Mapping of PM_{10} from domestic heating with firewood in Rotorua, New Zealand

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Contents

Summary

Exposure to particles (PM_{10}) may cause heart and respiratory diseases, especially among vulnerable groups such as asthmatics, elderly people and children. In New Zealand, new national standards for PM_{10} came into force in September 2005. The city of Rotorua has been found to exceed the guideline, which is based on a 24-hr average of $50\mu g/m^3$ with a maximum of one exceeding per year. Therefore countermeasures have to be taken to reduce the levels before 2013.

An important early step in finding ways to reduce the levels of PM_{10} is to analyse the main sources of PM_{10} in the city. The main hypothesis of the study were that the use of spatial analysis would give a more sophisticated understanding of air emission patterns in Rotorua to help identify “smart” policy strategies.

Domestic heating with firewood is regarded as one of the main contributors of particles in urban areas. Therefore the focus if the study was to analyse the emissions from domestic heating with firewood. The goal was to map the emission sources to see to what extent firewood contributes to the levels of PM_{10} in air. Spatial analysis of the data thereafter allowed analysis of where in the city the largest emissions occur. A number of simple technology scenarios for domestic heating in Rotorua was analysed to analyse how emissions from domestic heating in Rotorua was studied to analyse how emissions from domestic heating may change in the future as a result of new, more environmentally friendly technique. Furthermore, the calculations are compared with an earlier emission inventory from 2003. The methods used are calculations based on statistics and emission factors, as well as mapping and modelling in Geographical Information Systems (GIS). The study should be regarded as a preliminary study.

The analysis shows that the amount of PM_{10} emitted from existing combustion of firewood for domestic heating in Rotorua is near 330 tonnes per year. If all existing firewood stoves in Rotorua would be converted to wood pellet stoves, the emissions would decrease with nearly 95 %, to 14 tonnes per year. If all dwellings in the city that does not use bioenergy based heating today, would be converted to wood pellet stoves (i.e. converting from electric heating to heating with wood pellets), emissions of PM_{10} will only increase with 5 percent. This is if none of the existing firewood stoves are replaced with any other heating source. If all dwellings in Rotorua use pellet stoves for domestic heating, the emissions of PM_{10} from bioenergy based heating would be near 30 tonnes per year, i.e. 90% less than from existing firewood stoves.

Introduction

Air pollutants mainly arise from combustion processes and have existed as long as humans have used the fire. Traces of air pollutants from indoor cooking over open fires have been found in archaeological investigations [1]. However, the negative impacts caused by poor air quality were not discussed before the industrial revolution. During 1950 it was found that mortality and cases of bronchitis increased during episodes with high concentrations of particles, soot and sulphur dioxide in air [2]. The atmosphere consists of a number of gases and particles, the dominating ones are nitrogen (78 percent), oxygen (21 percent), argon (0.93 percent) and carbon dioxide (0.35 percent) [3]. The distribution of substances in air is not homogenous, it varies in both time and space and sometimes concentrations becomes so high that they are hazardous to human health or to the environment. Air pollutants are defined as gases or particles that, at certain concentrations, cause direct or indirect damage on physical or biological systems. The substances that are most hazardous to human health is particles, nitrogen oxide and carcinogenic substances such as VOC (Volatile Organic Compounds) and PAH (Poly Aromatic Hydrocarbons).

Particles are divided into classes due to size and they do not consist of any defined substance and vary in the chemical composition and shape. The most common classes are PM_{10} and $PM_{2.5}$ respectively. Particles are formed during incomplete combustion of biofuels, coal and oil, during photochemical reactions and from mechanical damage. Health effects caused by exposure to particles are a relatively new field of research. For a long period of time, particles were only considered as an irritating pollutant without any real threats to human health. Nowadays it is known that particles may cause heart and respiratory diseases, especially among vulnerable groups such as asthmatics, elderly people and children [2, 4, 5].

In New Zealand, new national standards for air quality came into force in September 2005. The standards cover particles (PM_{10}), carbon monoxide (CO), nitrogen dioxide (NO_2), ozone (O_3) and sulphur dioxide (SO_2) [6]. The city of Rotorua has been found to exceed the guideline of PM_{10} which is 50µg/m^3 per 24 hr [7] and Rotorua has therefore been designated as a Local Air Management Area. This means that a reduction of the emissions of PM_{10} has to be made before 2013 so that it does not exceed the standard. To improve the air quality and to find ways to reduce the levels of PM_{10}, one important step is to collect information and analyse the main sources of PM_{10} in the city. Firewood used for domestic heating is one contributor of PM_{10}. Its contribution is however difficult to determine as the emissions vary a lot depending on fuel quality, moisture of the fuel, technique used and way of managing the fire. Emissions of PM_{10} from motor vehicles consist of combustion-particles and particles from damage of roadways, wheels and breaks. Natural sources from geology and meteorology also affect the actual concentrations.

The main aim of this study is to analyse the emissions from one important source of PM_{10} in Rotorua, domestic heating with firewood. The goal is to map the emission sources to see to what extent firewood contributes to the levels of PM_{10} in air. Furthermore GIS based analysis allows identification of where in the city the largest emissions occur. A number of scenarios for domestic heating in Rotorua is analysed to give an indication of how emissions from domestic heating may change in the future, as a result of new, more environmentally friendly technique. The calculations are compared with an earlier emission inventory from 2001[8].

Methods

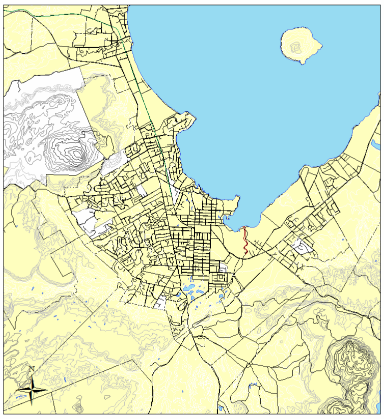
The main focus in this study was put on the domestic heating sector in Rotorua. Emissions from dwellings that today are using firewood stoves for heating was calculated. Furthermore, a number of simple technology scenarios for domestic heating in Rotorua were set up to analyse how emissions from domestic heating may change in the future as a result of new, more environmentally friendly technique.

The calculations are compared with an earlier emission inventory from 2003. The methods used are calculations based on statistics and emission factors, as well as mapping and modelling in Geographical Information Systems (GIS). The study should be regarded as a preliminary study.

Emission factors from small scale bioenergy combustions are relatively difficult to predict since the emissions depend on many different factors, for example combustion equipment, energy need for heating and the meteorological conditions in the concerned area. The background concentrations from other sources also affect the concentrations found in a particular area.

Study area

The area analysed was city of Rotorua, situated in Bay of Plenty on the north island of New Zealand, see map.1.



Map 1. Rotorua

Domestic heating, data and assumptions used

In the urban area of Rotorua, there are 22 685 dwellings and in 11 691 of them, a firewood based heating unit is installed [9]. In this study, five different scenarios were calculated to cover the situation today as well as in the future. The scenarios concerning future domestic heating options with bioenergy were performed in line with the ongoing project 100% Renewable Energy Rotorua, initiated by Scion

Research Institute. 100 % Renewable Energy Rotorua aims to assist decision makers in determining policies that turns the city of Rotorua into a 100 percent renewable energy city [10]. All calculations in this study were made on a meshblock basis for Rotorua and the appliances used were firewood stoves and modern pellet stoves. Meshblock is the smallest area where Statistics New Zealand's statistical data is publicly available. The size of a meshblock depends on the number of inhabitants and type of area covered. Generally, meshblocks in rural areas have populations of 100 – 150 people and in urban areas 150 – 200 people [11].

The efficiency for firewood stoves was set to 67 percent and for pellet stoves to 77 percent [12]. Pellet heaters are still uncommon in New Zealand. However, they may be a good way to decrease the emissions since pellets are more homogenous and drier than firewood and therefore have lower emission factors than firewood. All calculations was based on census statistics [9], emission factors and the assumption that each dwelling need 8 MWh per year for heating, which equals to 2 tonnes of firewood per year (plus losses due to the stove-efficiency) and dwelling.

Summary of figures and formulas used

Annual energy use in each meshblock

Number of dwellings * 8 MWh (1)

Annual energy use including losses from incomplete combustion in each meshblock

(1) * efficiency of combustion equipment (2)

Emissions of PM_{10} in each meshblock

(2) * emission factor (3)

Emission factors used

Table 1 Emission factors used

Scenario	1	2	3	4	5
Emission factor, firewood (mg/MJ)	900 (80 % of energy use) 110 (20 % of energy use)	-	900 (80 % of energy use) 110 (20 % of energy use)	-	900 (80 % of energy use) 110 (20 % of energy use)
Emission factor, wood pellets (mg/MJ)	-	35	35	35	-

Scenario 1 – emissions from firewood heating today

In 51 percent of the dwellings in Rotorua, there are firewood stoves installed for heating. The energy need for heating in those dwellings is 94 GWh per year. In scenario 1, the emissions from these firewood stoves were calculated. The emission factors for firewood varies a lot, depending on for instance different ways of managing the fire, oxygen supply and moisture content of fuel. Because of this, two different emission factors were used in this scenario. The assumption was made that the largest part of the fire cycle, low oxygen is available, since this makes the fire burning for a longer time, but with higher emissions as an effect. For 80 percent of the energy supply, the high emission factor was therefore used (900 mg/MJ [13]) to cover the time with low oxygen supply, and for the rest 20 percent of the energy need, the low emission factor was used (110 mg/MJ [14]) to represent the time with normal oxygen supply.

Scenario 2 –replacing all existing fire wood stoves with pellet stoves

In scenario 2, the amount of PM_{10} emissions were calculated assuming all firewood stoves in Rotorua are replaced by pellet stoves. The emission factor used for pellets was 35 mg/MJ [15]. The energy use for space heating was the same as in scenario 1, 94 GWh per year, since the same number of dwellings was concerned.

Scenario 3 – keeping existing firewood stoves and installing pellet stoves in all other dwellings

In scenario 3, it was assumed that all existing firewood stoves was kept and all other dwellings, that do not use bioenergy for heating today, install and use pellet stoves for domestic heating. The total energy use in this scenario was 181 GWh, divided between firewood (94 GWh per year) and pellets (88 GWh per year). To calculate emissions of PM10 in this scenario, emission factors used for firewood was the same as in scenario 1, (during 80 percent of the time the emission factor was assumed to be 900 mg/MJ [13] and during 20 percent the emission factor was assumed to be 110 mg/MJ [14]) and for pellets, the emission factor used was 35 mg/MJ [15].

Scenario 4 – all dwellings in Rotorua use pellet stoves for heating

In scenario 4, all dwellings in Rotorua were assumed to use pellet stoves for domestic heating. The energy use was 181 GWh per year and the emission factor used to calculate emissions of PM10 was 35 mg/MJ [15].

Scenario 5 – all dwellings use firewood stoves

In scenario 5, all dwellings in Rotorua were assumed to use firewood stoves for space heating. The total energy use for heating used for calculations was 181 GWh per year and as in scenario 1 and 3, the emission factors used for PM10 was 900 mg/MJ [13] for 80 percent of the energy supply and 110 mg/MJ [14] for the remaining 20 percent.

Potential sensitive areas due to meteorological and topographical characteristics

Knowledge about climatic conditions and local climate may be used for many purposes, for example to evaluate air quality. There are possibilities to analyse how the air move in a geographical area and in that way identify spots where there might occur problems with high concentrations of air pollutants. Examples of metrological and topographical characteristics that affect air quality are wind direction, atmospheric layering and elevation. In this study, the topography in Rotorua was analysed through visual interpretation in Geographical Information Systems (GIS). An elevation map was used to identify low situated areas (Arrow A in Fig 1) and areas where the elevation changes rapidly (Arrow B in Fig 1). These topographical characteristics may make the emissions stay at one spot and not dilute with surrounding air as if the emission source is situated in a more open area.

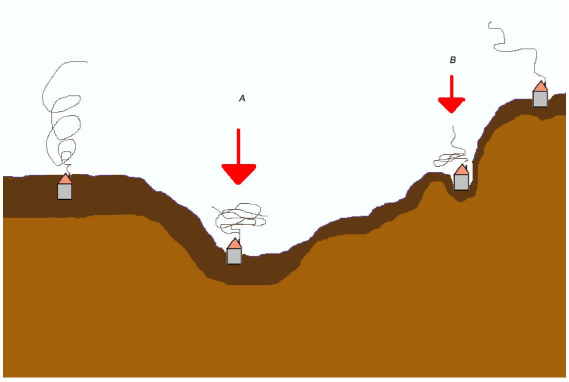


Figure 1. Example of elevation characteristics in an area that might be sensitive to air pollution. Arrow A=areas that are low situated, arrow B=areas where elevation changes rapidly.

Geographical Information Systems (GIS)

Since PM10 emission sources are connected to spatial locations, GIS is a useful tool when doing emission inventories. In this study, GIS was used to find and map emission sources and estimating their impact on the air quality in the urban area of Rotorua. By combining information about emission sources and calculating the amount of PM10 emitted from each source, it is easier to understand where the largest sources of PM10 are situated.

The software used in this study was Arc GIS software package. When analysing the topographical characteristics of Rotorua, an elevation raster map was used to identify low situated areas and rapid changes in elevation.

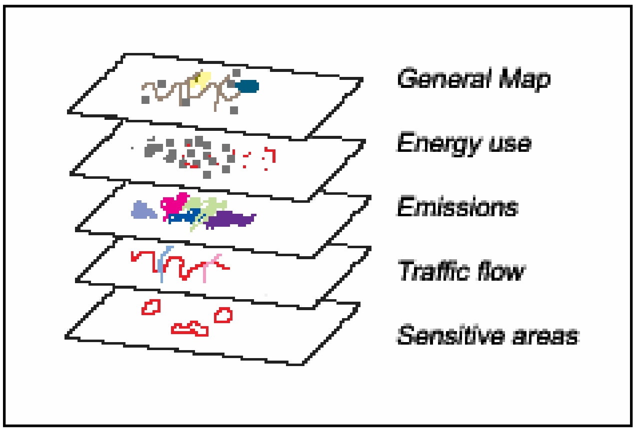
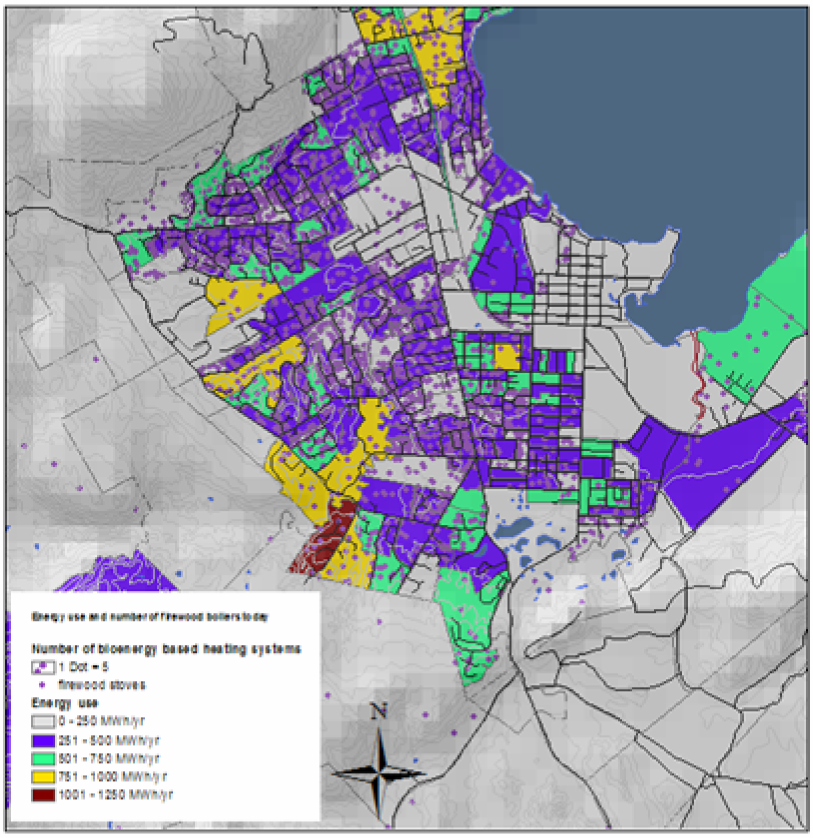


Figure 2. Example on how GIS can be used as a tool for emission inventories

Results

Energy use in Rotorua

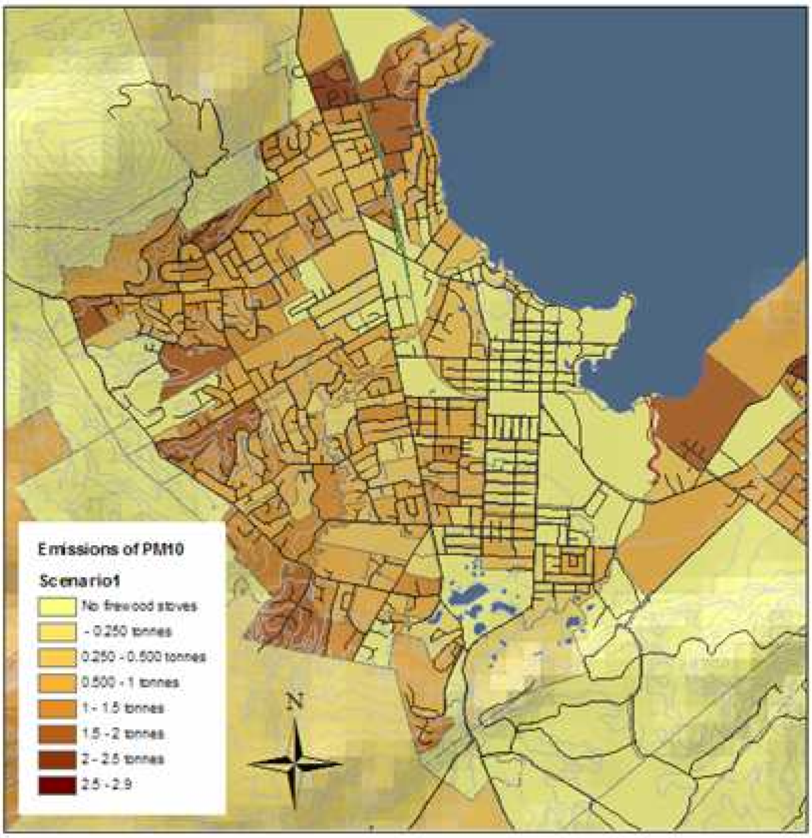
Map 2 shows the percentage of firewood stoves in different parts of Rotorua today. It also show the energy need for heating in each meshblock. The central and western parts of Rotorua use most energy for heating and the eastern parts and the outskirts of the city use less energy. The use of firewood stoves is even spread, but the largest amount of firewood stoves can be found in the smaller meshblock in the urban parts of the city. The energy use varies between 0 and 1.2 GWh in different meshblocks. The total energy need for heating in Rotorua is calculated to be 181 GWh and the total number of firewood stoves are 11 691 [9], i.e. there are firewood stoves in 52 percent of all dwellings in the city. The firewood stoves cover 94 GWh of the total energy need for heating.



Map 2. Map with energy need for heating and percentage of firewood stoves in central Rotorua. The dots represent percentage of firewood stoves and the different colours the energy need for heating in each meshblock.

Scenario 1 – emissions from firewood heating today

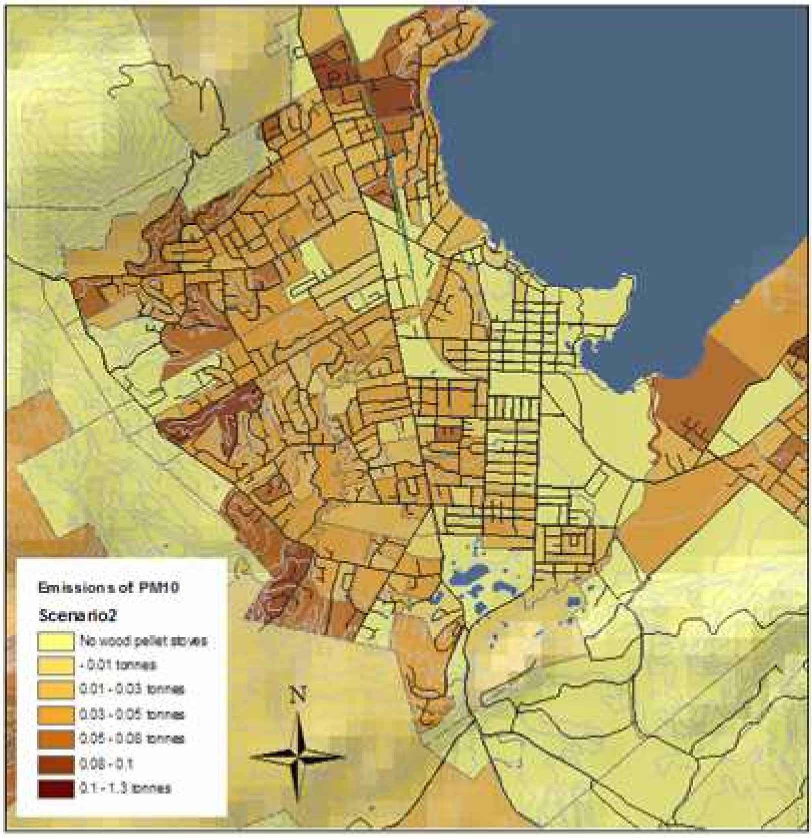
Map 3 shows the calculated emissions from existing firewood in each meshblock in Rotorua. The emissions vary from 0 to 2.9 tonnes in the different meshblocks and the total amount of PM_{10} emitted from all meshblocks is 327 tonnes per year. The largest amount of PM_{10} is emitted in the urban parts of Rotorua.



Map 3. PM_{10} emissions from existing firewood boilers in central Rotorua. PM_{10} emissions in different meshblocks range from 0 to 2.9 t/yr.

Scenario 2 –replacing all existing fire wood stoves with pellet stoves

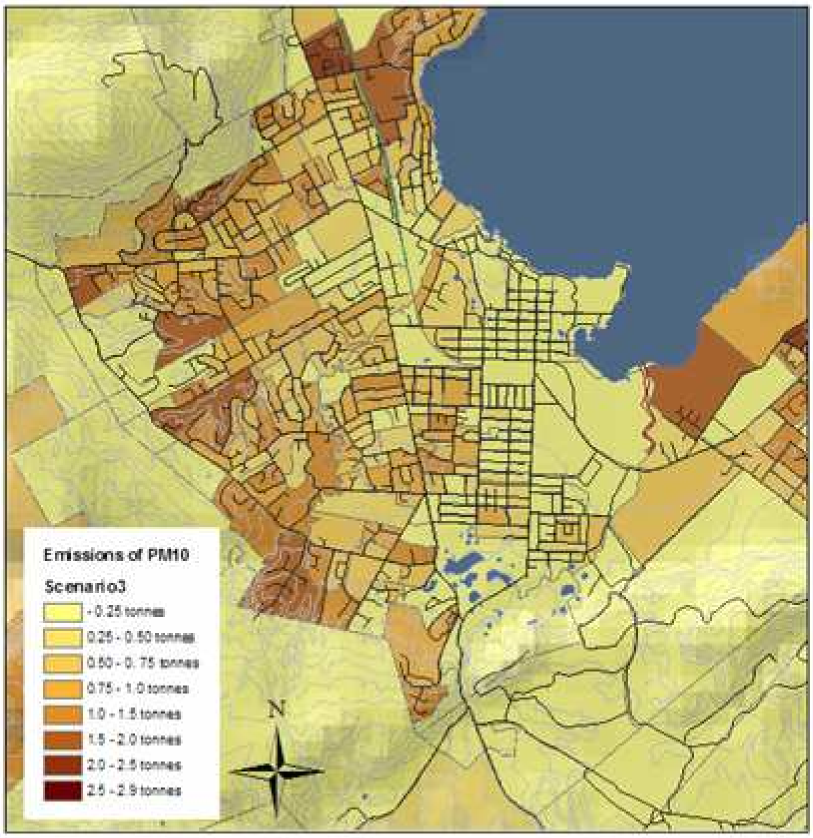
Map 4 shows the calculated emissions of PM_{10} in each meshblock if all existing firewood stoves in Rotorua would be replaced by pellet stoves. The emissions vary from 0 kg/yr to 126 kg/yr in different meshblocks. The total emissions from the modelled pellet stoves are calculated to be 14 tonnes/yr.



Map 4. PM_{10} emitted if all existing firewood stoves would be replaced with modern pellet stoves. PM_{10} emissions in different meshblocks range from 0 to 126 kg/yr.

Scenario 3 – keeping existing firewood stoves and installing pellet stoves in all other dwellings

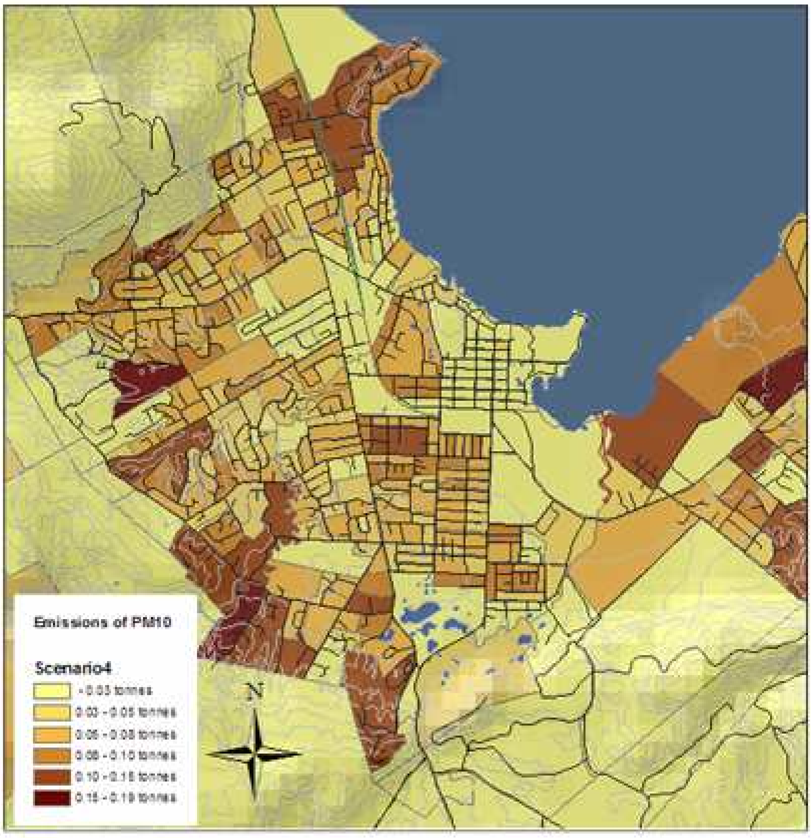
Map 5 shows the emissions of PM_{10} in each meshblock if existing firewood stoves in Rotorua are kept and the rest of the dwellings in the city start using pellet stoves for heating. The emissions in the different meshblocks vary from 0 kg/yr to 2.9 tonnes/yr. The total emissions from all meshblocks were calculated to be 341 tonnes per year. The largest amount of PM_{10} is still emitted in the urban parts of Rotorua.



Map 5. PM_{10} emissions from different meshblocks in Rotorua if existing firewood stoves are kept and all dwellings with other heating systems than bioenergy based install and use a pellet stove for heating. PM_{10} emissions in different meshblocks range from 0 to 2.9 t/yr.

Scenario 4 – all dwellings in Rotorua use pellet stoves for heating

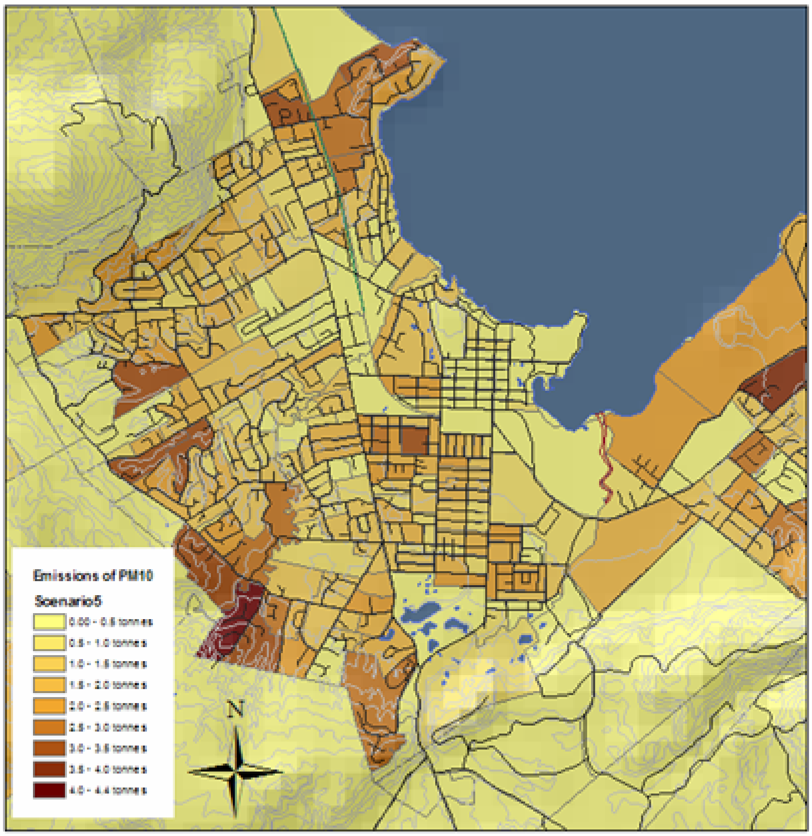
Map 6 shows the emissions of PM_{10} in each meshblock if all dwellings in Rotorua use pellet stoves for heating. The emissions from each meshblock vary from 0 kg/yr to 192 kg/yr. The total PM_{10} emissions calculated in this scenario are 28 tonnes per year.



Map 6. PM_{10} emissions if all dwellings Rotorua start using pellet stoves to cover their heat demand. PM_{10} emissions in different meshblocks range from 0 to 192 kg/yr.

Scenario 5 – all dwellings use firewood stoves

Map 7 show the emissions of PM_{10} in each meshblock if all dwellings in Rotorua use firewood stoves for heating. The emissions from each meshblock vary from 0 kg/ year to 4.4 tonnes/yr. The total emissions of PM_{10} are 635 tonnes per year.



Map 7. PM_{10} emissions if all dwellings in Rotorua start using firewood stoves for heating. Each colour on the map represents PM_{10} emissions in each meshblock. PM_{10} emissions in different meshblocks range from 0 to 4.4 t/yr.

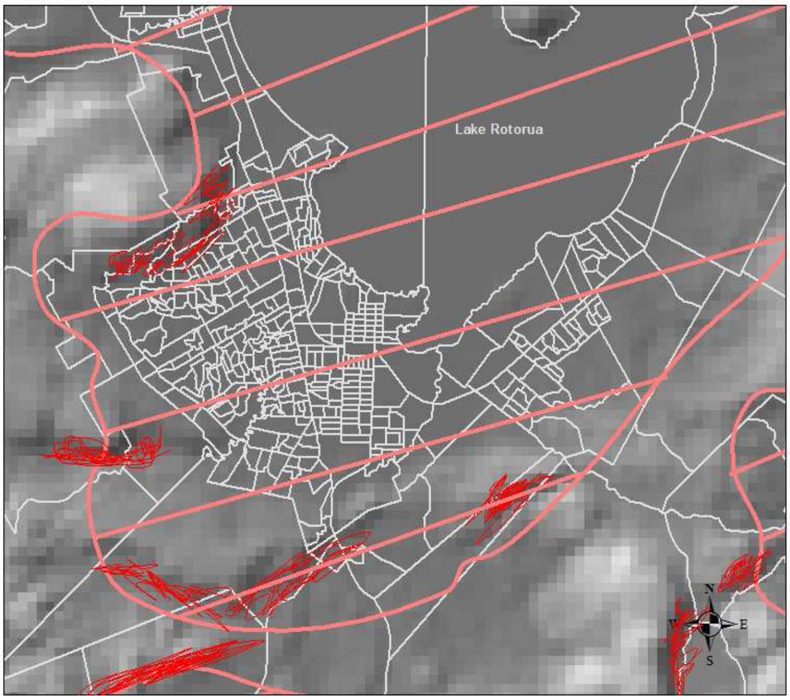
Summary of results

Table 2 Summary of results from scenarios

Scenario	1 (firewood today)	2 (wood pellet instead of firewood)	3 (firewood and wood pellet)	4 (all dwellings use wood pellet)	5 (all dwellings use firewood)
Energy use, GWh/yr (including stove efficiency)	122	114	230	222	238
Emissions of PM_{10} (tonnes)	327	14	341	28	635
% emissions compared to scenario 1	+-0	5	104	8	194

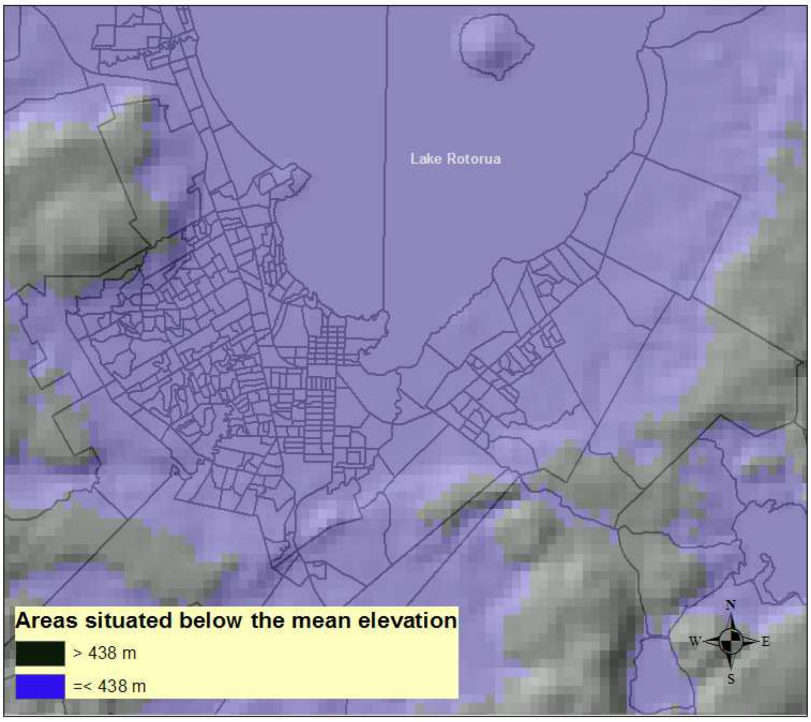
Potential sensitive areas due to metrological and topographical characteristics

Map 8 show low situated areas and areas with rapid elevation changes, obtained through visual interpretation of an elevation raster covering Rotorua. The light red lined areas show where the lowest parts of Rotorua seem to be situated and the red coloured areas show where there seem to be rapid changes in elevation.



Map 8. Low situated areas (light red colour) and rapid changes in elevation (red colours). Obtained by visual interpretation.

Map 9 shows areas that are above and below the average elevation in Rotorua, i.e. 438 meters above sea level (masl).



Map 9. Areas situated below 438 masl are coloured in blue

Conclusions and discussion

The PM_{10} concentration in Rotorua is exceeding the New Zealand national guideline for particle emissions. This study aimed to calculate the amount of PM_{10} emitted in Rotoura and also to analyse where in the city the largest amount of PM_{10} is emitted. In both cases the main focus has been on emissions from firewood stoves.

The study used two basic set of data:
1) density of energy use for heating in different parts of Rotoura,
2) density of firewood stoves in different parts of the city.
These spatial data are used to calculate the amount of PM_{10} emitted in the different parts of the city. The calculations show that PM_{10} emissions from existing firewood stoves in Rotorua are 327 tonnes per year. It is also possible through the spatial analysis to identify the “hot spots” of particle emission from firewood stoves in the city.

The calculated amount of particle emissions is much larger than the emissions of PM_{10} calculated in the emission inventory performed in 2003 [8], where 117 tonnes per year were calculated covering all heating systems. Why is the figure almost three times as high in the present study? Both calculations are based on a lot of assumptions because of lack of real life measurements. Three assumptions are very critical: 1) annual consumption of firewood in the households which uses firewood for heating. 2) which firewood stove technology is assumed and what is the age of the technology? 3) which type of firewood is assumed and which moisture content is assumed? 4) which load is the firewood stove run at, and which emission factor should then be used for the calculations? Assumptions on each of these levels are all important for the final results and for each one of them the data can vary with more than a factor 2. Seen from the end-users point of view the actual emissions depend on the individual house owners, the way they manage the fire, how much firewood they are using and the quality of the fuel they use.

The analysis shows that there is a potential to decrease emissions of PM_{10} if less firewood stoves and more wood pellet stoves are used. Pellets are more homogenous and drier than firewood, which create a cleaner combustion process and higher combustion efficiency. The calculated emissions of PM_{10} from scenario 4 were 28 tonnes per year, where it was assumed that all dwellings in Rotorua would use wood pellet stoves instead of their existing heating system. This is less than the total emissions from existing firewood stoves and less than the total emissions from existing firewood stoves and less than the calculated emissions from the 2003 emission inventory for domestic heating in Rotorua.

The analysis clearly indicates significant improvements by changing from firewood stoves to wood pellet stoves. The dilemma is, however, that firewood is a renewable energy source as well as wood pellets are. If all dwellings in Rotorua would use firewood stoves and the user not manage the fire properly, for example not supplying enough oxygen to the fire, using moist firewood etc, the emissions of particulates would increase remarkably as scenario 5 illustrates. In this case the national standards for PM_{10} would be exceeded even more than today. It is therefore very important that the best technology is used before promoting renewable energy.

Urban Rotorua is situated in quite low terrain comparing to the surroundings which is shown in map 9 and map 10. Pollutants tend to stay close to the city as a consequence and the turnover rate of the air is low. The analysis of the topographical characteristics was however very brief in this study and was only performed through visual interpretation. A proper air dispersion modelling has to be performed to get a correct analysis of the dispersion pattern in the city.

Concerning other sources of PM_{10}, traffic is often mentioned as a large source. However, their peaking times are somehow different. First of all, emissions from bioenergy heating are mainly occurring during wintertime, when heating is needed. Furthermore, the use of heating appliances occurs when people are at home, i.e. during evening time. Cars are used mostly in mornings, to some extent during lunch time and during early evening, when people are on the way from work. Therefore, the emissions of PM_{10} origin from different sources during different times of the day. To identify most effective ways to decrease emissions of PM_{10}, it is therefore important to monitor the emissions to determine the time of the day where the guidelines are exceeded and where those emissions come from. Measurements of particle emission over a longer time period (24 hours) are useful because the chemical composition of particles from various sources are different and it is therefore possible to determine the dominant source of emissions. These measurements therefore give an indication of total impact at a specific site. With this information it is possible to further advance the analysis. At least these measurements can be used to verify modelled scenarios. Changing all firewood stoves to wood pellet heaters is obviously a very simplistic scenario and is only used to establish a modelling framework. Many heating sources are available and future modelling can be based on more advanced technology scenarios. It would also be interesting to investigate the possibilities of combining pellet heating with other renewable energy systems, such as heat pumps and geothermal heating. Combining these heating systems could be one way to lower not just the emissions of PM_{10} but also the use of fossil fuels in the energy systems. It could also be relevant to model other emissions than particles such as NOx and SOx. The latter is of particular interest to Rotorua due to its natural geothermal activities. The natural emission of Sulphur does, however, put significant challenges on carry out such analysis.

Acknowledgements

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