ray path generation was set to 250 m. The propagation plane of the ray is then intersected with a geometrical model, buildings, and reference temperature and relative humidity value to account for attenuation due to geometrical divergence, building diffractions, and atmospheric absorption, respectively. Attenuation effects from ground reflections and terrain were not considered. As such this is not a full implementation of the CNOSSOS-EU method. Equivalent day, evening, and night-time noise levels are estimated at the receiver points together with the composite L$_{den}$. Noise levels at receiver points can then be assigned to each building. This is shown in Fig. 4 below.

Figure 4. Assigning noise symbology to buildings

3.4 Ground truthing

To assess the performance of the model and the predicted noise levels, 60-second A-weighted equivalent sound level (L_{eq}) measurements were taken at 94 buildings (facades) throughout the study area. The Velleman DEM 202 Sound Level Meter was used to make the recordings. Coordinates of each measuring point were recorded using the Garmin Montana 610/680 GPS and Ktrans, a mobile GPS application for smartphones. The street name together with a description of the façade was recorded to make up for the low accuracy in GPS readings that result from bad weather and signal blockage which could not be avoided because of the urban environment. Samples were taken at areas corresponding to varying land use designations (residential, commercial, industrial) and at different facades (most exposed facades and at quiet facades). L_{eq} measurements recorded at each façade were averaged using the expression below:

$$Avg\ L_{eqf} = 10 \times log \sum_{i=1} 10^{\left(L_{eq,i}/10\right)} \tag{20}$$

where $Avg\ L_{eqf}$ is the average equivalent noise level at a facade, and $L_{eq,i}$ is the ith equivalent noise level recorded in dB at a facade.

3.5 Interpolation

Although noise levels can be visualized using buildings and their corresponding symbology for noise levels, the scale of the study would make such visualization impractical and difficult to assimilate. Moreover, sound is a spatially continuous phenomenon perceived everywhere in space although modeled as receiver points on building facades in this study. To create a spatially continuous surface for noise level, noise levels at the receiver points were used for interpolation. Before interpolation, however, some modifications had to be made to the points layer. The search distance of 250 m used for ray tracing resulted in a number of no data values for building facades exceeding the search limit. Noise levels for points in shadow areas are also not generated. This is shown in Fig. 5 below.
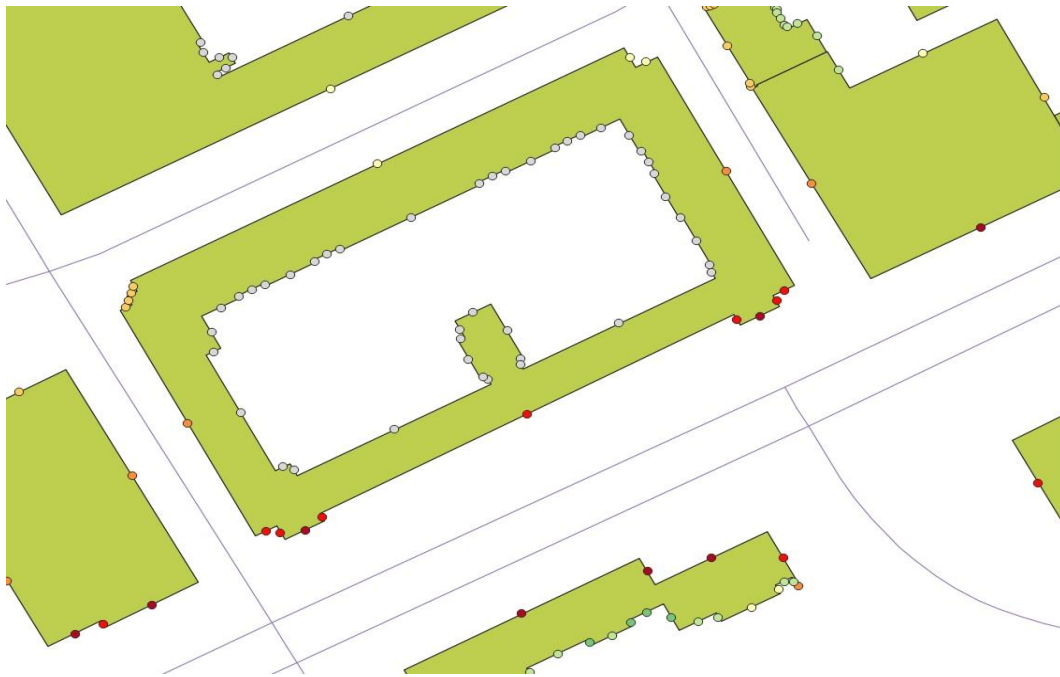
Figure 5. No data points in gray

In some cases, all facades of the building were too far away while in other cases, exposed noise levels for exposed facades were predicted while hidden facades were not. For all such receptor points, no noise levels were predicted. As a workaround, default values were assigned corresponding to the EEA's recorded noise limits in urban areas. Also, receptor points were densely concentrated in the city as they were generated from buildings. As such, open areas, waterways, forests and all other land cover designations with few or no buildings had few points at best. To compensate for this, a 1000 m by 1000 m grid was generated over the study area. In each grid, the number of receiver points was counted. All grids with a receiver point count of less than 50 were selected.

For these grids, 50 points were generated randomly and assigned a range of values corresponding to the EEA suggested values for quiet areas for L_{day}, $L_{evening,}$ and L_{night} respectively. Fig. 6 below shows the grid lines created over the study area together with the selected grids to which random points were generated. Perhaps a simpler solution than the one described above would be to create receiver points in open areas to serve as input in OpeNoise. However, this option was not explored. Inverse distance weighting was then used for interpolation. This method was chosen because it is efficient, intuitive, and relatively simple to implement. The sound intensities were used for interpolation and converted back to decibels. The default mathematical power (2) was used for interpolation. The highway runs through the western part of the study area from north to south. While this road was removed before noise modelling, for the purpose of interpolation and to be as accurate as possible, all grid

cells covering the highway were selected. 30 random points were generated and assigned noise values exceeding 80 dB (A) (85 dB for day, 75 dB for evening, and 70 dB for night periods) as an estimate of noise levels. These values were chosen in order to exceed noise levels typical in urban environments (around 70 dBA to 80 dBA). The flowchart of the methodology is presented in Fig. 7 to facilitate understanding.
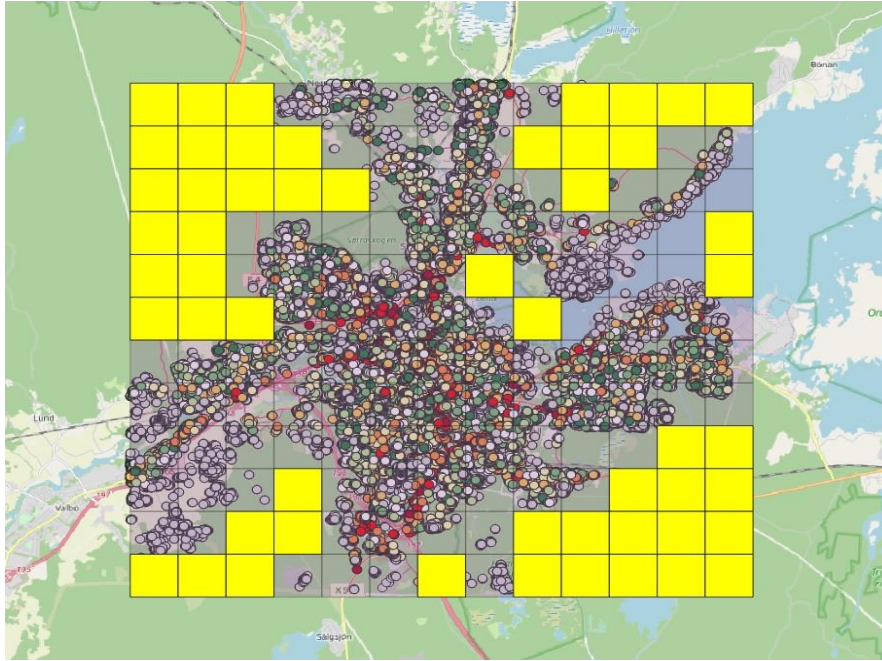
Figure 6. Selecting grids with less than 50 receiver points (selection in yellow)

3.6   Measured noise values: data preparation and comparison

To assess the performance of the CNOSSOS-EU method in predicting road traffic noise, 96 samples of 60-second equivalent noise (L_{eq}) levels were recorded during daytime hours (7:00–19:00) to be compared with predicted equivalent daytime noise levels (L_{day}). Of these, 12 samples were discarded because of errors in recording their coordinate information. The ground-truthing was carried out in two land use designations. These are residential and mixed land use (residential/commercial) types. Here, mixed land use types in the study area refer to buildings close to the city center which may or may not be used for commercial activities. For the residential area, noise measurements were taken in Sätra and for the mixed land use, noise measurements were taken in the city center and its environs.

The average sound intensity was calculated for each sample location. This is the mean of 60 recordings taken per sample location. Since the decibel scale is only a logarithmic ratio, of sound pressure, a direct aggregation of any two values would be erroneous. As such all dB values were first converted to their original intensity values using the expression below:

$$sound\ intensity = 10\text{^}(dB/10) \tag{21}$$

The average sound intensity for each point was then calculated and then converted to decibels using the expression below:

$$dB = 10 * log\ (sound\ intensity) \tag{22}$$

The measured values were then compared to the predicted noise levels to find the difference between individual measurement points as well as the overall mean difference between the two (see Tab. 6 and Tab. 7) using the methods described in this section.

3.7 Correlation analyses

To further assess the performance of the CNOSSOS-EU method, the linear relationship between the predicted and measured values was explored. At a high level, correlation analysis was run for all 84 points. Following this, outliers were removed, and the dataset was further disaggregated into the two land use designations. In the study, outliers were determined to be all differences exceeding 10 dB (A) between predicted and measured values. This value threshold value was considered suitable after a review of the range of differences across the dataset. It was also chosen because it aligns with one of the common noise band intervals (see Alberts and Alférez(2012)). In all, 17 pairs were excluded in the subsequent analyses. Of these, 12 pairs belonged to residential areas.
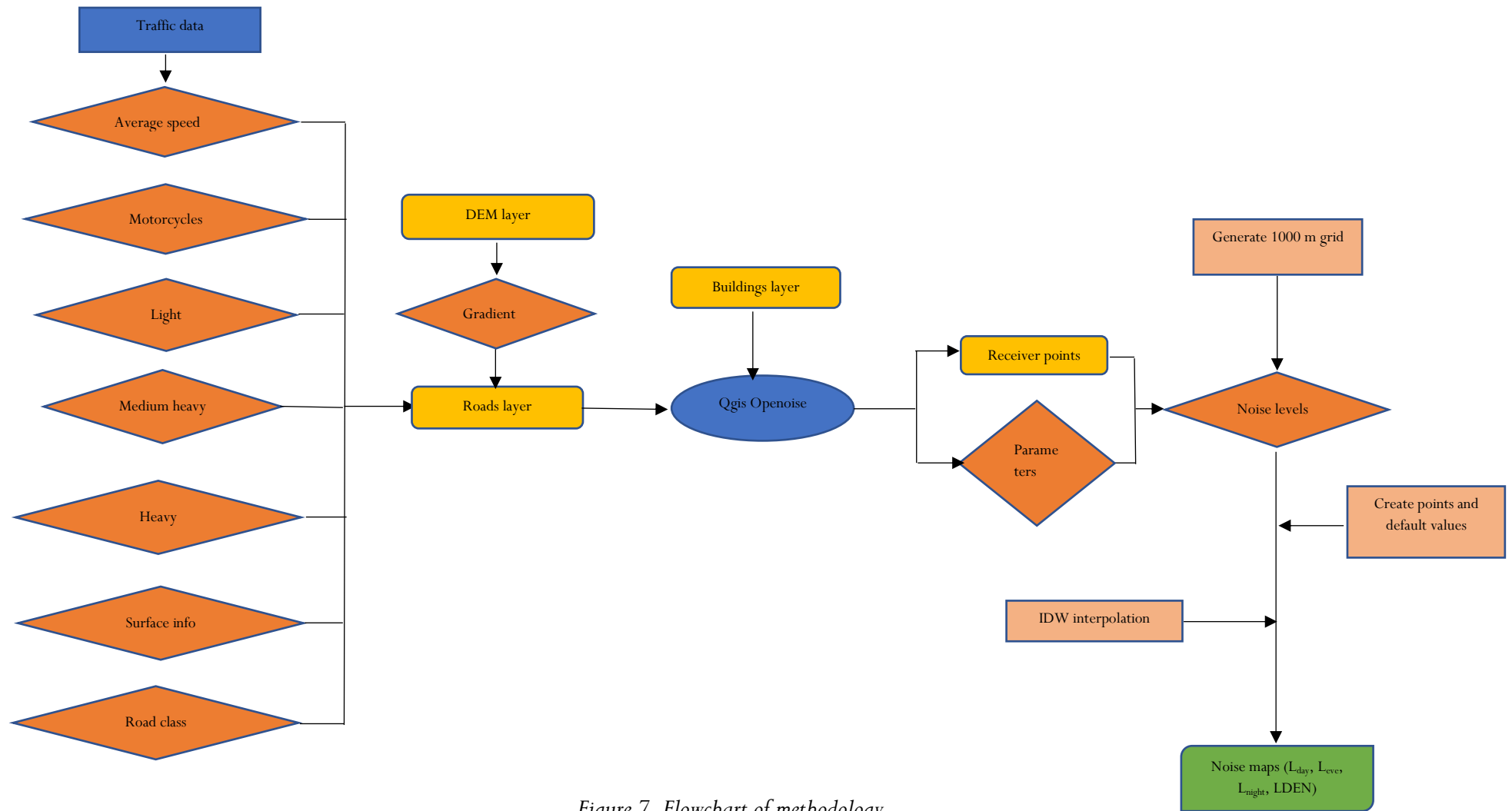
Figure 7. Flowchart of methodology

4 Results

The output of noise modelling is reported in this chapter. This includes highlights of the predicted noise levels in decibels for the individual day, evening, and night periods as well as for the overall daily average. Findings from ground-truthing are also reported and compared with the predicted noise levels.

4.1 Predicted noise levels (Final noise maps)

The noise modelling from QGIS yielded four output fields for each receiver point representing day (12 hours), evening (4 hours), nighttime (8 hours) equivalent noise levels, and the daily average LDEN (combined 24-hour period). These values were interpolated using Inverse Distance Weighting method to produce noise maps for the various periods. To aid interpretation and to facilitate understanding, the noise levels are presented in different categories (noise exposure classes) to highlight significant threshold values for each noise indicator type. The color scheme used follows the recommendation of Alberts and Alférez (2012). Results (text) are presented for the Gävle township (built-up area) while summary tables cover the entire study area and residential buildings in each class in the urban area. The noise exposure classes used were of the following class limits: very low (< 45 dB (A)), low (45-54 dB (A)), moderate (55-64 dB (A)), high (65-75 dB (A)) and high (> 74 dB (A)). These limits are altered for L_{night} and L_{den}.

4.1.1 Equivalent daytime noise level (L_{day}) from road traffic

Equivalent daytime noise level was observed in a range from 0 dB (A) to 85 dB (A). Areal percentages of the built-up area exposed to each noise exposure class are described below. Some 44 hectares (1%) fall in the very high noise exposure class, 265 hectares (8%) fall in the high noise exposure class, 1394 hectares (31%) fall in the moderate noise exposure class, 2020 hectares (46%) fall in the low noise exposure class, while 627 hectares (14%) fall in the very low noise exposure class. Fig. 8 shows road traffic noise levels for the entire study area and a closer look at the Gävle township (populated area). Tab. 2 summarizes areal percentages of each noise exposure class for both study extents together with the number of residential buildings in the built-up area.
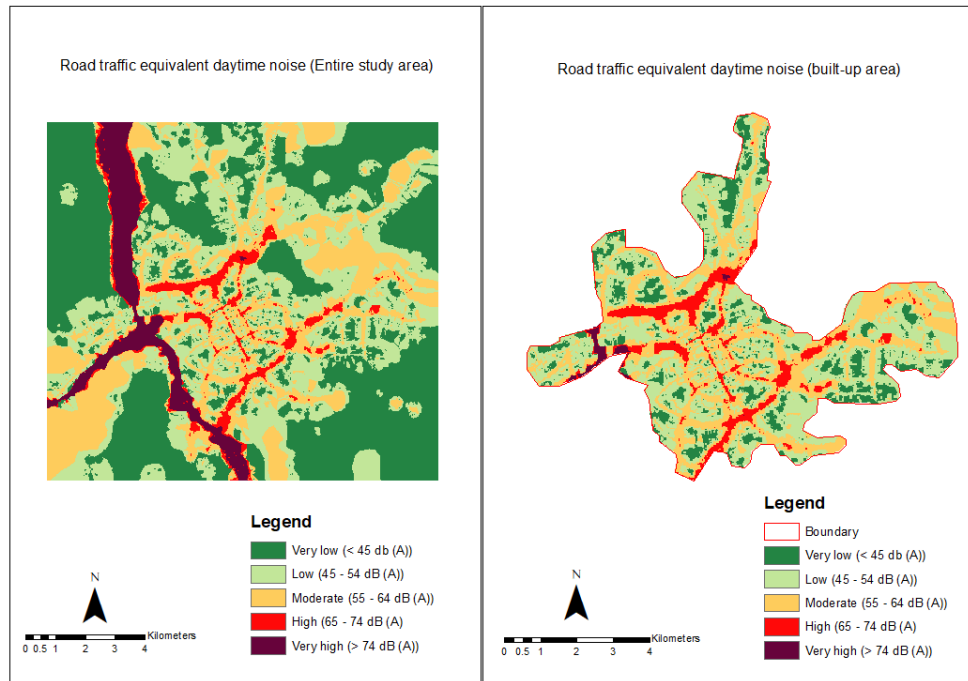
Figure 8. Road traffic equivalent daytime noise levels presented for the study area.

Table 2. Summary of road traffic equivalent daytime noise levels (areal coverage, residential buildings)

Noise exposure class	Entire study area		Gavle (suburbs)		
	Area (ha)	% total	Area	%total	# Residential buildings
Very low (<45 dB (A))	6377	40	627	14	857
Low (45-54 dB (A))	4664	30	2020	46	2463
Moderate (55-64 dB (A))	3269	21	1394	31	1472
High (65-74 dB (A))	561	4	365	8	235
Very high (>74 dB (A))	935	6	44	1	3

4.1.2   Equivalent evening time noise level (L_{eve}) from road traffic noise

Equivalent evening time noise from road traffic was observed in a range from 0 dB (A) to 80 dB (A). Noise maps showing exposure levels for the study area are shown in Fig. 9. For the built-up area (Suburbs in Gävle), 33 hectares (1%) fall in the very high noise exposure class, 224 hectares (5%) fall in the high noise exposure class, 1140 hectares (26%) fall in the moderate noise exposure class, 1934 hectares (43%) fall in the low noise exposure class, while 1119 hectares (25%) falls in the very low noise exposure class. Tab. 3 is a summary of noise exposure classes per hectare for both extents together with the number of buildings in the urban area.
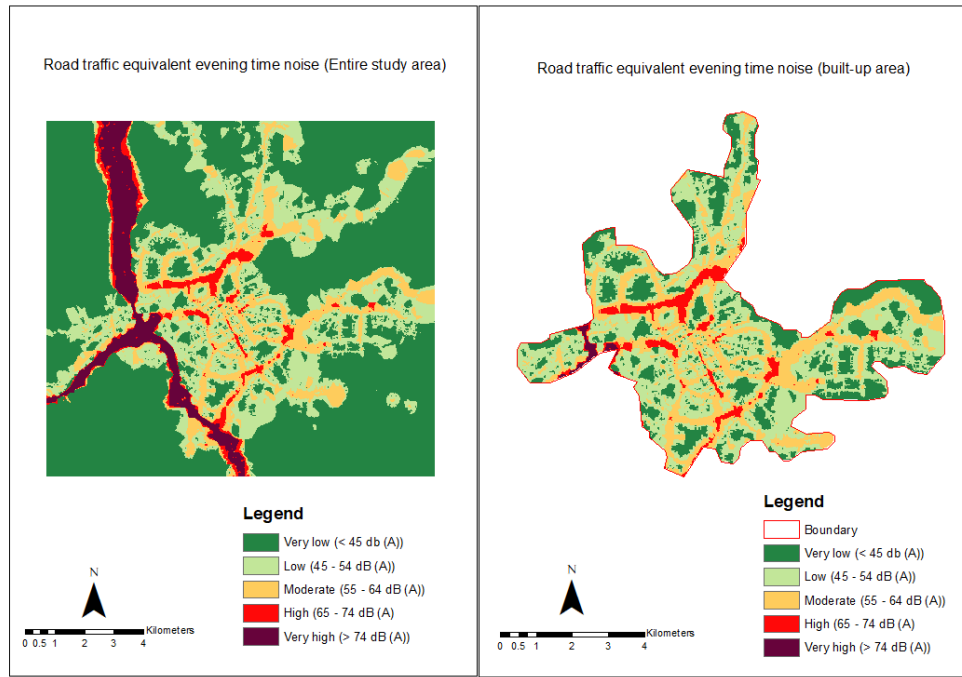
Figure 9. Road traffic equivalent evening time noise levels presented for the study area

Table 3. Summary of road traffic equivalent evening time noise (areal coverage, residential buildings)

Noise exposure class	Entire study area		Gavle (suburbs)		
	Area (ha)	% total	Area	%total	# Residential buildings
Very low (<45 dB (A))	9562	60	1119	25	1456
Low (45-54 dB (A))	3325	21	1934	43	2376
Moderate (55-64 dB (A))	1674	11	1140	26	1075
High (65-74 dB (A))	441	3	224	5	122
Very high (>74 dB (A))	804	5	33	1	1

4.1.3   Equivalent nighttime noise level (L_{night}) from road traffic

Equivalent nighttime noise levels were found in a range from 0 dB (A) to 75 dB (A). Here, the class limits are altered slightly to reflect the guideline limit for L_{night} and L_{den} (40 dB (A)). The new class limits are < 41 dB (A) for the very low noise exposure class, 41–50 dB (A) for the low noise exposure class, 51–60 dB (A) for the moderate noise exposure class, 61–70 dB (A) for the high noise exposure class, and >70 dB (A) for the very high noise exposure class. Noise maps for the entire study area and the urbanized areas are shown in Fig. 10. A tabular summary of the areal coverage per noise exposure class and the number of residential buildings is presented in Tab. 4.

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In the area, 30 hectares (1%) fall in the very high noise exposure class. 112 hectares (3%) fall in the high noise exposure zone, 778 hectares (17%) fall in the moderate noise exposure class, 1856 hectares (42%) fall in the low noise exposure class while 1674 hectares (38%) fall in the very low noise exposure class.

Figure 10. Road traffic equivalent nighttime noise presented for the study area

Table 4. Summary of road traffic equivalent nighttime noise (areal coverage, residential buildings)

Noise exposure class (Lnight)	Entire study area		Gavle (suburbs)		
	Area (ha)	% total	Area	%total	# Residential buildings
Very low (<41 dB (A))	10576	67	1674	38	2098
Low (41-50 dB (A))	3052	19	1856	42	2213
Moderate (51-60 dB (A))	1072	7	778	17	671
High (61-70 dB (A))	342	2	112	2.3	47
Very high (>70 dB (A))	765	5	30	0.7	1

4.1.4   Equivalent day-evening-nighttime noise (L_{den}) from road traffic

The maximum predicted road traffic day-evening-nighttime noise was 85 dB (A). The noise map was manually reclassified into five classes using the same limits as used in

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presenting equivalent nighttime results. Fig. 11 shows the road traffic noise exposure map for the entire study area as well as for the built-up area. Areal coverage of each noise exposure class in the populated area shows that 136 hectares (3%) fall in the very high noise exposure class, 796 hectares (18%) fall in the high noise exposure class, 2019 hectares (45%) fall in the moderate noise exposure class, 1254 hectares (28%) fall in the low noise exposure class while 244 hectares (6%) fall in the very low noise exposure class. Tab 5. Presents a summary of these results.
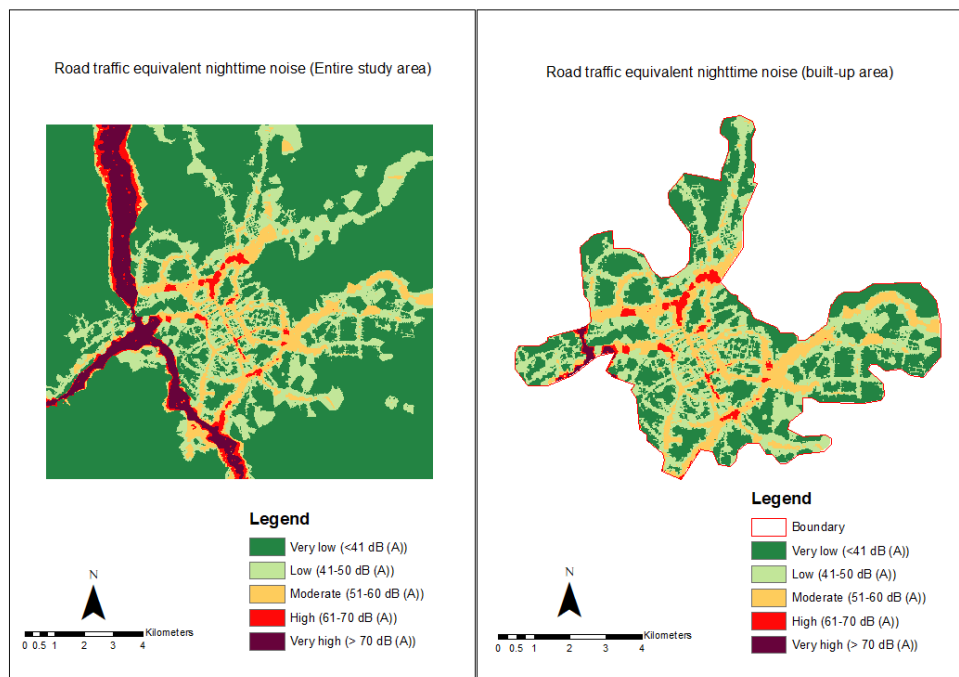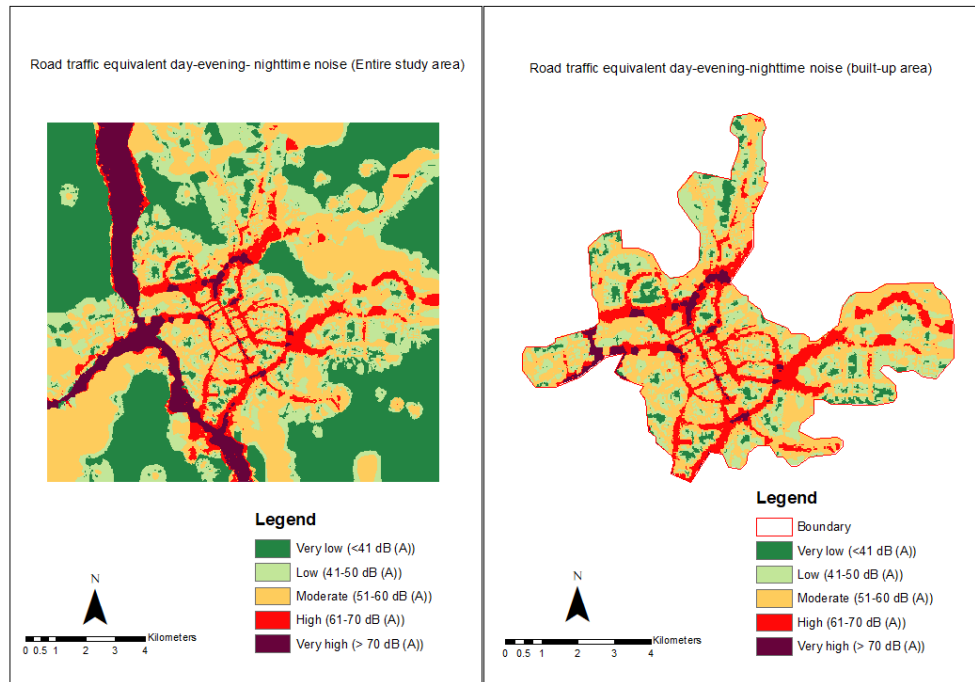

Figure 11. *Road traffic equivalent day-evening-nighttime noise presented for the study area*

Table 5. *Summary of road traffic equivalent day-evening-nighttime noise (areal coverage, residential buildings)*

Noise exposure class (LDEN)	Entire study area		Gavle (suburbs)		
	Area (ha)	% total	Area	%total	# Residential buildings
Very low (<41 dB (A))	5387	34	244	6	355
Low (41-50 dB (A))	3350	21	1254	28	1532
Moderate (51-60 dB (A))	4860	31	2019	45	2417
High (61-70 dB (A))	1114	7	796	18	685
Very high (>70 dB (A))	1095	7	136	3	41

4.2 Noise levels and Street Categorization

Overall noise levels (L_{den}) were found to correspond to the street categories used in the noise modelling process, where the streets were categorized based on traffic flow (number of vehicles per hour). Areas with low noise levels coincide with streets with low traffic flow whiles areas with high noise levels coincide with streets with high traffic flows. Fig. 12 below is an overlay of the roads in the study area with the equivalent day-evening-nighttime noise map. Main roads in the study area fall within the high and very high noise exposure classes (above 60 dB(A)). Small main roads predominantly lie in areas with moderate noise exposure (51-60 dB (A)). Collecting roads lie in areas with low noise exposure (41-50 dB (A)) while service roads lie in areas with very low noise exposure (below 41 dB(A)). The highway is not included in this observation (though present on the map) as no traffic information for all such roads was available. Similarly, a focus on the distribution of traffic flow (Fig. 13) per road category shows a significant increase in traffic flow values from service roads (least) to main roads (greatest). The box plot shows very little dispersion or variation in the distribution of traffic flow for service roads but more variation for the other road categories most especially main roads and small main roads with no overlaps between the categories.
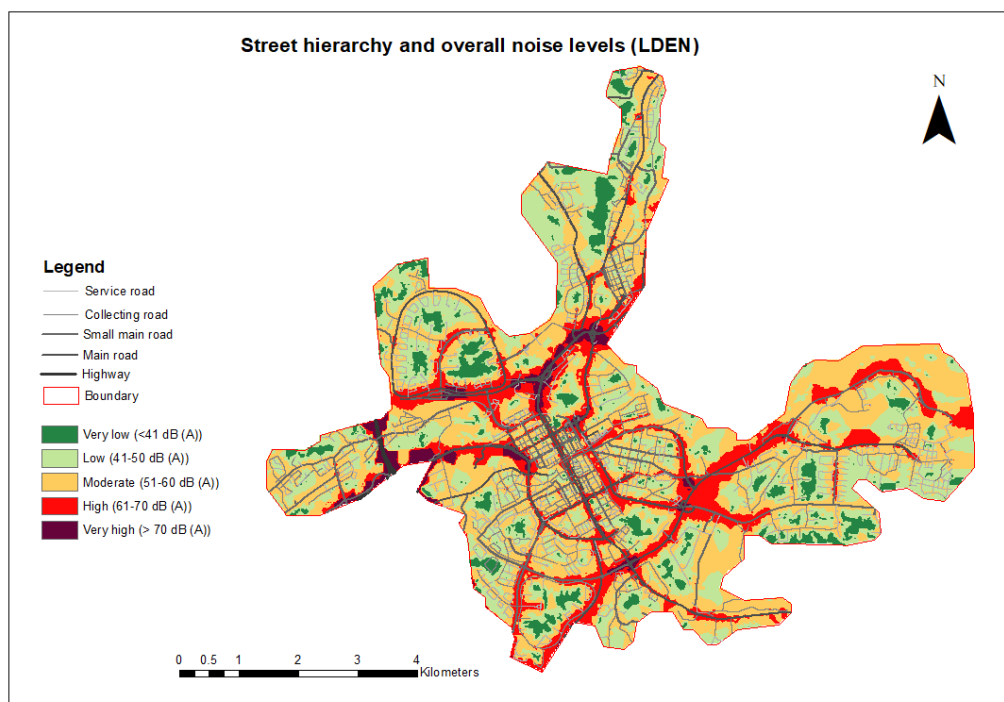
Figure 12. *Street categorization and equivalent noise levels (L_{den})*
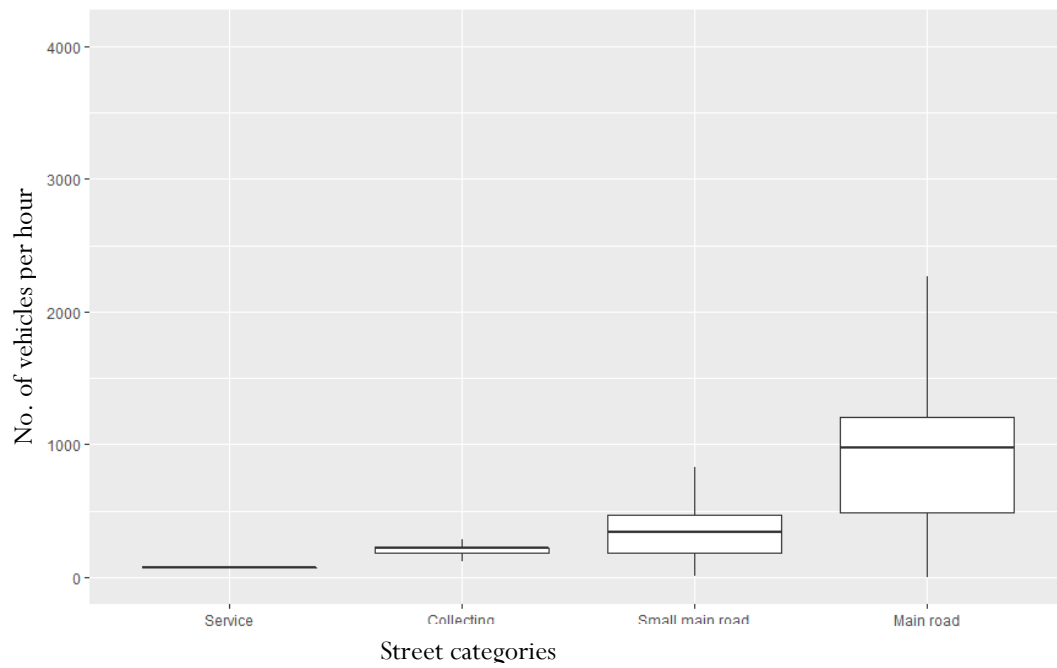
Figure 13. *Distribution of traffic flow (vehicles per hour) by road categories*

4.3   Model performance

To assess the performance of the CNOSSOS-EU method, predicted noise values were compared with the measured samples. Fig. 14 shows a comparison of the observed and predicted equivalent daytime noise levels in the sampled areas. While it shows relatively marginal differences between observed and predicted values for most sample points, there are a few points with significantly large differences between the measured and predicted values.
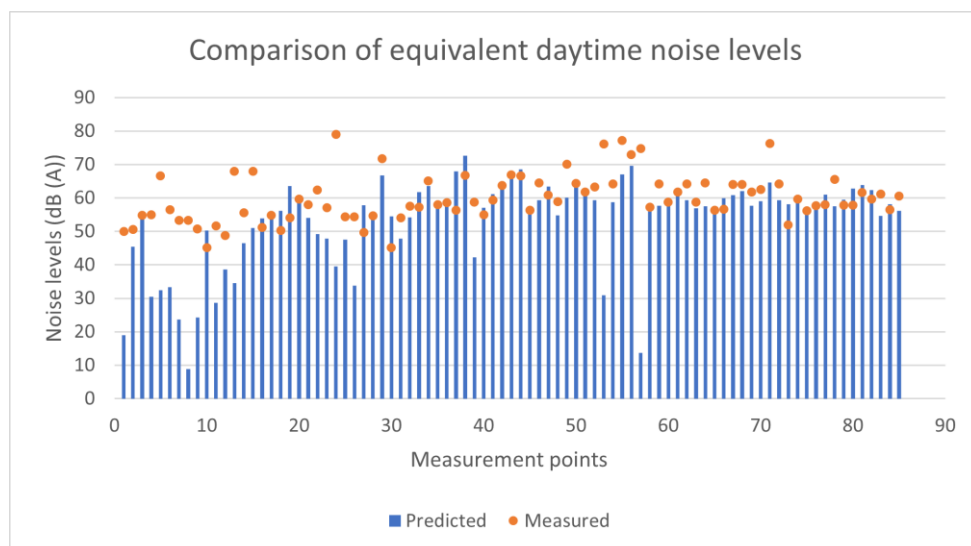
Figure 14. Comparison between measured and predicted noise levels.

4.3.1 Predicted noise vs measured noise (residential)

The measured and predicted values were further disaggregated into the land use designations to identify trends in accuracy for residential areas and areas of mixed land use. In the residential area, 31 points were taken. Of these, 25 points were underestimated from comparing the predicted values to the measured ones whiles seven points were overestimated. Tab.6 is a summary of the difference between predicted and measured values.

Table 6. Noise level difference between predicted and measured values (residential)

Residential			
Point	Predicted	Measured	Difference
1	19	50	-31
2	45.4	50.5	-5
3	56	54.8	+1
4	30.4	55	-25
5	32.4	66.6	-34
6	33.4	56.4	-23
7	23.7	53.3	-30
9	24.3	50.7	-26
10	50.3	45.2	+5
11	28.6	51.7	-23
12	38.7	48.7	-10
13	34.6	67.9	-33
14	46.5	55.5	-9
15	51	67.9	-17
16	53.9	51.2	+3
17	54.7	54.8	-0
18	56.1	50.3	+6
19	63.5	54	+10
20	59.6	59.7	-0
21	54	58	-4
22	49.2	62.3	-13
23	47.9	57.1	-9
24	39.6	79	-39
25	47.6	54.4	-7
26	33.8	54.4	-21
27	57.8	49.6	+8
28	53.7	54.7	-1
29	66.7	71.7	-5
30	54.5	45.1	+9
31	47.8	54	-6
32	54.2	57.5	-3
Mean	**55.7**	**65.9**	**+1**

4.3.2   Predicted noise vs measured noise (mixed land use)

In the mixed land-use area, the measurement differences between predicted noise levels and measured noise levels are shown in Tab. 7. From the 53 sampled points, 21 sample points were overestimated whiles 33 points were underestimated.

Table 7. Noise level difference between predicted and measured values (mixed land use)

	Mixed land use		
Point	Predicted	Measured	Difference
33	61.7	57.2	+5
34	63.6	65.1	-2
35	57.6	58	-0
36	57.7	58.6	-1
37	67.9	56.3	+12
38	72.6	66.8	+6
39	42.3	58.7	-16
40	57.1	55	+2
41	61.1	59.3	+2
42	62.8	63.7	-1
43	66.8	66.9	-0
44	68.5	66.6	+2
45	57.2	56.3	+1
46	59.3	64.5	-5
47	63.4	60.8	+3
48	54.8	58.9	-4
49	60.1	70	-10
50	64.7	64.3	+0
51	61.5	61.7	-0
52	59.4	63.2	-4
53	30.9	76.1	-45
54	58.7	64.2	-5
55	67.1	77.1	-10
56	69.6	73	-3
57	13.7	74.7	-61
58	56.0	57.2	-1
59	57.7	64.2	-6
60	58.6	58.7	-0
61	61.3	61.8	-1
62	59.4	64.1	-5
63	56.9	58.8	-2
64	57.5	64.5	-7
65	57.3	56.3	+1
66	60.0	56.6	+3
67	60.9	64	-3
68	62.1	64	-2
69	57.6	61.7	-4
70	59.1	62.5	-3
71	64.7	76.3	-12
72	59.3	64.2	-5
73	58.1	51.9	+6
74	58.9	59.7	-1
75	56.2	56.2	+0
76	58.6	57.7	+1
77	61.0	58	+3
78	57.5	65.6	-8
79	59.5	57.8	+2

80	62.8	57.8	+5
81	63.9	61.6	+2
82	62.3	59.7	+3
83	54.7	61.2	-6
84	58.1	56.5	+2
85	56.1	60.5	-4
Mean	**62.6**	**67.04**	**+1**

4.3.3 Underestimations at hidden facades

As a result of assumptions made for diffraction, geometric divergence, and atmospheric condition, it is expected that the farther away a point is from a noise source (by distance and location of façade), the greater the probability for error. All the measured points were grouped into exposed and hidden (not exposed) facades. This is shown in Tab. 8 below. It shows that for all hidden facades, the predicted levels were underestimated mostly by large margins exceeding 20dB (A).

Table 8. Noise level differences (predicted vs measured) at hidden facades per land use

Sample point	Predicted	Measured	Difference	Land use
1	19.0	50.0	-31.0	Residential
2	45.4	50.5	-5.1	Residential
4	30.4	55.0	-24.6	Residential
5	32.4	66.6	-34.2	Residential
6	33.4	56.4	-23.0	Residential
7	23.7	53.3	-29.6	Residential
8	8.9	53.3	-44.4	Residential
9	24.3	50.7	-26.4	Residential
11	28.6	51.7	-23.1	Residential
12	38.7	48.7	-10.0	Residential
13	34.6	67.9	-33.3	Residential
14	46.5	55.5	-9.0	Residential
24	39.6	79.0	-39.4	Residential
25	47.6	54.4	-6.8	Residential
26	33.8	54.4	-20.6	Residential
39	42.3	58.7	-16.4	Mixed
51	61.5	61.7	-0.2	Mixed
53	30.9	76.1	-45.2	Mixed
57	13.7	74.7	-61.0	Mixed

4.3.4 Correlation and Regression analyses results

The results for the test of the degree of association between predicted and measured noise values together with their linear relationships are presented in the figures (15-

20) below. The results are further summarized in Tab. 9. The analysis of all 84 pairs revealed a low degree of association between predicted and observed values with a correlation coefficient of 0.21. The analysis was run again after outliers (all differences greater than 10 dB (A)) were removed. The results showed a stronger degree of association between the predicted and measured values with a correlation coefficient of 0.69.
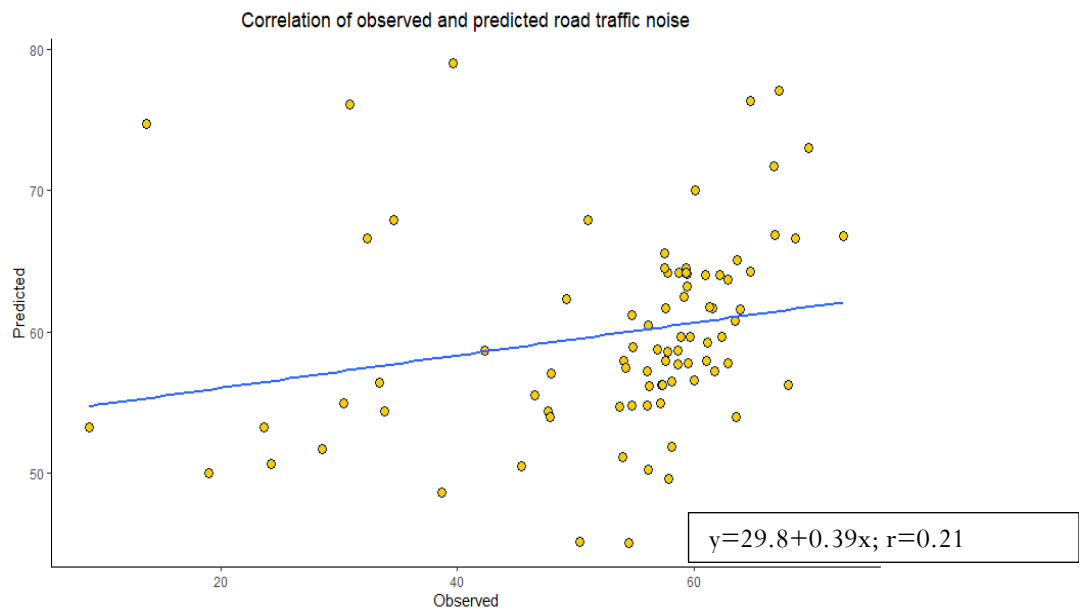

Figure 15. *Correlation of observed and predicted road traffic noise levels*
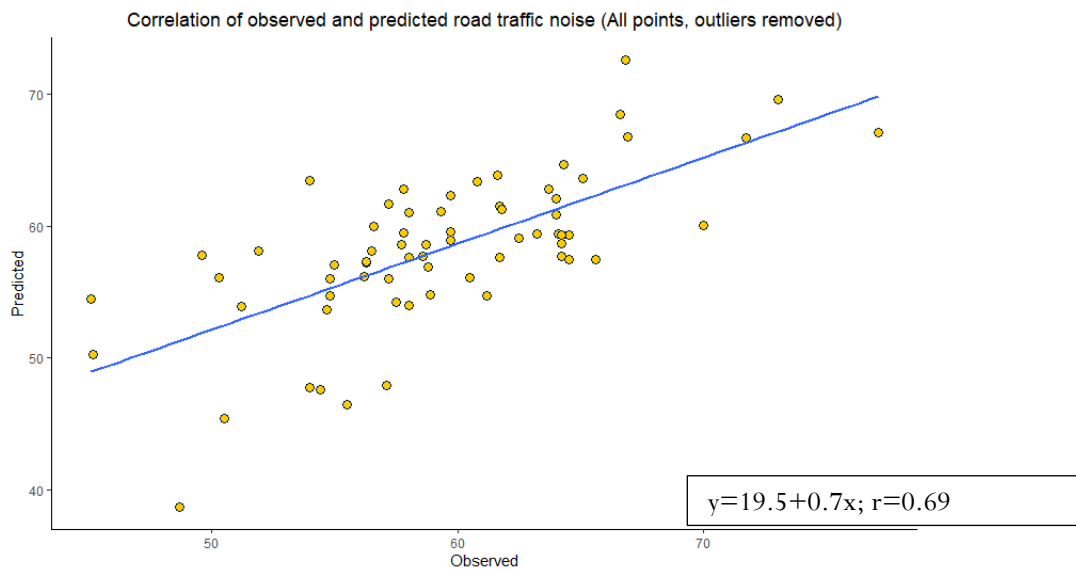

Figure 16. *Correlation of observed and predicted road traffic noise levels excluding outliers*

When grouped according to land use designations, predicted noise levels in residential areas showed a weak positive association with the measured levels with a correlation coefficient of 0.09. With the exclusion of outliers (12 pairs), the strength of the association increases giving a correlation coefficient value of 0.5. The correlation analyses for these are seen in the figures below.
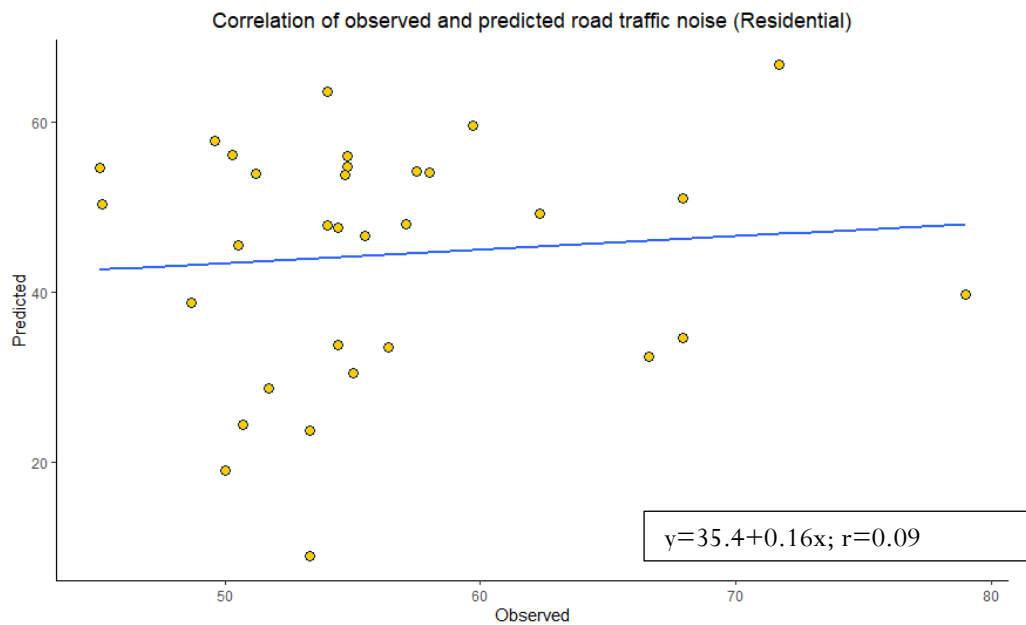

Figure 17. *Correlation of observed and predicted road traffic noise levels in residential areas*

Figure 18. *Correlation of observed and predicted road traffic noise levels in residential areas excluding outliers*

For sample points in mixed land use designations, a weak negative association was initially found between predicted and observed values with a correlation coefficient of -0.2. With the exclusion of outliers (5 pairs), a strong positive association is observed with a correlation coefficient value of 0.6. The regression analyses for these are seen in the figures below.
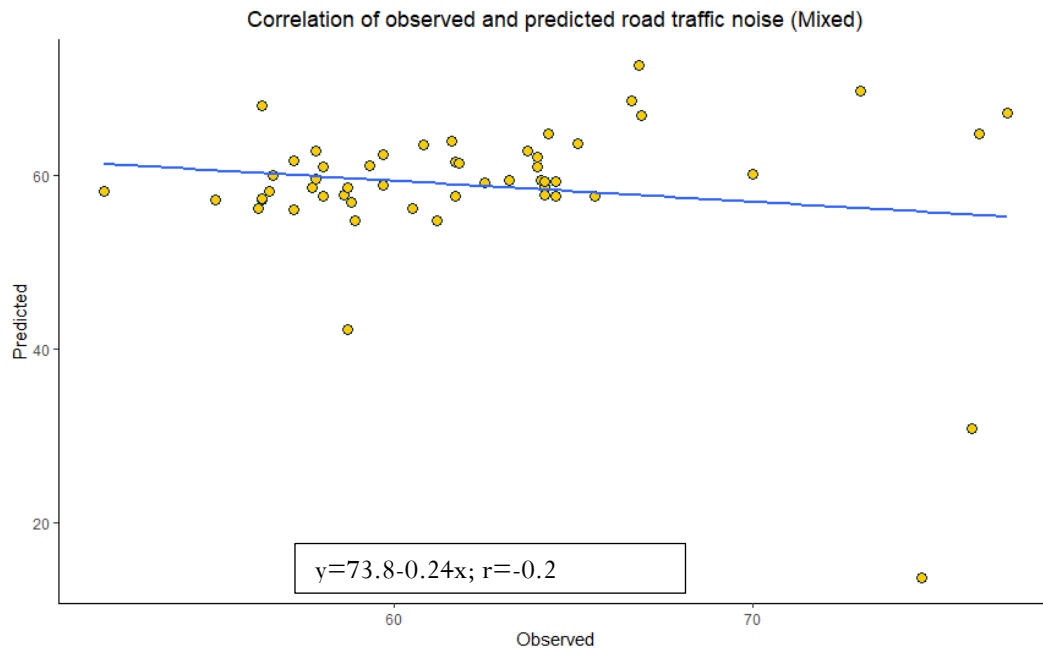
Figure 19. *Correlation of observed and predicted road traffic noise levels in mixed land use areas*
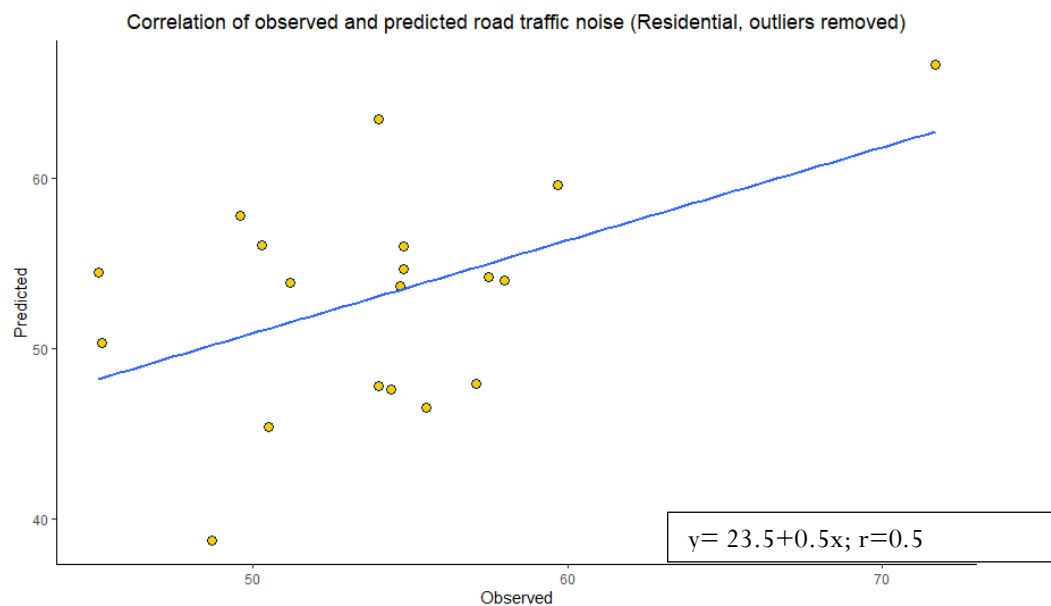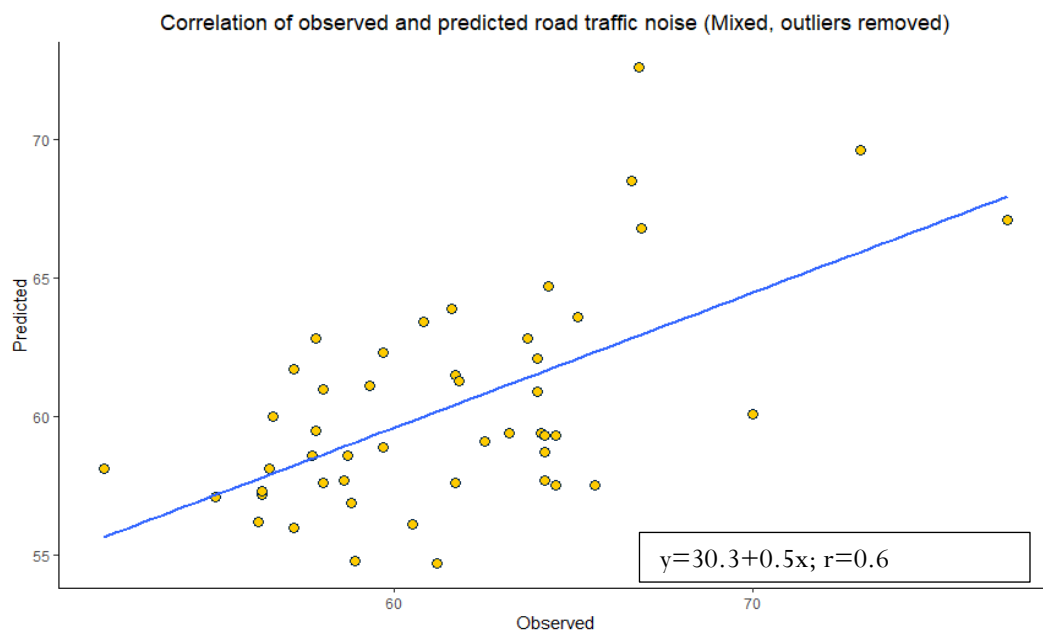

Figure 20. *Correlation of observed and predicted road traffic noise levels in mixed land use areas excluding outliers*

Table 9. Summary table of regression parameters

	All points	All outliers removed	Residential all	Residential outliers removed	Mixed all	Mixed outliers removed
Slope	0.39	0.7	0.16	0.5	-0.24	0.5
Intercept	29.8	19.5	35.4	23.5	73.8	30.3
Correlation Coefficient	0.21	0.69	0.09	0.5	-0.2	0.6

5 Discussion

This section takes a closer look at the results obtained in the study in comparison with existing knowledge especially on noise exposure effects and thresholds for the various noise indicators. Also, the methods employed in the study and how they influence the overall validity of the results obtained are discussed.

5.1 Predicted noise levels and exposure effects

The maximum noise levels predicted for L_{day} (85 dB (A)), $L_{evening}$ (80 dB (A)), L_{night} (75), and L_{den} (85 dB (A)) are very high and are a cause for concern. While these noise levels are predicted for relatively small portions of the study area (Tabs. 3, 4, 5), they have implications to the people that may be exposed to these levels by way of commuting through the area or because people may reside in these areas. This is a major problem where noise pollution is concerned. It affects the entire population albeit in varying degrees. Noise exposure studies (Berglund et al., 1995; World Health Organization, 2009) have shown noise thresholds beyond which become harmful to health and wellbeing. Therefore, while the noise maps presented in the study may refer to a noise exposure class as low in relation to another exposure class, it may not be free from affecting people negatively and may therefore be more beneficial to pay attention to the known thresholds.

For instance, for daytime periods, a noise level above 55 dB (A) is a good indicator of the measure of annoyance in people (Berglund et al., 1995). From Tab 3, a significant difference can be seen between the areal coverage of noise levels that exceed the 55 dB (A) limit for the entire study area (31%) and the smaller populated part (40%). The same can be seen for L_{eveing} results (Tab. 4) at the same threshold as L_{day}. The areal coverage of harmful noise levels is significantly higher in the built-up area (32%) than in the entire study area (19%). L_{night} (33% vs 62%) and L_{den} (66% vs. 95%) results follow the same pattern at even wider margins than in the day and evening periods. This is because noise levels exceeding 40 dB(A) cause sleep disturbance and general annoyance for nighttime, and overall 24-hour periods (European Environment Agency, 2010). Exposure to harmful noise levels is much higher and affects a larger area in the urban populated area than it does in the entire study area. The result tables also show many buildings situated within these noise classes. According to SCB (2020), 94.2% of people in Gävle live in the urban area. This translates to approximately 96,935 persons exposed to high noise levels.

5.2 Traffic variables and Street categorization

The conditions of road traffic form the foundation for road traffic noise modelling. Knowledge of traffic variables such as traffic flow, vehicle type, vehicle speed, and road condition are combined with other environmental variables to estimate noise levels for any given area. Of these variables, traffic flow is known to have the greatest influence on the levels and variability of urban road traffic noise. As such traffic flow is often used to stratify or categorize streets before sample data is obtained for noise modelling in the form of Average Daily Traffic (ADT) and Annual Average Daily Traffic (AADT). In this study, streets were categorized (into service, collecting, small main roads, main roads) per the guidelines described in the Good Practice Guide for strategic noise mapping ((European Commission Working Group Assessment of Exposure to Noise (WG-AEN), 2006)). Consequently, the noise maps reflect the underlying street categories used in the prediction method (see Chapter 3). The highest predicted noise levels: 85 dB (A) L_{day}, 80 dB (A) L_{eveing}, 75 dB (A) L_{night}, and 85 dB (A) L_{den} were found on and around the highway. Moderate to high noise levels outside of areas surrounding the highway were consistent with the main roads and small main roads. Low noise levels were consistent with collecting roads whiles very low noise levels were consistent with service roads.

Street categorization predominantly by traffic flow has become the choice method for obtaining sampling points for noise modelling. This is because of its relative simplicity in comparison to older methods like the grid method. Barrigón Morillas et al. (2005) mention that the results from the grid method are dependent on the grid size used and the process is cumbersome. Alternatively, street categorization by traffic flow before sampling has shown to be simple but effective. The method is considered objective and free from observer bias during sampling (Gómez Escobar & Pérez, 2018) provided definitions for each street category are made clear. A key principle for validating the categorization of traffic variables for noise modelling is the independence of the categories. That is, there should be no overlap in the distribution of the traffic variable (eg. traffic flow) between street categories. In this study, all street categories were independent of each other (see Fig. 13). Studies dedicated to assessing the effectiveness of street categorization have been largely successful.

Some studies have also performed street categorization according to street function. For instance, Barrigón Morillas et al. (2005) performed an assessment of noise levels in five medium-sized Spanish towns using a preset classification of streets based on their function. This method relies on the known street hierarchy and street connectivity. In this sense, this method is subjective in comparison to street categorization according to traffic flow. Gómez Escobar & Pérez (2018) compared street categorization by ADT and street function. They observed that the ADT

method outperforms the street function method in the ability to yield independent classes.

5.3 Model performance

It is imperative to mention that noise prediction results must be validated with measured observations with sufficient measuring intervals representative of the noise indicator period. Yearly average exposure indicators ideally require long measuring campaigns at different times of the year. In this study, 60-second equivalent noise levels were measured and compared with the predicted L_{day} levels.

5.3.1 Predicted vs Measured noise levels

A comparison of the measured 60-second equivalent daytime noise levels with the predicted ones shows that the model performed quite well. This can be seen from the mean noise difference between the predicted and measured levels (Tabs. 6 and 7) disaggregated into residential and mixed land use areas, respectively. The overall mean of predicted and observed noise levels was similar in both land use cases. For residential areas, the mean of predicted noise was 55.5 dB (A) while 65.7 dB (A) was obtained for measured values. The mean difference between each measured point and its predicted value was however only +1dB (A). For points in the mixed land-use area, the mean of predicted noise was 62.6 dB (A) while a mean of 67 dB (A) was realized for measured noise. The average of differences between observed and predicted levels at the measured points was +1 dB (A). The values obtained are below the ±2 dB acceptable error margin as stated by Murphy and King (2014).

Also, the correlation analysis performed between observed and predicted values showed an initial low degree of association between observed and predicted values. This was however realized because of the influence of large errors in observed values (underestimations and overestimations). These values were considered as outliers and removed from further analyses. After the removal of these outliers, strong correlation coefficient values were observed for all paired points as well as when disaggregated into the residential and mixed land use classes (See Figs. 15-20 and Tab. 9).

By looking at the number of underestimations to overestimations regardless of the land use designation, 58 predicted levels were underestimated whiles 27 predicted levels were overestimated. While differences in overestimations were marginal, large differences could be observed in the underestimated values. This can in part be attributed to the type of façade (Tab.8). Hidden facades are calculated by considering parameters for building diffraction, the assumptions for this thereby introducing errors. Khan et al. (2021) mention that the algorithms for diffraction together with ground attenuation and the definition of the mean ground plane in the CNOSSOS-EU

method cause inaccuracy in predicted noise levels. Also, many underestimations in predicted levels were found in residential areas. Such areas are interspersed with green spaces that help promote well-being. The noise levels measured in these areas can be attributed to other environmental, but still noise, sources such as the rustling of leaves and the chirping of birds and not to road traffic alone. As traffic flow in residential areas is considerably lower than for instance in commercial areas, and given the short measurement period, this assumption can be trusted.

Furthermore, the underestimations observed for residential areas can also be attributed to the weaknesses inherent in the CNOSSOS-EU model. Can et al. (2016) mention that static models based on averages of traffic variables are unable to predict variations in sound levels. Also, energetic, and composite indicators such as the L_{den} while performing well for assessing long-term exposure effects, are poor in the perceptive evaluation of urban noise. In residential areas, fluctuations in sound levels are high because single noise events such as an occasional passing of a vehicle interspersed with long periods of background noise are dominant. Coupled with the influence of other noise sources, noise level predictions will most likely be inaccurate. Bastián-Monarca et al. (2016) rightly mention that for streets in residential neighbourhoods, vehicular traffic is not the main noise source. To overcome the limitation of energetic indicators, it is possible to assess noise levels using two indicators. That is one energetic indicator for long-term exposure in conjunction with a parameter to quantify sound fluctuations. For instance, Brambilla et al. (2020) successfully classified urban noise using L_{Aeq} and the intermittency ratio (IR),

5.3.2 Sources of uncertainty and errors

Environmental noise is a complex and computationally burdensome process. For road traffic noise, there are several parameters to be considered and used. However, data availability and the need for reasonable computational times call for simplifying assumptions and work-around methods for many parameters. There are ongoing efforts to make the process less cumbersome. For instance, Murphy and King (2016) explored the possibility of integrating sound-level data obtained from smartphones into the noise mapping process as a potential substitute for traffic data. Such ideas hold promise for facilitating the noise mapping process.

In this study, a few assumptions had to be made. First, the method used did not include all attenuation parameters stated in the CNOSS-EU documentation. Attenuation due to ground reflection and terrain were not considered. It is difficult to find a method that fits all and even more so for places where complete data is unavailable. On data availability, road traffic data was used. Attributes include vehicle flow or intensity and vehicle speeds for all vehicle categories and all roads. Available data covered selected roads in the city. This was extrapolated for roads for which no data was available. Extrapolation could not be done for the European road as this is

not advised by the Good Practice Guideline. The default values assigned to them before interpolation may not be accurate. Again, the available data for powered two-wheeled motorcycles was not specified as belonging to the <50 CC category or > 50CC category. The worse scenario was chosen in this study (> 50 CC). Because the terrain was not considered, noise barriers were also not included in the modeling process. Lastly, the 60-second equivalent noise levels collected as ground truth data may not reflect the true traffic environment especially as it was compared to a long-term (predicted) indicator. Regardless of these, the study produced good results and the difference between predicted and measured levels were within an acceptable margin.

5.4   Environmental sustainability considerations

Environmental noise is one of the many challenges in all countries, developed and developing alike. More specifically, road traffic noise levels affect the largest number of people than all other noise sources. Epidemiological studies continue to establish cause-effect associations between exposure to road traffic noise and poor health ranging from general well-being and comfort to severe clinical conditions (Babisch et al., 2013; Sørensen et al., 2012; World Health Organization, 2009). Sustainability in urban areas continues to wane not only from road traffic noise. The addition of air and water pollution makes for a complex problem. For the urban landscape to be more sustainable, and capable of promoting good health and well-being, concerted efforts must be made in research, and policy to address the problem, especially on local scales. Noise prediction continues to be an overly technical and cumbersome process. Gaps exist in the communication of noise levels and their implication for all life in the urban space. Citizen science initiatives must be encouraged and new pathways to the prediction of noise levels must be advocated. Noise mitigation measures should include land use planning, and citizen engagement to existing mitigation measures if a reduction in noise levels can be achieved in the future.

6 Conclusion

Environmental noise from road traffic sources continues to be a major concern not only in urban areas but also in green areas. As such, the health and well-being of the urban populations as well as for biodiversity in areas surrounding cities to a large extent depends on a good overview of noise levels from road traffic in the urban landscape on a regular basis. This study employed open-source GIS to model road traffic noise pollution for the mid-sized city of Gävle using the CNOSSOS-EU method for four noise indicators.

The city experiences maximum equivalent day, evening, night, and daily average noise levels of 85, 80, 75, and 85 dB (A) respectively. A reclassification of the noise maps into noise exposure classes (very low, low, medium, high, and very high) to the exposure effect threshold for each noise indicator showed continuously high noise levels with increasing human exposure to higher noise levels for the evening and the 24-hour periods. This points to poor overall sound quality as large proportions of the urban space experience noise levels above threshold limits which trigger annoyance and sleep disturbance.

Noise levels over the study area were found to follow the various street categorizations used. Areas around the most trafficked streets had high noise levels while areas around the least trafficked streets found in residential areas and serving a small subset of the urban population had low noise levels below the exposure effect threshold values. The highest noise levels across all indicator types were found on the highway which is located outside of the populated area but directly intersects vast forest lands.

Predicted noise levels performed well when compared with 84 points of 60-second equivalent noise levels taken in residential and mixed land use classes. The mean difference between predicted and measured points was less than 2 dB (A), although significant underestimations (outliers) were made for hidden facades in residential areas. Also, correlation and regression analyses performed on observed and predicted values showed an initial weak correlation and linear relationship. The removal of outliers improved the analysis showing a strong linear relationship between observed and predicted noise values with a correlation coefficient value of 0.69. These outliers obtained in observed values can be attributed to the assumptions made for attenuation due to building diffraction, as well as the influence of other noise sources other than road traffic in the residential areas.

The result of the model is promising for the relatively new CNOSSOS-EU method. The apparent weakness in the noise indicator choice is the limitation in revealing fluctuations in sound levels. As is the case with all noise indicators, no method fits all, and a single noise indicator may not be enough to fully describe noise levels in a given

area. The same is true for selecting a noise model. No ideal method exists, as such, a comparison of different models should be explored and a model best suited to the specific urban reality adopted. This can be a consideration for future works in the study area. The use of the OpeNoise in open-source GIS is a commendable contribution to the efforts made to simplify the noise modelling process without compromising on the accuracy of results. The method incorporates three different prediction models giving users the flexibility to choose a model that suits their data at hand, or the model known to best reflect the urban noise nature. The method also allows users to be creative with input data for modelling. That said, a limitation of the method is that it does not consider the influence of terrain and reflections. Therefore, it does not fully implement the CNOSSOS-EU model. Given the rapid development and use of such tools, it is possible these can be incorporated in the future.

Despite past and present efforts to reduce road traffic noise levels, they continue to rise and affect not only humans but plants and animals as well. Noise levels must be assessed for all urban areas regardless of size to inform land-use planning. Should this be coupled with mitigation measures at noise sources, road traffic noise levels may begin to reduce in some years to come.

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Appendix A

Table 1. Vehicle Designations from measured data to CNOSSOS-EU vehicle classes.

Vehicle	Description	CNOSSOS vehicle category
MC	Motorcycles	
P20/ Passenger car	Passenger vehicle with 2 axles and no trailer	Light motor vehicles
P21	Passenger vehicle with 2 axles and trailer with one axel	
P22	Passenger vehicle with 2 axles and trailers with 2 axels	
L20	Truck with 2 axels and no trailer	Medium-heavy vehicles
L21	Truck with 2 axels and a trailer with 1 axel	
L22	Truck with 2 axels and trailers with 2 axels	
L23	Truck with 2 axels and trailers with 3 axels	
L24	Truck with 2 axels and trailers with 4 axels	
L30	Truck with 3 axels and no trailer	Heavy vehicles
L31	Truck with 3 axels and a trailer with 1 axel	
L32	Truck with 3 axels and trailers with 2 axels	
L33	Truck with 3 axels and trailers with 3 axels	
L34	Truck with 2 axels and trailers with 4 axels	

Table 2. Calculations for measured points

Point	y	x	Total Leq	Average	dB value
1	6730103	615883	6019713.7	100328.6	50
2	6730148	615877	6733485.3	112224.8	50.5
4	6730113	615870	18123214.8	302053.6	54.9
5	6730080	615863	19293747.5	32152.45	55.1
6	6730044	615810	275926082.1	4598768.035	66.6
7	6730051	615805	26297611.39	438293.5232	56.4
8	6730051	615805	13002397.22	216706.62	53.4
10	6730182	615748	707400.464	117911.6744	50.7
12	6730234	615726	2002653.737	33377.56	45.2
13	6730036.1	615839.88	8851385.498	147523.0916	51.7
14	6730118.1	615772.253	4402766.663	73379.4	48.7
16	6729980.3	615888.388	30466680	507228	57
17	6729985.8	615911.483	369115178.1	6151919.635	67
19	6729926.8	616085.347	21218075.27	353634.5878	55.5
21	6729922.7	615930.867	372732247.3	6212204.121	67.9
22	6729905.9	615879.35	7825117.573	130418.6	51.1
23	6729915.4	615863.166	18169584.01	302826.4	54.8
24	6729857.9	615909.029	6356864.15	105947.73	50.2
25	6729798.2	615980.032	15185115.9	253085.26	54
26	6729798.2	615980.032	56321467.62	93691012	57.9
27	6729785.8	616051.345	37631872.4	627197.8	57.9
28	6729738.3	616130.486	101345045.5	1689084.091	62.2
29	6729717.1	616140.885	31096854.52	5182809.086	57.1
30	6730336.8	614686.232	4777794376	7962990806	79
31	6730231.3	614656.656	1048885.56	7174814.27	52.4
32	6730284.5	614921.764	5474191.3	91236.5	49.6
33	6728682.8	616408.753	17504733.5	291745.5	54.6
34	6728656.2	616434.761	878283832.2	14638063.8	71.65
35	6728647.7	616441.703	1934840.5	32247.34	45.08
41	6728536.5	616574.013	33792577.5	563209.6	57.5
42	6728497.5	616592.005	31783875.3	529731.2	57.24
43	6728567.2	616673.954	192104370.5	320139.5	65.5
44	6728654.8	616813.738	142163647.1	2369394.118	63.74
45	6728770.5	616828.901	274703992.9	4578399.882	66.8
46	6728861.6	616775.106	25533855	425564.2	56.2
47	6728787.1	616583.766	168649259.9	2810820.9	64.5
48	6728813.6	616859.762	72502507	1208375	60.8
49	6728836	616923.495	470.13647	783560.8	58.9
50	6728931.3	616855.519	596430788.7	9940513.145	69.9
51	6729000.6	616811	161357821.9	2689297.032	64.2
52	6728975.8	616927.888	88798144	1479969	61.7
53	6728950.7	616972.65	124377734	2072962.23	63.1
54	6728866.3	616976.535	2463216681	41053611.35	76.1
55	6728799	617004.612	157687668.7	2628127.812	64.1

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56	6728807.5	617113.266	3049767730	508829462.2	77.06
57	6728800.2	617115.51	1182517293	19708621.55	72.9
58	6728740	617110.563	1755322363	29255372.72	74.6
59	6728704.8	617104.318	31531091	525518.2	57.2
60	6728725.6	617180.441	159184086	2653068.1	64.2
61	6728668.5	617255.598	44187104	736451.7	58.6
62	6728497.4	617384.746	91424191	1523737	61.8
63	6728354.7	617107.662	155969653.9	2599494.232	64.1
64	6728311.3	617048.457	348347593	5805793.21	67.63
65	6728269.5	617001.466	22856653	380944.2	55.8
66	6728336.9	616841.649	171499736	2858328.93	65.5
67	6728381	616789.371	25792178	429896.6	56.4
68	6728381	616789.371	27658145	460969.1	56.6
69	6728540.3	616823.003	89535816	1492264	61.7
70	6728527.9	616753.63	106969210.3	1782820.171	62.5
71	6728563.4	616680.399	425072704.1	42507270.41	76.2
72	6728619.7	616682.108	158885923.2	2648098.72	64.2
73	6728607.5	616548.852	58219398	970323.3	59.8
74	6728204.9	616855.158	56607313	943455.2	59.7
75	6727954.3	616945.893	24925455	415424.2	56.1
76	6727976.1	616998.391	34946617	582443.6	57.6
77	6727889.4	616999.456	37690194	628169.9	57.9
78	6727813.1	616921.605	44067514	3672293	65.6
79	6727763	616941.656	35888435	598140.58	57.7
80	6727836.2	617092.129	36280084	604668.1	57.8
81	6727828.5	617136.599	87502572	1458376	61.6
82	6727087.8	617196.014	55481622	924693.7	59.65998
83	6727749.4	617245.312	78607107	1310118	61.7
84	6727687.9	617202.357	26742514	445708.6	56.4
85	6727577.1	617265.3	68613522	1143559	60.6

Appendix B
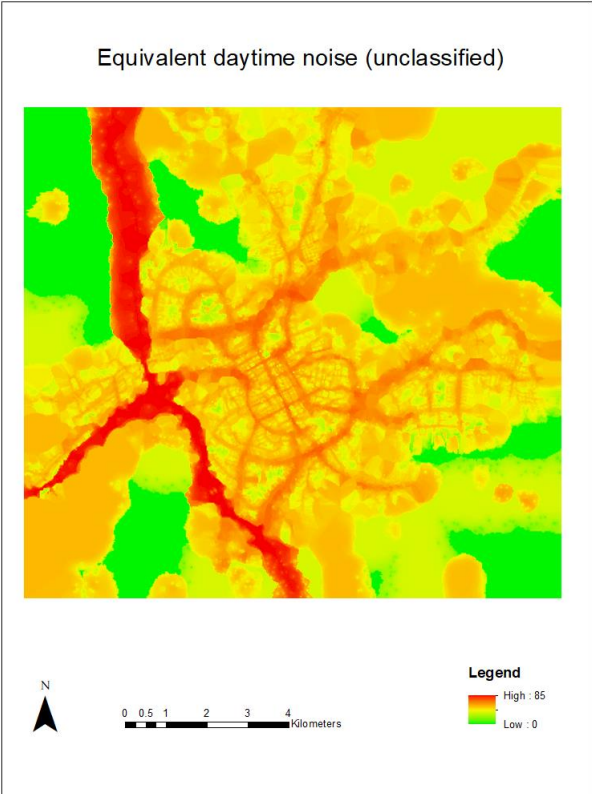
Figure B1. Unclassified noise map, L_{day}
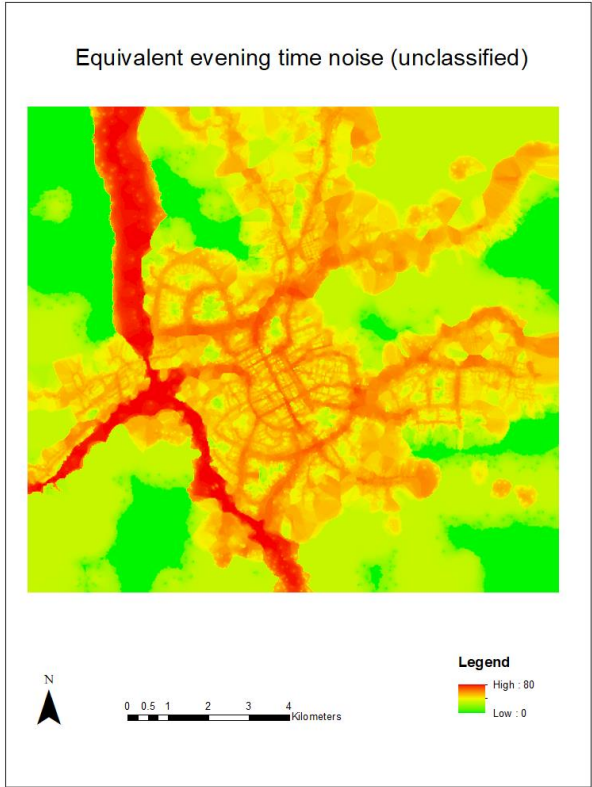

Figure B2. Unclassified noise map ($L_{evening}$)
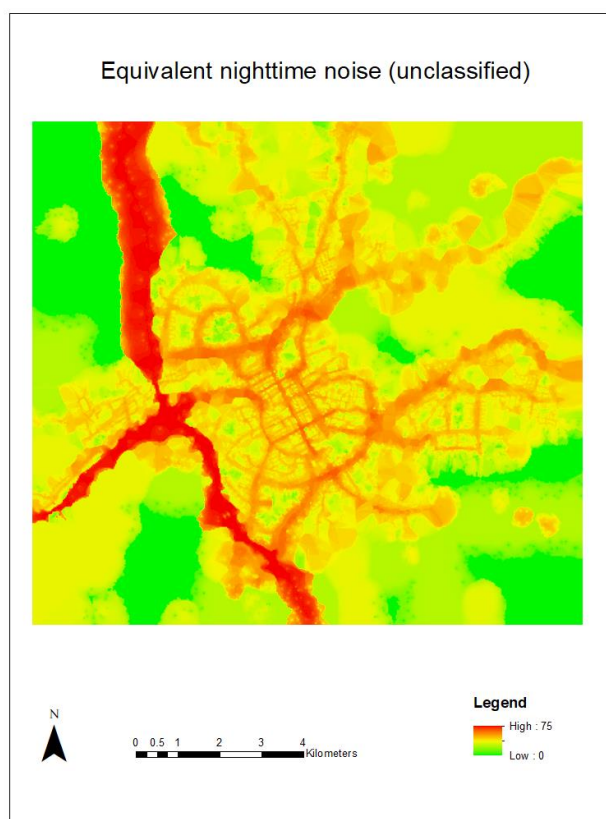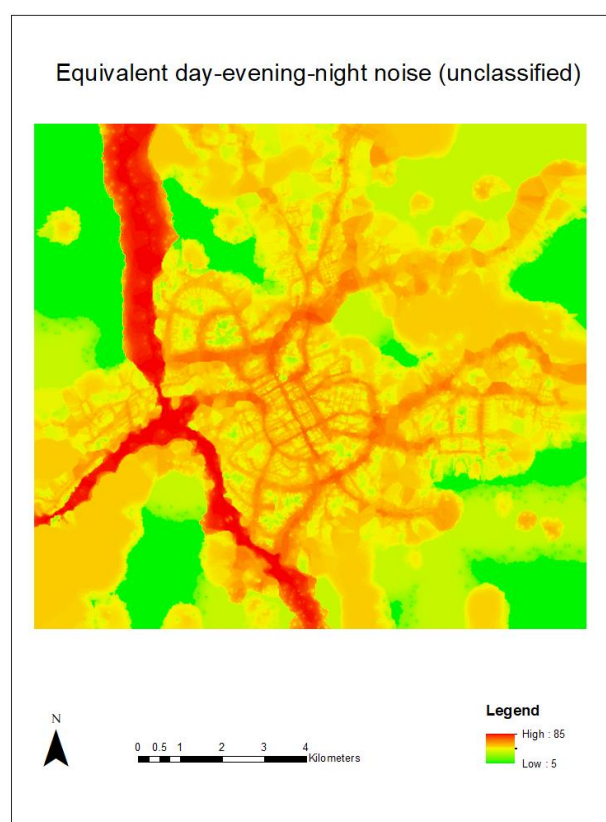
Figure B3. Unclassified noise map (L_{night})

Figure B4. Unclassified noise map (L_{den})

B2