Hydrogen Sulphide in Rotorua, New Zealand:

Personal Exposure Assessment and Health Effects

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Abstract

Long-term exposure to low level hydrogen sulphide (H_2S) may be a health risk. However, research on this has been scarce. Rotorua offers a unique opportunity for such an investigation as its population is regularly exposed to geothermal H_2S and few co-pollutants are present.

To date, only ambient H_2S concentrations have been investigated. The current study aimed to measure personal exposure levels and to assess potential health effects. In particular, the study involved:

1. Method development to measure exposure, including the adaption of a personal sampler
2. Analysis of personal exposure levels including personal and ambient air measurements
3. Identification of the main determinants of exposure
4. Assessment of the association between personal exposure and health effects involving the respiratory, the circulatory and the nervous systems.

The Chemcassette® tape was found to be a suitable and cost effective personal sampler. More than 75% of participants had exposure levels below 5 parts per billion (ppb). The group of remaining participants had exposure levels between 5 and 90 ppb, which were five times higher than those measured in the other two groups (CI: 3.71-6.73). Those participants had frequented a 1-2 km wide north-south corridor in central Rotorua for longer than 2 hours. Previously, the corridor had been identified as an area of elevated H_2S concentrations in geological and ambient air surveys. However personal exposure levels were considerably lower than air monitoring data in this area. Whether this is attributable to the mobility of participants or the sheltering effect of buildings is unclear. Personal samplers with readings above 90 ppb were associated with proximity to geothermal sources and/ or buildings with H_2S intrusion. Personal exposure levels varied between trials in the central corridor, while western and eastern Rotorua consistently showed low levels (<5 ppb). Higher H_2S concentrations (up to 3.5 times CI

2.07-5.76) in the central corridor were associated with north-north-easterly to easterly winds carrying additional H_2S from the Sulphur Bay geothermal area on the eastern margin of the corridor (effect estimate coefficient: 3.5, CI 2.07-5.76). An indication of an increased asthma risk was found for the southern part of the corridor (OR: 2.9, CI: 1.17-7.18), but the association needs further investigation.

In conclusion, this study found elevated personal H_2S levels along a central corridor in Rotorua and the possibility of an association with asthma.

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The following statement is included at the request of the Massey University Human Ethics Committee:

“This project has been evaluated by peer review and judged to be low risk. Consequently, it has not been reviewed by one of the University’s Human Ethics Committees. The researcher(s) named above are responsible for the ethical conduct of this research

If you have any concerns about the conduct of this research that you wish to raise with someone other than the researcher(s), please contact Professor Sylvia Rumball, Assistant to the Vice-Chancellor (Ethics & Equity), telephone 06 3505249, e-mail humanethics@massey.ac.nz”

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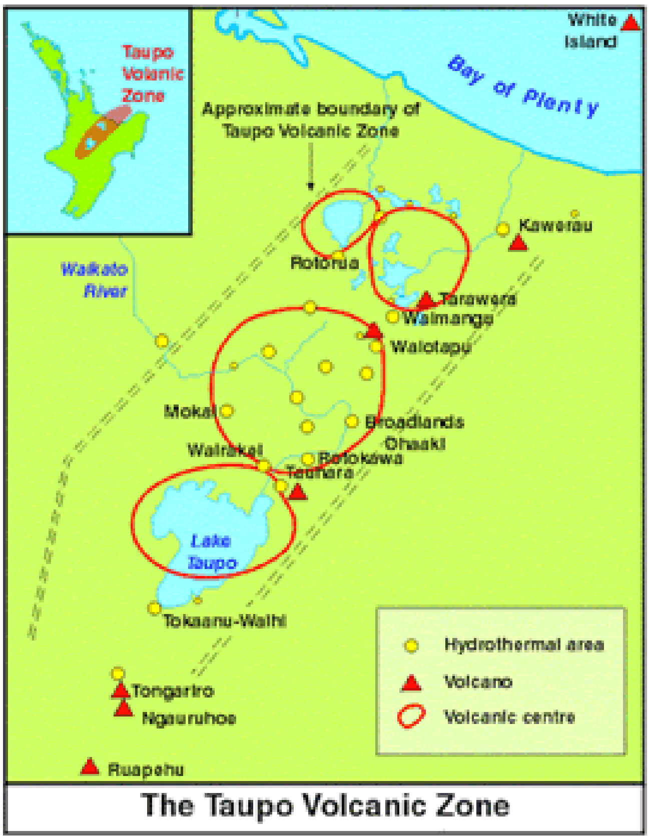
Rotorua Caldera

(Source: Geological and Nuclear Sciences (GNS))

Chapter 1: Introduction

Rotorua is situated in the Central North Island of New Zealand, where it is partially built over the Rotorua Geothermal Field (RGF), one of many in the Taupo Volcanic Zone (Figure1-1). It is renowned for its geothermal features and the distinctive “rotten egg smell” of hydrogen sulphide.



(Source: GNS Science)

Figure 1-1: The Taupo Volcanic Zone.

Hydrogen sulphide (H_2S) is toxic to humans at high doses and on rare occasions, fatalities due to H_2S poisoning have occurred in Rotorua. However, very little is known about the health effects of long-term low dose exposure (WHO, 2003) such as is prevalent in Rotorua.

Low dose exposure to H_2S from industrial sources has caused health concerns in the United States in occupational and community settings, but due to the presence of other pollutants, and difficulties in establishing exposure levels, uncertainties remain and these studies cannot be a basis for setting health related guidelines of exposure (WHO, 2003; Campagna *et al.*, 2004; Inserra *et al.*, 2004; Legator *et al.*, 2001; Logue *et al.*, 2001; Richardson, 1995).

The unpleasant odour of H_2S starts to occur at very low concentrations and current guidelines on ambient air levels for H_2S are based on preventing odour annoyance and the resulting impacts on wellbeing rather than specific health effects. The level set by the World Health Organisation (WHO) and by the Ministry for the Environment in New Zealand is 7 $\mu g/m^3$ (~ 4.9 ppb) for a ½ and an 1-hour average respectively and may not be suitable for geothermal areas.

Previous investigations into an association between low level H_2S exposure and adverse health effects in Rotorua pointed toward potential adverse health effects on the respiratory system, the nervous system and eyes (Bates *et al.*, 1997; Bates *et al.*, 1998; Bates *et al.*, 2002; Durand and Wilson, 2006). However, because the analyses were based on hospital discharge data and individual exposure levels were unknown, inferences to the individual level and to causality were limited. In order to investigate possible health effects in more detail, researchers from the University of Otago, Wellington, the University of California, and Stanford University are currently conducting a large scale cross-sectional study of the Rotorua population called CHEERS (Community Hydrogen Sulphide Exposure and Effects: the Rotorua Study) (Bates and Crane, 2008).

So far, wide scale personal exposure data are not available for the Rotorua population. Exposure models have been based on ambient air monitoring data, and it is uncertain how ambient air measurements relate to personal exposure levels. Although air monitoring data are a suitable proxy for exposure, there is a risk of misclassification, because H_2S concentrations vary between locations in Rotorua and people move between the different exposure areas. Furthermore, only limited air monitoring data are available for the whole Rotorua area, and daily and seasonal fluctuation in H_2S concentrations (Iremonger, 2008) further complicate exposure modeling.

Meteorological and environmental factors have been identified as major contributing factors to such fluctuations in emission and distribution of geothermal gases (Carapezza *et al.*, 2003; Viveiros *et al.*, 2008; Viveiros *et al.*, 2009).

1.1 Research objectives and thesis structure

The aim of this thesis was to undertake a personal exposure assessment to H_2S in Rotorua and to assess a link with possible health effects. In order to achieve this aim, the study was conducted in the following 4 steps:

1. Method development to measure exposure
   This step was necessary, because a commercially manufactured personal sampler was not available. A personal sampler was adapted using the Chemcassette® tape, which necessitated a validation and calibration study of the sampler.
2. Analysis of personal exposure levels including personal and ambient air measurements
3. Identification of the main determinants of exposure
4. Assessment of the link between personal exposure and possible health effects involving the respiratory, the circulatory and the nervous systems. The data on health were provided by a previous health survey conducted by the Public Health Unit -Toi Te Ora, Rotorua under Dr Phil Shoemack.

Accordingly the chapters on Materials and Methods, Results and the Discussion were subdivided into these four aspects of the study.

Table 1-1 provides an overview of the specific research aims, the data used and its collection methods and the analytical methods applied for each separate area of the thesis.

Finally, raw data were not included in the appendices of this thesis because some data contained confidential information which is not available for public perusal.

Table 1-1: Table of research aims, data used, collection methods, exposure location and length and analytical methods utilised at each separate study area of this thesis.

Study/Analysis	Research aim	Data	Data collection methods	Exposure location/ Exposure length	Analytical methods
Validation	to establish that samplers discolour uniformly	groups of samplers were exposed together	Chemcassette® tape samplers were scanned and grayscale values recorded.	the samplers were exposed at the same location for the same length of time, remaining at one location	comparison of grayscale values between samplers in each group and between groups
	to establish the sensitivity of the Chemcassette® tape to other environmental influences	groups of samplers were either exposed or sheltered from humidity and sunlight. a group was exposed close to a wood burner to establish whether the smoke would cause changes in the grayscale readings.	as above as above	as above as above	comparison of grayscale values between the groups as above
	to establish whether the storage of the samplers was appropriate	samplers were stored in a jar which travelled unopened to Rotorua and back.	as above	as above	comparison of grayscale values pre and post exposure
Calibration	to quantify the discolouration of the Chemcassette® tape by assigning H_2S concentrations to grayscale values and by interpolation	grayscale values of samplers and H_2S concentrations of ambient air	Chemcassette® tape samplers were scanned and grayscale values recorded. MDA Scientific Toxic Gas Analyser	the samplers and the analyser were exposed together at one location for 24 hours. the 15-minute recordings of the Analyser were converted to 24-hour averages.	mathematical modeling resulting in the use of the spline 190 model on log-transformed data
Personal exposure	to establish personal exposure levels to H_2S in Rotorua	H_2S concentrations of personal samplers, converted from grayscale values using the spline 190 model	Chemcassette® tape from personal samplers were scanned and grayscale values were converted to H_2S concentrations	personal samplers were given to participants, who lived or worked in Rotorua to carry for 24 hours.	descriptive statistics
	to investigate temporal and spatial distribution patterns of personal exposure levels in Rotorua	the trials were conducted 4 times during 2008 and participants were categorised into 3 groups (east, west and central Rotorua).	as above	personal samplers were exposed for 24 hours during all four trials.	multiple regression analysis, mapping

Study/Analysis	Research aim	Data	Data collection methods	Exposure location/ Exposure length	Analytical methods
	to investigate the relationship between personal exposure levels and air H_2S concentrations	H_2S concentrations of personal samplers, home samplers and other environmental sampler	personal exposure, home and environmental samplers used the Chemcassette® tape, MDA Scientific Toxic Gas Analyser and previous air monitoring data	personal samplers were exposed for 24 hours home samplers were exposed for 15 to 18 hours in one location at participants' homes during one trial environmental control samplers were placed in locations frequented by groups of participants for 24 hours.	descriptive statistics
	to exclude unlikely locations of exposures or to identify areas of higher exposure	H_2S concentrations of home samplers and other environmental sampler	as above	as above	mapping
Identifying main determinants of exposure with a focus on meteorological data	to investigate the effect of meteorological factors on spatial and temporal variations in H_2S concentrations of ambient air	H_2S concentrations in ambient air and meteorological data	MDA Scientific Toxic Gas Analyser and weather data collected by the New Zealand Meteorological Service	the 15 minute recordings of the analyser were converted to hourly averages meteorological data from Rotorua Airport were reported in hourly averages.	multiple regression analysis
Health survey	to investigate the association between H_2S concentrations and health effects	incidence/prevalence rates of diseases from a previous health survey, whose participants were categorised into high, medium and low exposure groups depending on the area of residence and work	previous health survey and H_2S exposure area classifications from ambient air data after Horwell *et al.* (1998)	the Health survey was conducted in 1999. the ambient air study was conducted over a weekly and a monthly period twice during 1997.	logistic regression analysis
	to investigate the spatial distribution patterns of diseases which were associated with H_2S exposure, and their relationship to the distribution pattern of the personal samplers	disease data and residential address from the health survey and personal exposure maps	as above	as above the personal exposure study was conducted over a 24-hour period 4 times during 2008	mapping

Chapter 2: Background and Literature Review

When looking at personal H_2S exposure in Rotorua, two main questions arise: 'What are the levels of exposure?' and 'What are the health effects on the population of Rotorua?' Accordingly, this chapter has been divided into two parts. The first will look at the concentrations and distribution patterns of H_2S in Rotorua and what the influencing factors are, while the second part will look at the health aspect of human exposure to H_2S.

2.1 H_2S concentration and distribution in Rotorua

The city of Rotorua is located in the southern part of the Rotorua caldera which formed during a volcanic eruption around 140,000 years ago. The city is partially built over the Rotorua Geothermal Field (RGF), which covers 18 km^2 on land or 28 km^2 including the area within Lake Rotorua (Mroczek *et al.*, 2004). Surface expressions of geothermal activity in the RGF are geysers, neutral to alkaline hot springs and pools, turbid acid pools and lakelets, mud pools and cones, fumaroles and solfatara, barren warm and steaming ground, dolines and craters (Cody and Scott, 2005). These all form entry points of geothermal gases into the atmosphere. The RGF and areas of geothermal activity are shown in Figure 2.1.

2.1.1 H_2S concentrations in the subsurface

In the RGF, deep geothermal fluids contain dissolved gases originating from the underlying magma plume. Rising towards the surface these fluids experience a reduction in pressure which may induce boiling, releasing the dissolved gases into steam. Once in the vapour phase, it is possible for the gases and the associated hydrothermal fluids to take different routes to the surface, because the geothermal fluids are constrained by the hydrological gradient. Thus gases tend to rise more vertically compared to geothermal fluids, which may travel horizontally over long distances

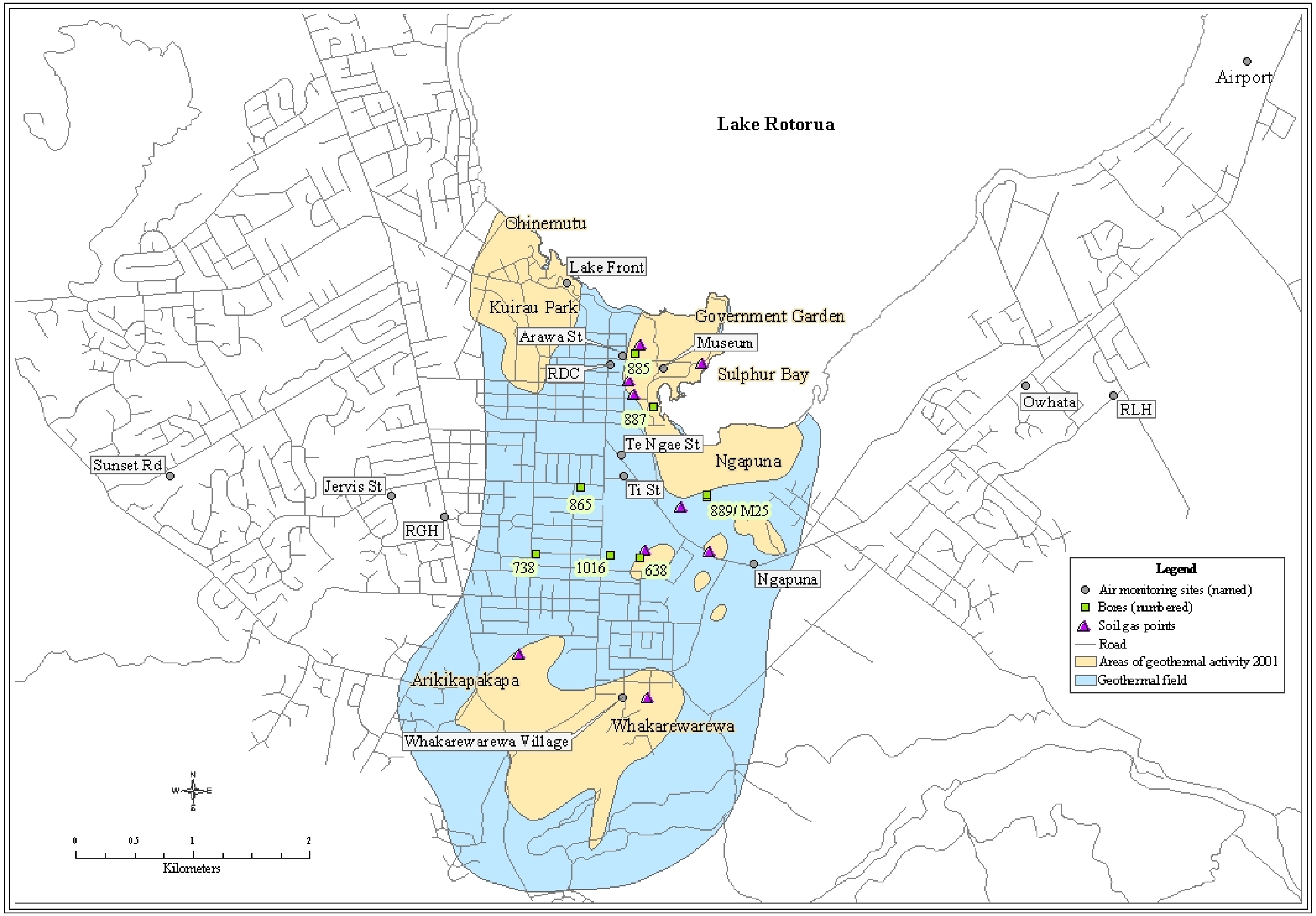


Figure 2-1: Location map of the Rotorua residential area.

(Data Sources: Environment Bay of Plenty and Rotorua District Council)

Displayed are the geothermal field, areas of geothermal activity, air monitoring sites, bores with H_2S concentrations > 100 mmol/mol and soil gas points with H_2S concentrations > 2 mole%.

RGH: Rotorua Girls High
RLH: Rotorua Lakes High
RDC: Rotorua District Council

(Giggenbach and Glover, 1992). Nevertheless, the path and the distribution pattern (centralised or diffuse venting) of the gas may be modified by the porosity and permeability of the overlying rock and soil layers, and geological structures such as faults, fractures and aquifers.

The H_2S concentrations in the ascending geothermal fluid and vapour may be lessened by chemical reactions with rock, by oxidation when in contact with air or shallow groundwater which is rich in oxygen, and by cooling. Cooling of the geothermal fluids reduces boiling and steam production, while cooling of the vapour induces condensation. Both processes retain H_2S in solution, allowing for chemical reaction with the surrounding rock.

Hydrological models suggest two chemically distinct areas of upwelling geothermal fluids in the RGF. Very simplified, one is located along the south-eastern side of the RGF encompassing the Sulphur Bay-Ngapuna area and possibly Whakarewarewa, where geothermal fluids undergo boiling and release dissolved gases into the steam. The other area is located in the north-west, encompassing Kuirau Park and Ohinemutu, where less degassing occurs, mainly due to the contact of geothermal fluids with groundwater. Mroczek *et al.* (2004, 2005) provide a summary of geothermal flow models for the RGF and their effect on the chemistry of the geothermal fluids and gases, while Wood (1992) and Gordon (2005) give a detailed description of the geological structures and their influence on geothermal fluids.

H_2S emissions may also be altered by physical and chemical changes in the magma plume, seismic activity and fluctuations in the lake level. Lake level changes may modify the size of the degassing area along the lake shore or the emission rate. As Symonds *et al.* (2001) noted in their study of volcanic scrubbing in crater lakes: “Venting of unscrubbed magmatic volatiles from magma to atmosphere may only require the drying of a narrow crack rather than depleting water from the edifice.”

Bore (Giggenbach and Glover, 1992; Mroczek *et al.*, 2004) and soil gas (Finlayson, 1992) surveys of the RGF indicate that the model of two chemically distinct areas of upwelling fluids is also applicable for H_2S concentrations in vapour. Chemical gas analysis from bores at a depth of 65 to 235 meters showed that the relative proportions of H_2S concentration of dry gas were lower in the north-western part of the RGF at Kuirau Park and Ohinemutu than in the eastern areas. A similar trend of H_2S distribution was found in a soil gas survey, which collected gas samples at a depth of one metre. However an additional area of significant emission was located at Arikikapakapa. Both studies found that within the RGF raised H_2S concentrations are highly localised. Bores and soil gas points with raised levels of H_2S are shown in Figure 2-1, while the original data from these studies are found in Appendices 1 and 2.

Although the geothermal field extends under Lake Rotorua and there is evidence of degassing under the lake floor (Davy, 1992; Glover, 1992; Mongillo and Bromley, 1992; Pearson, 2007; Whiteford, 1992), data are not available to determine if H_2S enters ambient air from this source or if the interaction with the lake water completely eliminates H_2S emissions.

2.1.2 H_2S concentrations in ambient air

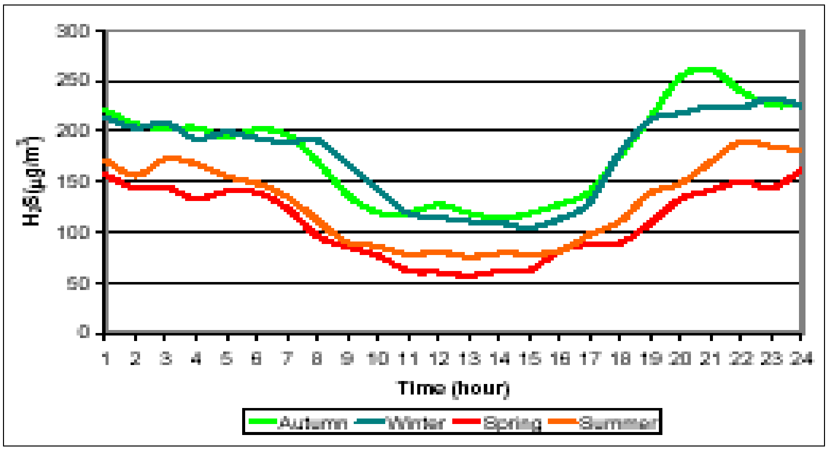
Even though the subsurface studies of H_2S concentrations would suggest higher levels on the eastern side of the RGF alongside central Rotorua, H_2S concentrations in ambient air depend not only on the relative concentration of the gas, but also on the emission rate and the size of the emission area. Furthermore, H_2S distribution and dispersion are influenced by a multitude of factors, including surface terrain and weather conditions, which are discussed in detail in later chapters. It is doubtful that H_2S concentration would reach far beyond the city limits, as H_2S levels drop sharply with distance from the source (Vasilakos *et al.*, 2005). H_2S has a relatively short lifetime in ambient air (Vasilakos *et al.*, 2005) and is heavier than air making it unlikely that H_2S is rising up over long distances beyond the surrounding hills created by the caldera. On the other hand, the wind sheltered location makes Rotorua more susceptible to a reduction in mixing depth, which is defined as "the height to which pollution emitted from the surface can disperse" (Fisher, 2007). Thus low mixing depth, which has been observed in Rotorua (Fisher, 2007), could trap H_2S emission and as a result increase ambient air concentrations.

H_2S measurements in ambient air have been obtained by the regional council, Environment Bay of Plenty (EBOP) (Iremonger, 2004; Iremonger, 2008), the National

Institute of Water and Atmospheric Research (NIWA)(Petersen *et al.*, 1998; Wegműller and Peterson, 1998), Horwell *et al.* (1998, 2004, 2005) and Siegel *et al.* (1986). These studies show a similar distribution pattern to the studies of subsurface H_2S, with a north to south trending corridor of higher concentration along central Rotorua in the east of the RGF. Additionally Horwell *et al.* (2005) concluded that the north-east of Rotorua occasionally experiences higher H_2S concentrations due to wind drift from the central corridor.

EBOP (Iremonger, 2004; Iremonger, 2008) have recorded H_2S concentrations at Arawa Street and at Ti Street (see Figure 2-1) beginning in 1998, and reported up to 2005, providing the longest record so far. For this time period the hourly mean and median values for Ti Street were approximately[1] 103 and 42 ppb respectively, which are about double the values of 53 and 18 ppb for Arawa Street. However, at Arawa Street maximum values (1 hour fixed average) have been higher with recordings up to 3000 ppb.

A distinct diurnal pattern in H_2S concentrations was observed for both monitoring sites: H_2S concentrations rise during the late afternoon and early evening, remaining higher during the night, declining during the morning and remaining lower during the day. Although this pattern occurres all year round, H_2S concentrations during autumn and winter were higher than during summer and spring. The graph below displays these patterns (Figure 2-2).



(Source: EBOP NERM Report 2007 (Iremonger, 2008))

Figure 2-2: Diurnal pattern at Ti Street (Data 1998-2005).

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[1] H_2S values were reported in µg/m^3 by EBOP and NIWA. For ease of use these values were converted to ppb using the H_2S Conversion Converter – ERCB available at www.ercb.ca/docs/documents/directives/Directive056_ConversionCalculator.xls

H_2S monitoring by NIWA (Petersen *et al.*, 1998; Wegműller and Peterson, 1998) was conducted at seven sites - at Whakarewarewa Village, Sunset Road, Te Ngae Road, Owhata, Jervis Street, Arawa Road and at the Lake front (see Figure 2-1). Monitoring did not occur concurrently, but lasted for one to three months per site. Therefore concentrations cannot be compared directly as they might be affected by daily and seasonal variation, but patterns in the distribution of H_2S are detectable. The NIWA readings at Te Ngae Road, which is in proximity to Ti Street, showed the highest H_2S concentrations with an overall half-hour mean value range[2] between 72 and 108 ppb. Whakarewarewa Village and Arawa Street also had relatively high concentrations with an overall average mean range of 66 to 100 ppb, and 7 to 54 ppb respectively. In contrast, at Jervis Street, Owhata, Lake Front and Sunset Road observations were relatively low, with H_2S concentrations of 4, 4, 3 and 0.3 ppb respectively. Looking at the distribution pattern of H_2S concentrations, the monitoring sites with higher recordings lie again in a north-south trending area along central Rotorua with lower concentration to the west and east indicating that indeed higher H_2S concentrations are confined to a limited area of Rotorua city. Additionally the same diurnal pattern as reported by EBOP was observed for all sites in this study. From these findings a map showing possible exposure levels (Wegműller and Peterson, 1998) was produced (Figure 2-3).

Horwell *et al.* (2005) conducted a survey over the Rotorua residential area using passive samplers in a 500 metre grid, allowing for simultaneous monitoring of approximately 70 sites for a 7 and a 28-day period during June and December 1997. The highest H_2S concentrations, between 320 and 800 ppb over a 7-day period, were again found along a corridor in central Rotorua with one sampler having an estimated concentration of 2500 ppb, while the west had lower concentrations (0 – 40 ppb) and the east experienced medium concentrations around 500 ppb. During summer (December) the concentrations in the east were lower than in winter (June).

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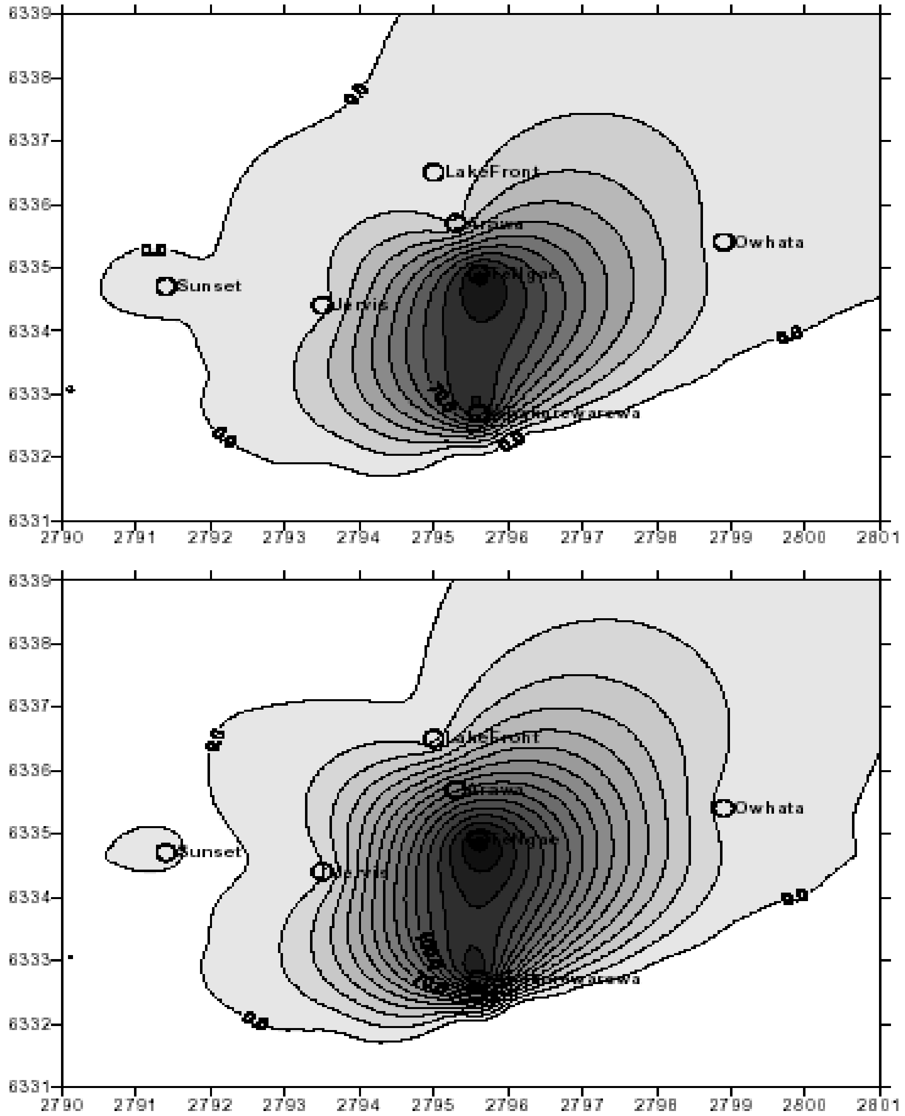
[2] For some sites with higher exposure, NIWA reported a range for the mean value, as the monitor did not record values below 50 ppb. The lower number gives the minimum possible mean value, while the upper number gives the maximum possible mean value.
Please note: NIWA reported overall half hourly mean values while EBOP reported hourly mean values. Horwell *et al.* (2005) reported H_2S concentrations over a seven day period.

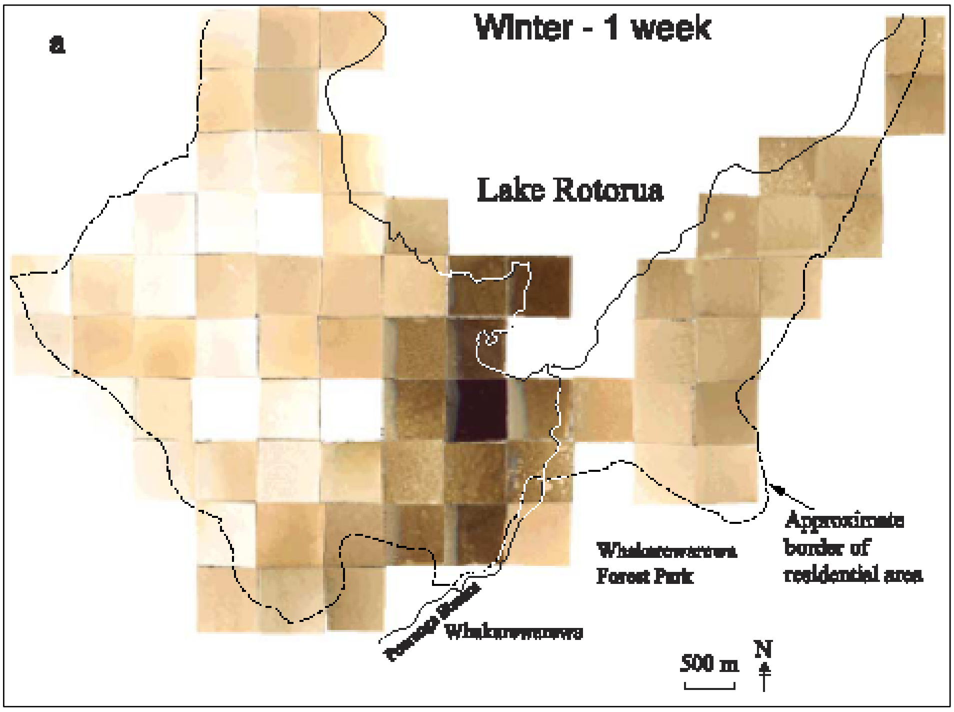


(Source: Niwa Report AK98013 **(Petersen et al., 1998)**)

Figure 2-3: Contour map of H_2S concentrations in Rotorua.

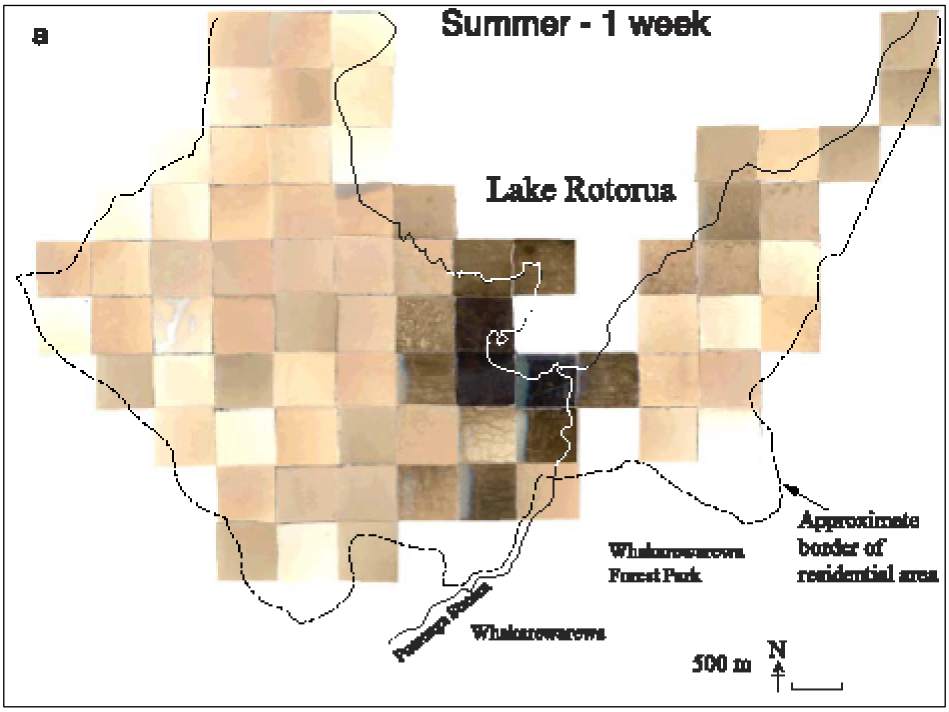
The top figure shows the average concentration from the low estimate, while the bottom figure shows the average of the high estimate. Contour intervals are in 10 µg/m^3 increments.

Looking at the prevailing wind direction over the 28-day period, Horwell *et al.* (2005) attributed these lower H_2S concentrations to a change in the prevailing wind direction. In winter the wind blew from the south / south-west pushing a 'plume' of H_2S from the central corridor towards the north-eastern parts of Rotorua, while during summer the prevailing wind directions were from the west to the north-east. Thus the east of Rotorua probably experienced variable H_2S concentrations depending on wind direction (Horwell, 1998; Horwell *et al.*, 2005). The 7-day exposure maps from Horwell *et al.* (2005) are reproduced below (Figure 2-4 and Figure 2-5).



(Source: Horwell *et al.*, 2005)

Figure 2-4: Map of H_2S concentrations over a 7-day period, June 1997.



(Source: Horwell *et al.*, 2005)

Figure 2-5: Map of H_2S concentrations over a 7-day period, December 1997.

The colour change from white to dark brown to black corresponds to an increase in H_2S concentrations from 0 to 800 ppb over a 7-day period. Black samplers were out of the range of linear response.

Horwell (1998) conducted a further trial placing samplers over shorter distances in the central corridor. The results showed higher H_2S concentrations to be greatly localised, with sites in close proximity to each other having very contrasting readings.

Siegel *et al.* (1986) investigated H_2S concentrations along the lake shore and found a noticeable increase in concentrations from the north of Sulphur Bay at Ohinemutu towards the south of Sulphur Bay at Ngapuna. Levels north of Ohinemutu were 5 ppbV; from Ohinemutu to the northern tip of Sulphur Bay concentrations were 3 to 115 ppbV with one of the seven observation sites in this sector having a larger range of 15 to 290 ppbV. The upper Sulphur Bay area had concentrations in the range of 105 to 1200 ppbV and the lower Sulphur Bay sites had a range from 1200 to 2700 ppbV. The two sites measured in the Government Gardens, inland to the west of upper Sulphur Bay, showed slightly lower concentrations than the upper Sulphur Bay readings. The results of this study may be indicative only, as measurements were taken just on one to three occasions per site, and exposure times of the samplers varied between 10 and 60 minutes.

2.1.3 Influence of human activity on H_2S concentrations

H_2S distribution patterns in Rotorua have been altered by human activity in many ways. Geothermal bores have long been used for heating domestic water, space heating and pools. Venting tubes from active bores may emit H_2S, and during calm weather conditions this cannot disperse, so accumulates in the surrounding air.

Before 1987 about 500 wells existed in the RGF. This was reduced to about 200 after the introduction of the bore closure programme in 1986, which was introduced to safeguard natural geothermal surface activity, an important part of the Rotorua tourist industry (Gordon *et al.*, 2005; Scott and Cody, 2000).

Furthermore, metal parts of bores and venting tubes are very susceptible to corrosion, causing leakage of H_2S. Although most disused bores have been grouted, some venting tubes have not and the occasional bore has been forgotten over time. Figure 2-6 shows one such bore. Leakage from damaged bores, venting tubes and pipes connected to the bore head may increase H_2S concentrations, usually over a highly localised area. If venting occurs into confined or poorly ventilated spaces, H_2S concentrations may reach levels above 500 ppm (Brownbridge, 2009b).

Bore found while landscaping a new subdivision. The bore had been capped, buried and forgotten about. The casing has rusted through.

(Source: Rotorua District Council (Brownbridge, 2009a))

Figure 2-6: Photo of disused bore showing corrosion.

Central Rotorua is extensively developed with commercial and private buildings, roads, car parks and pavements. These surfaces are only slightly permeable or impermeable, blocking the emission of geothermal gases into the air. Instead the gases are channelled, sometimes concentrated and released wherever there is an escape route (Durand and Scott, 2005). Such seepage points were identified by Durand and Scott (2005) in gaps and cracks of pavements, roads and other surface covers as well as from walls, from storm water drains, from sealed foul-water manhole covers and from cable casing. H_2S concentrations between 0.1 and 200 ppm have been recorded at these points.

Indoor H_2S pollution may occur when geothermal gases are confined (*e.g.* under buildings) and directly leak into buildings through cracks and gaps in floors, walls and ceilings, or when H_2S is channelled into buildings in or along subsurface ducts, pipes and cables. Additionally indoor air pollution may occur by way of normal air exchange, if the outside air is heavily polluted (Baxter *et al.*, 1999; Carapezza *et al.*, 2003; Durand and Wilson, 2006; Viveiros *et al.*, 2009). In Rotorua, Durand and Scott (2005) found H_2S concentrations between 2.9 and >200 ppm at such entry points into the inside with one extreme case recording 435 ppm. Away from the vent, concentrations dropped rapidly in ambient air both outside and inside, but H_2S pooled if there was a lack of ventilation *e.g.* behind furniture and in closed cupboards.

It is interesting to note that Viveiros *et al.* (2009) observed an increase in indoor CO_2 concentrations in a geothermal area in the Azores, Portugal, after some rainfall periods. These higher concentrations were partially attributed to the fact that the soil beneath the buildings remained dry, while the surrounding ground was saturated with rain and consequently soil gas emission and CO_2 concentrations increased below the dwellings.

Based on the above mentioned studies, personal exposure was expected to be elevated along a north-south trending corridor in central Rotorua on the eastern site of the RGF, to be low in the west and to be variable, depending on weather conditions, in the east. Furthermore, diurnal and seasonal fluctuations in H_2S concentrations may have an additional impact on levels of personal exposure, which may be a problem in small localised areas. Personal high exposure may also occur indoors.

2.2 Health effects of H_2S

Personal exposure to a substance is defined by the concentration of the substance and the length of exposure. In high concentrations, H_2S is toxic to humans leading to physical collapse and death. For loss of life to occur H_2S concentration is much more important than duration of exposure (Woodall Jr *et al.*, 2005). Inhalation is the most common route of exposure to H_2S, which is rapidly absorbed through the lungs and distributed widely in the human body producing olfactory, respiratory, ocular, neurological, cardiovascular, metabolic and reproductive effects (WHO, 2003). Table 2-1 below lists some of the health effects for acute H_2S poisoning.

Table 2-1: Toxicity table of H_2S.

Exposure (ppm)	**Health Effects**
0.008-0.2	“rotten eggs” smell detectable
10	Beginning eye irritation
20	Fatigue, loss of appetite, headache, irritability, poor memory
50	Prolonged exposure may cause eye and upper respiratory tract irritation
100	Eye and respiratory tract irritation and loss of smell after two to five minutes
200-300	Marked conjunctivitis and respiratory tract inflammation after one hour Prolonged exposure causes pulmonary oedema
500-700	Loss of consciousness and possible death in 30 to 60 minutes
700-1000	Rapid loss of consciousness and cessation of respiration
1000-2000+	Immediate loss of consciousness with early cessation of respiration and death in a few minutes

(Sources: adapted from tables by The International Volcanic Health Hazard Network, 2009, Department of Labour, 1999 and D’Alessandro *et al.*, 2009)

The major metabolic pathway for detoxification of H_2S is oxidation in the liver followed by excretion in the urine (WHO, 2003). The rapid metabolism and excretion of H_2S limits its accumulation and storage in the body. However, uptake and elimination depends on individual physiology. For example, humans with asthma, the elderly, pregnant women and young children represent sensitive subpopulations due to compromised respiratory function or higher oxygen demand (WHO, 2003).

In contrast, recent studies using animal models found low dose H_2S to have a beneficial health effect. For example, a study in mice has shown that inhaled H_2S reduced inflammation and lung injury from mechanical ventilation (Faller *et al.*, 2010).

In his editorial Ritter (Ritter, 2010) compared H_2S to the other gaseous mediators, nitric oxide and carbon monoxide, and stated “All three have vasodilator effects, and all have anti-inflammatory and cytoprotective effects at low concentrations in contrast to causing cellular injury at higher concentrations – consistent with Paracelsus’ aphorism that the distinction between drugs and poisons is determined exclusively by the dose.” Even though it is uncertain whether a beneficial health effect would occur in healthy humans, these studies place increased importance on the investigation of exposure levels.

2.2.1 Long-term health effects of H_2S

Long-term health effects (*i.e.* chronic neurological sequelae) have been reported after acute poisoning but causality is difficult to prove as oxygen deprivation or head trauma when losing consciousness may produce similar long-term symptoms (Woodall Jr *et al.*, 2005).

It has been suggested that repeated and chronic low level exposure to H_2S has a cumulative health effect, causing disease and pathological changes such as the disruption of mucosal layers, chronic irritation and inflammation, altered immune defence and altered tissue repair processes (Roth and Goodwin, 2003).

Most human data obtained to establish a link between H_2S exposure and long-term health effects were derived from acute poisoning case reports, occupational exposures and community studies. However although more data have become available over the last 25 years, the challenge remains to establish at which H_2S concentration a health risk exists to the general population and sensitive individuals for repeated and chronic low level exposure (Roth and Goodwin, 2003). This is because many of the symptoms (*e.g.* headaches, nausea and lack of concentration) are non-specific, the exposure levels are unknown, or H_2S emissions originated from industrial sources and were part of a mixture of pollutants. Roth and Goodwin (2003) and Woodall *et al.* (2005) provide a detailed summary of many of these studies up to 2000 A.D., while the website of The International Volcanic Health Hazard Network (IVHHN) provides an extensive list of articles on health hazards by volcanic gases and aerosols (The International Volcanic Health Hazard Network, 2009).

2.2.2 Studies into long-term health effects from H_2S exposure in Rotorua

Studies using hospital discharge and cancer incidence data have been conducted to establish whether there is an association between low level hydrogen sulphide exposure and adverse health effects in Rotorua. Bates *et al.* (1997, 1998) investigated mortality, morbidity and cancer incidence, comparing Rotorua with the remainder of New Zealand for the time period of 1981 to 1990, controlling for age, gender and ethnicity. The main findings were:

1. elevated mortality risks for diseases of the respiratory system particular among Maori women (SMR[3] = 1.61; 95% CI[4] = 1.19 – 2.12)
2. little evidence of elevated cancer risk, except for cancers of the trachea, bronchus and lung among Maori women (SIR[5] 1.48; 95% CI 1.03 – 2.06),
3. elevated morbidity risk for diseases of the peripheral nervous system, ICD-9 codes[6] 350 - 359 (SIR 1.35, 95% CI 1.21 - 1.51)

The authors caution that ethnicity misclassification may have accounted for the elevated SMR and SIR values detected for Maori women.

In a follow-up study Bates *et al.* (2002) used the classification of high, medium and low exposure areas in Rotorua established by Horwell (1998) to categorise residences into corresponding exposure groups. Morbidity was compared in the exposure groups with the remainder of New Zealand for the years 1993 to 1996. Additionally, morbidity was compared in the high and medium exposure groups with morbidity in the low exposure group. The SIR results (comparison group: the remainder of New Zealand) and the RR[7] results (comparison group: residents of the low exposure area in Rotorua) had generally similar patterns (Bates *et al.*, 2002), showing elevated SIR and RR values for all three major disease groups, *i.e.* diseases of the nervous system and sense organs, diseases of the circulatory system and diseases of the respiratory system (Table 2-2).

Exposure-related trends were found for diseases of the nervous system and sense organs and for diseases of the respiratory system. For the former disease group, stratification for ethnicity (Maori/non-Maori) and gender showed exposure-related trends for all 4 ethnicity–gender groups, while a slightly less consistent pattern was found for the later disease group. Table 2-2 reproduced from Bates *et al.* (2002), gives the results of the Poisson regression but not the stratification analysis. It also includes noteworthy minor disease groupings.

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[3] Standardised Mortality Ratio: is calculated as the quotient of the observed and the expected number of deaths from a disease or disease group. The expected number of deaths is estimated from national average rates controlled for by possible confounders such as age and gender

[4] 95% Confidence Interval

[5] Standardised Incidence Ratio: is calculated as the quotient of the observed and the expected number of cases of a disease or disease group. The expected number of cases is estimated from national average rates controlled for by possible confounders such as age and gender

[6] International classification of Diseases 9th Revision

[7] Relative Risk: is the risk of developing a disease relative to exposure. Relative risk is a ratio of the probability of developing the disease in the exposed group versus a non-exposed group.

Table 2-2: Table of relative risk estimates for major disease groups and noteworthy minor disease groups.

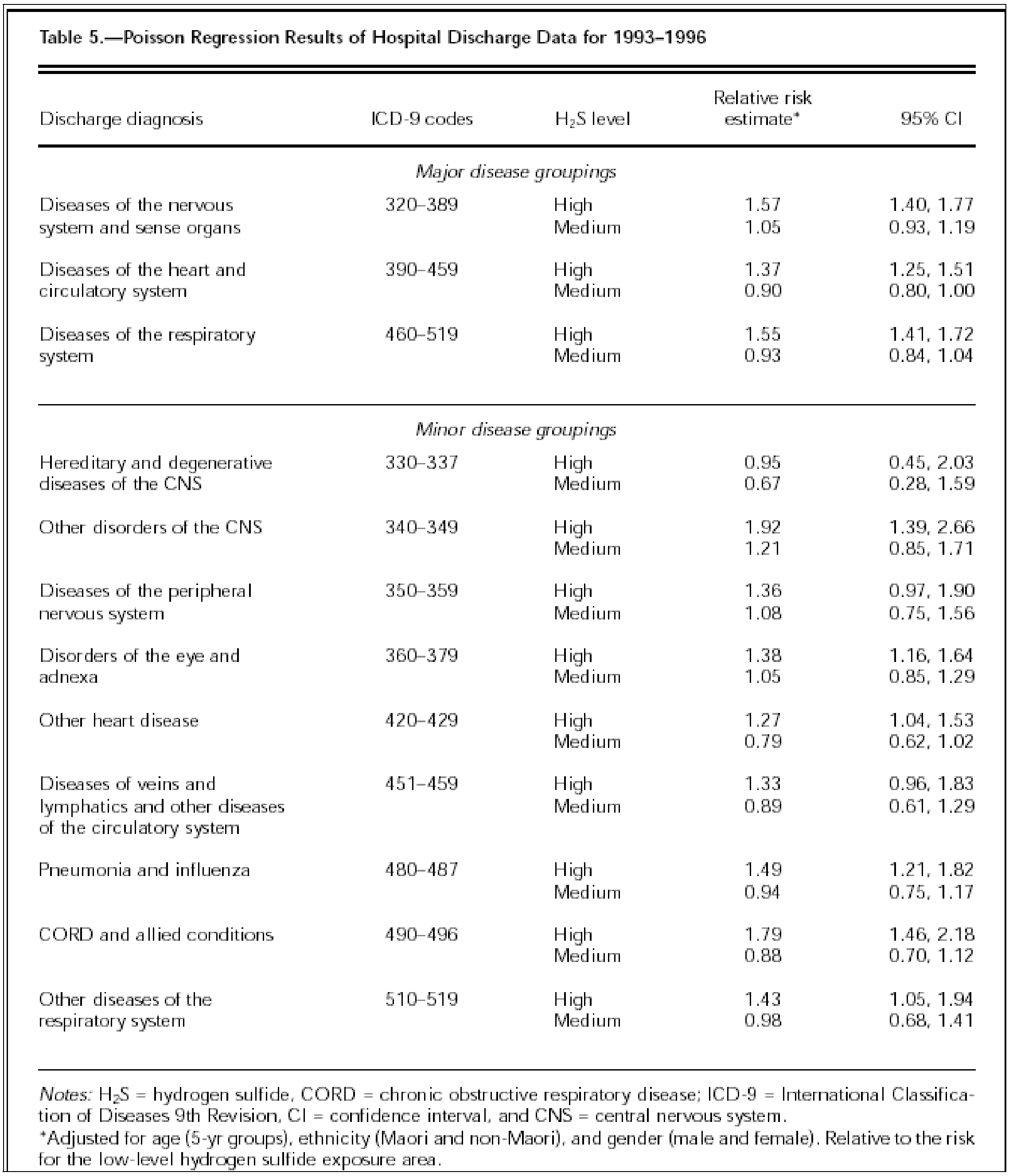

Table 5.—Poisson Regression Results of Hospital Discharge Data for 1993–1996

Discharge diagnosis	ICD-9 codes	H_2S level	Relative risk estimate*	95% CI
		Major disease groupings		
Diseases of the nervous system and sense organs	320–389	High	1.57	1.40, 1.77
		Medium	1.05	0.93, 1.19
Diseases of the heart and circulatory system	390–459	High	1.37	1.25, 1.51
		Medium	0.90	0.80, 1.00
Diseases of the respiratory system	460–519	High	1.55	1.41, 1.72
		Medium	0.93	0.84, 1.04
		Minor disease groupings		
Hereditary and degenerative diseases of the CNS	330–337	High	0.95	0.45, 2.03
		Medium	0.67	0.28, 1.59
Other disorders of the CNS	340–349	High	1.92	1.39, 2.66
		Medium	1.21	0.85, 1.71
Diseases of the peripheral nervous system	350–359	High	1.36	0.97, 1.90
		Medium	1.08	0.75, 1.56
Disorders of the eye and adnexa	360–379	High	1.38	1.16, 1.64
		Medium	1.05	0.85, 1.29
Other heart disease	420–429	High	1.27	1.04, 1.53
		Medium	0.79	0.62, 1.02
Diseases of veins and lymphatics and other diseases of the circulatory system	451–459	High	1.33	0.96, 1.83
		Medium	0.89	0.61, 1.29
Pneumonia and influenza	480–487	High	1.49	1.21, 1.82
		Medium	0.94	0.75, 1.17
CORD and allied conditions	490–496	High	1.79	1.46, 2.18
		Medium	0.88	0.70, 1.12
Other diseases of the respiratory system	510–519	High	1.43	1.05, 1.94
		Medium	0.98	0.68, 1.41

Notes: H_2S = hydrogen sulfide, CORD = chronic obstructive respiratory disease; ICD-9 = International Classification of Diseases 9th Revision, CI = confidence interval, and CNS = central nervous system.
*Adjusted for age (5-yr groups), ethnicity (Maori and non-Maori), and gender (male and female). Relative to the risk for the low-level hydrogen sulfide exposure area.

(Source: Bates *et al.* (2002))

Durand and Wilson (2006) investigated the rates and spatial pattern of respiratory disease in Rotorua using hospital discharge and census data for the years 1991 to 2001 and spatial scan analysis to identify clusters of disease, based on the place of residence. A cluster was defined as a collection of adjacent Census Area Units (CAU)[8] where incidence rates were statistically significantly elevated compared to the rest of the study

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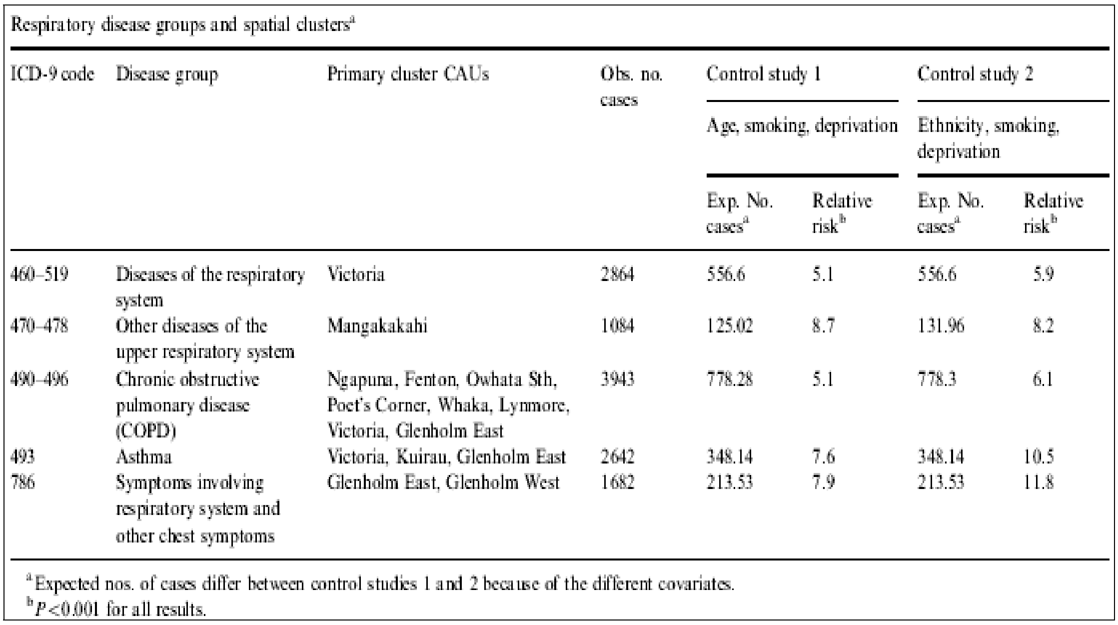
[8] An area unit used by Statistics New Zealand: within urban areas a CAU normally contains a population of 3,000–5,000 people and generally coincides with suburbs. (Source: Statistics New Zealand)

area. The risk of the respective health outcome within the cluster was then statistically compared with that of the population of Rotorua (Durand and Wilson, 2006). Two separate analyses were conducted because combined age and ethnicity data were not available for all census years, controlling for age, smoking and deprivation in one analysis, and ethnicity, smoking and deprivation in the other. Smoking and deprivation status was estimated from census data, as information on an individual level was not available. The statistical results showed strongly elevated risks for respiratory diseases in some CAU areas and are shown in more detail in Table 2-3. The location of the CAU areas and the spatial distribution of the clusters are shown in Figure 2-7.

Table 2-3: Table showing the statistics for the cluster analysis of respiratory diseases in Rotorua.



Respiratory disease groups and spatial clusters[a]

ICD-9 code	Disease group	Primary cluster CAUs	Obs. no. cases	Control study 1		Control study 2	
				Age, smoking, deprivation		Ethnicity, smoking, deprivation	
				Exp. No. cases[a]	Relative risk[b]	Exp. No. cases[a]	Relative risk[b]
460–519	Diseases of the respiratory system	Victoria	2864	556.6	5.1	556.6	5.9
470–478	Other diseases of the upper respiratory system	Mangakakahi	1084	125.02	8.7	131.96	8.2
490–496	Chronic obstructive pulmonary disease (COPD)	Ngapuna, Fenton, Owhata Sth, Poet's Corner, Whaka, Lynmore, Victoria, Glenholm East	3943	778.28	5.1	778.3	6.1
493	Asthma	Victoria, Kuirau, Glenholm East	2642	348.14	7.6	348.14	10.5
786	Symptoms involving respiratory system and other chest symptoms	Glenholm East, Glenholm West	1682	213.53	7.9	213.53	11.8

[a] Expected nos. of cases differ between control studies 1 and 2 because of the different covariates.
[b] $P<0.001$ for all results.

(Source: Durand and Wilson, (2006))

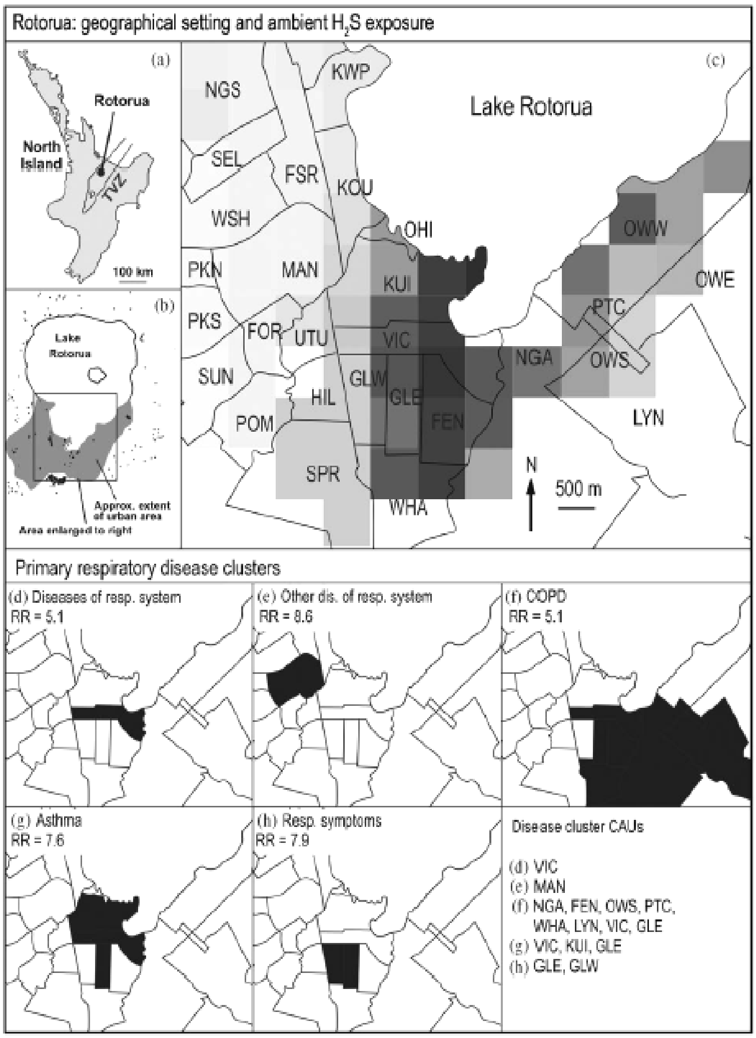


Fig. 1. Rotorua geographical setting, ambient H_2S exposure, and primary respiratory disease clusters. (a and b) Geographical setting of Rotorua city, Rotorua caldera, and the city within New Zealand and the Taupo Volcanic Zone. (c) H_2S exposure and census area units [shaded grid shows ambient H_2S exposure estimates after Horwell et al. (2005); polygons denote CAU boundaries]. (d–h) CAUs containing primary respiratory disease clusters [headings show ICD-9 subgroups and relative risks calculated by the spatial scan statistic].

(Source: Durand and Wilson (2006))

Figure 2-7: CAU areas in Rotorua overlaid by H_2S exposure estimates after Horwell et al. (2005) and clusters of respiratory diseases.

The RR values found by Durand and Wilson (Table 2-3) were substantially higher than the ones reported by Bates *et al.*, which could be due to the following reasons:

1. Bates *et al.* used only the first admission, omitting repeat admissions for any individual for which the same ICD-9 code was recorded, while Durand and Wilson could not remove these repeat visits from their analysis due to the absence of individual identifiers in their data (Bates *et al.*, 1997; Bates *et al.*, 1998; Bates *et al.*, 2002; Durand and Wilson, 2006). Considering that a large proportion of the diseases are chronic and severe forms of these illnesses require patient hospitalisation, the likelihood of readmission over a 10 year period is particularly high, notably for

diseases like emphysema, bronchiectasis and asthma. Thus the inclusion of repeat admissions in the analysis by Durand and Wilson is most likely the main contributor to the high RR values.

2. The studies used different analytical methods, creating different reference populations. Bates *et al.* used the remainder of New Zealand and the low exposure group as reference, while Durand and Wilson used the remainder of Rotorua outside the clusters.
3. The studies had different spatial resolutions. Durand and Wilson investigated clusters of diseases at the CAU levels, while Bates at al. investigated disease occurrence for the whole of Rotorua in their earlier studies and divided Rotorua into three parts, containing a minimum of four CAU areas in their last study. Durand and Wilson suggest that the smaller spatial resolution used in their study may be more sensitive to showing exposure-response relationships, which in turn would increase the RR.
4. There were also differences in controlling for confounders (Durand and Wilson, 2006). Bates *et al.* did not control for smoking and deprivation, which are both known to increase rates of respiratory diseases. Although Durand and Wilson controlled for smoking and deprivation, the use of census data to estimate smoking on the individual level has its own problems. Misclassification could affect the RR either way, depending whether more smokers were misclassified as non-smokers or vice versa.

The design of the above studies using hospital and census data caused the inherent problem that inference to the individual level and to causality which can be drawn from the data, is limited. For example, hospital data excluded cases with milder symptoms from the analysis, *e.g.* asthmatics who have never been hospitalised, whereas hospitalisation rate in asthmatics could be due to differences in treatment or in access to health care, and not be a reflection of a higher incidence rate in asthma. Furthermore, exposure was only based on the place of residence, but a large percentage of the population moves within Rotorua during the day and consequently levels of exposure may vary from the place of residence (Bates *et al.*, 2002; Durand and Wilson, 2006).
Nevertheless these studies were the first to investigate possible health effects of H_2S exposure in Rotorua, providing significant information. As the previous authors have pointed out, the observed trends deserve further investigation.

Chapter 3: Materials and Methods

3.1 Validation and calibration of the personal sampler

The Chemcassette® tape was adapted as a personal sampler since a suitable and affordable commercial H_2S sampler was not available. Although commercially produced samplers are available for occupational settings, they lack the ability to record low H_2S concentrations (<10 ppb) over short periods of time (24 hours). Therefore, these samplers cannot be used for the identification of specific locations and other determinants of increased personal exposure. The sampler developed by Horwell (2004) requires a shelter as it is sun-sensitive, and air monitors are too bulky (and expensive) to be suitable for the specific aims of this study (i.e. measuring personal exposures).

The tape usually runs inside the MDA Scientific Toxic Gas Analyser (Figure 3-1), which is used for the monitoring of air H_2S concentrations.

Figure 3-1: Photo of the MDA Scientific Toxic Gas Analyser monitor with Chemcassette® tape.

The monitor uses an optical scanning system to detect the presence of gas by a colour change on the chemically impregnated paper tape (Chemcassette® tape). The monitor reads colour intensity changes and determines the gas concentration by comparison to a known gas response pre-programmed into the instrument, and the output is recorded by a data logger. The analyser can measure H_2S concentrations in two ranges 0-90 ppb and 50-1500 ppb. For the lower range, the time interval of air sampling before the paper tape is advanced is 15 minutes, whereas for the upper range it is one minute. For this study, all air sampling was done in the lower range except for the December 2007 trial.

The prospect of adapting the Chemcassette® tape as a personal sampler was based on the observation that the tape discoloured correspondingly to H_2S concentrations even outside the analyser (Timpany, 2007). In order to establish whether the tape was suitable, a validation study was done on the 11-12.12.2007. H_2S concentrations were high (137-482 ppb) causing some problems in the interpretation of the results, and the validation study was repeated during the later trials, but with a smaller number of samplers.

It was hoped that the colour change of the tape could be quantified by feeding the paper strips back into the analyser, but the monitor rejected the strips and an additional calibration study was required. In order to quantify the change in colour intensity in the tape, the paper strips were scanned using Photoshop S52 and allocated a grayscale value from 255 (white) to 0 (black). The grayscale values were transformed into H_2S concentrations by mathematical modelling. A similar method has been used previously by Horwell *et al.* (1998, 2004).

3.1.1 Validation study

The aims of the validation study were:

1. to establish whether samplers exposed in the same location over the same time period would react uniformly
2. to establish whether the samplers were affected by direct sunlight, humidity or other pollutants such as carbon dioxide
3. to establish the exposure range (upper and lower detectable limit) of the samplers
4. to confirm that 24 hours would be an appropriate exposure length.

For the validation studies, paper strips were prepared in Wellington two days before exposure in Rotorua to avoid unintentional exposure to H_2S during preparation.

The paper tape was removed from its cassette and cut into strips, using powder-free latex gloves to prevent contamination of the paper surface. Then the paper strips were labelled at the edge of the reactive site and kept in air tight jars until their exposure in Rotorua.

After 24 hours of exposure the samplers were collected, placed in jars and scanned on return to the NIWA office. The delay between collection and scanning was between 5 and 30 minutes for the December 2007 trial and between 5 and 15 minutes for the November 2008 trial. On each paper strip a rectangular area of 45000 pixels (300x150 pixels) was scanned to keep the number of pixels uniform between the samplers and to avoid the area of labelling and the edges of the tape, where discolouration was often stronger. Date, time, location and the statistics of the grayscale histogram (median[9] and standard deviation) from each sampler were recorded, as were any unusual occurrences.

In the December 2007 trial, the samplers were exposed at three locations in Rotorua: at Te Ngae Road, at the waste water plant which lies to the south-east of the Te Ngae Road site and at the Polytechnic which lies just to the west of the Arikikapakapa geothermal area. At each site 20 paper strips were directly exposed to the air and an additional 40 paper strips were placed in tubes with an opening at the bottom to protect the samplers from humidity and exposure to sunlight (Figure 3-2). Unfortunately the opening of the tubes was too narrow and occasionally the tape had creased, leading to a very uneven discolouration of the sampler.

Figure 3-2: Photo of the validation study setup, December 2007.

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[9] The median was used rather than the mean value as a few samplers had little specks on them due to contamination with water or mud.

For the November 2008 trial, cups which had a wider opening were used, and the tape was put into key tags with a cardboard backing to avoid creasing. Samplers were exposed either directly to the environment or sheltered by a clear or darkened cup with 5 samplers in the uncovered group and 4 samplers in each sheltered group (Figure 3-3).

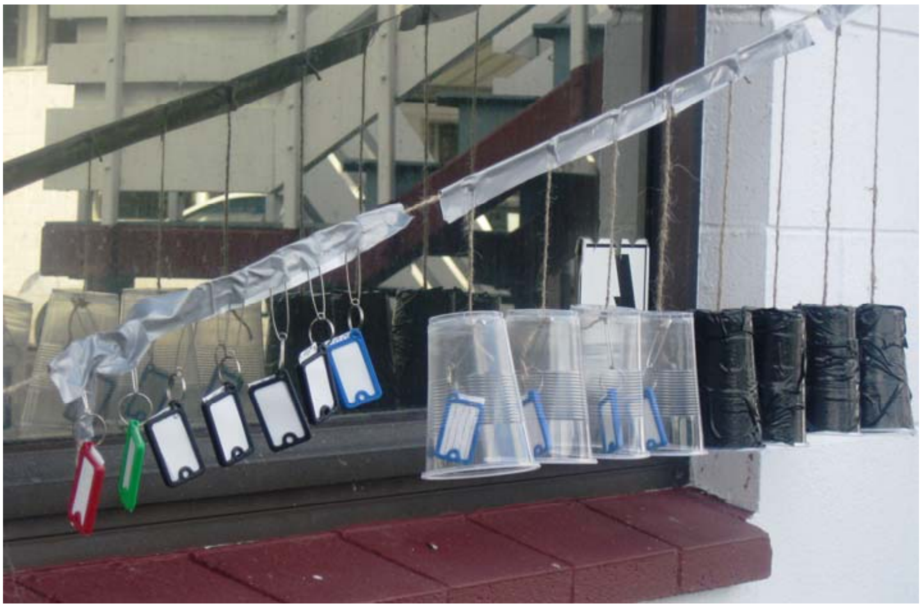

Figure 3-3: Photo of the validation study setup, November 2008.

3.1.2 Calibration Study

For the calibration study, the samplers were located next to the air intake tube of the gas analyser at Te Ngae Road. Because the gas analyser was simultaneously used to take outside air samples for the study on the influence of meteorological factors on air H_2S concentrations, the calibration samplers needed to be located on the outside, too. During the June and October 2008 trials, all samplers showed silver discolouration with the exception of one set of samplers, and during the April 2008 trial the gas analyser had malfunctioned. Due to the ensuing lack of data, it was decided to move the November 2008 calibration setup to Luxor Place in western Rotorua where H_2S concentrations were generally lower. However over the next 24 hours, H_2S concentrations at Luxor Place remained at zero and the setup was moved back to Te Ngae Road, but this time inside the NIWA office to reduce exposure levels (Figure 3-4).

Figure 3-4: Photo of the calibration setup, November 2008.
The white tubing in the centre is the air intake tube of the gas analyser.

Because the discolouration of the tape was also time dependent (the analyser uses different exposure lengths for the two measuring ranges) especially in the first 6-8 hours, the duration of exposure was set at 24 hours.

Eight sets of samplers (6 samplers each) were exposed for 24 hours during the 25th and 26th of November 2008. Of these 8 sets, 2 showed silver discolouration, leaving 6 sets available for calibration plus one set from the June 2008 trial and the two sets of zero exposure.

The average H_2S concentrations for each 24-hour time period were calculated from the 15-minute recordings of the gas analyser. For H_2S concentrations exceeding the maximum detectable limit (90 ppb) of the analyser, the data logger recorded a value of 90 ppb. This value was also used in the calculation of the 24-hour average. Additionally the number of readings above the upper detectable limit was recorded for every 24-hour period, as it indicated how accurate the 24-hour average values were. The H_2S concentrations were log transformed and different mathematical models were applied using STATA® 10.

3.2 Personal exposure study

3.2.1 Recruitment of participants

For the personal exposure study, pupils from Rotorua colleges, and a smaller group of adults, residing or working in Rotorua who were suspected to have higher exposure levels were recruited.

The pupils were recruited by contacting the five colleges in Rotorua. Two colleges, Rotorua Girls High (RGH) and Rotorua Lakes High (RLH) agreed to participate. A presentation was either given at assembly or in the classrooms to explain the aim and set up of the study and how to use the samplers and maps. Potential participants received an information sheet (Appendix 3), a copy of the Low Risk Notification by Massey University's Human Ethics Committee, and a parental consent form (Appendix 4), if applicable.

In 2007, an initial visit to Rotorua included discussions with the Rotorua District Council, Toi Te Ora - Public Health Service (Rotorua office), and NIWA Rotorua. All three parties were of the opinion that the percentage of the population which would be exposed to higher H_2S concentrations (>0.1 ppm) would be very small.

Based on this information and in order to establish exposure levels for the higher exposure group, it was decided to recruit a group of participants assumed to be exposed to higher H_2S concentrations owing to the location of their residence or work. The recruitment for this group was done with the help of the Rotorua District Council. Potential participants were approached individually and received the same information as the pupils. This group was referred to as Rotorua District Council (RDC).

Participants were notified of their individual results in November 2009 (Appendix 5).

3.2.2 Personal exposure sampler

The samplers were prepared using the same method as in the validation/calibration study. To enable the participants to wear the samplers outside their clothing, the paper tape was put into key tags with a cardboard backing for support, and a safety pin was attached to the key tag (Figure 3-5).

Samplers were marked with a unique identification number, one allocated to each participant and used for all trials.

Figure 3-5: Photo showing personal samplers.

The same storage and grayscale scanning methods were used as in the validation/calibration study with the exception that samplers were not always scanned immediately, but scanned in Wellington 24 - 48 hours later.
To ascertain that the delay did not affect the grayscale readings, 20 samplers were scanned immediately in Rotorua and then rescanned in Wellington after 48 hours without detecting any difference in 18 samplers, while two samplers showed a difference of around 2 in the grayscale readings. These samplers were the only samplers with grayscale readings below 150 (brown discolouration) and as the precision of the grayscale readings decreases rapidly with increasing discolouration, a difference of 2 is negligible at this scale range.

3.2.3 Statistical analyses

During the validation trial in December 2007, it was realised that the Chemcassette® tape had an upper detectable limit (section 4.1.1.2), corresponding to an H_2S value of 90 ppb. To not have to exclude samplers that exceeded the maximum detectable limit from the statistical analyses, an arbitrary value of 150 ppb was given to these samplers, which is around 75% of the maximum detectable limit added to 90 ppb.

The same method was applied to the minimum detectable limit of 1 ppb, allocating an arbitrary value of 0.25 ppb to samplers with a grayscale reading of 255 (no detectable change). The following tables show the number of affected samplers for each group and trial.

Table 3-1: Number of personal and home samplers given the value of 150 ppb.

Group	**April 2008**	**June 2008**	**October 2008**	**November 2008**	**total**	**Home**
RDC	2	2	3	5	12	0
total % of returned samplers	2 1.98	2 1.96	3 3.33	5 5.95	12 3.18	0

Table 3-2: Number of personal and home samplers given the value of 0.25 ppb.

Group	**April 2008**	**June 2008**	**October 2008**	**November 2008**	**total**	**Home**
RGH	0	0	0	0	0	5
RLH	0	0	2	1	3	9
RDC	0	0	0	0	0	4
total % of returned samplers	0	0	2 2.22	1 1.19	3 0.79	18 21.96

In the statistical analyses, the group variables were a proxy for location and matched loosely the exposure areas classified by Horwell *et al.* (1998, 2005). RGH represented the western site of Rotorua, RLH the eastern site and RDC the corridor along central Rotorua.

The trials were a proxy for different time periods, as it was expected that personal exposure levels would vary over time depending on changes in weather conditions and/or geothermal activity.

As the H_2S concentrations from the personal samplers were strongly skewed towards the lower end of the scale, several transformation models were tested, ultimately concluding to log transform the data.

The data were analysed by univariate analysis, multiple regression analysis and stratified by group and trial using STATA® 10 software. Group and trial were the independent variables and both were categorical. For the groups, RGH was used as the reference group, because its participants were mainly located in the west, where consistently low H_2S concentrations were recorded (Horwell *et al.*, 2005; Petersen *et al.*, 1998), while for trial, the November 2008 trial was used as a reference variable, because the lowest H_2S concentrations in ambient air and personal samplers were recorded during this trial.

3.2.4 Mapping

The software used for mapping was ArcGIS 9.2. For each trial, the locations participants had marked on the maps were entered into a road map of Rotorua. The personal sampler identification number, the H_2S concentration of the personal sampler, the time spend at that location, inside and outside times and any remarks were entered into the attribute table of the map. If a participant visited more than one location in Rotorua, all locations were given the H_2S concentration of the participant's personal sampler, because only rarely was it possible to identify the exact location of exposure.

3.2.5 Home sampler

To further reduce the number of possible exposure locations and to compare personal vs. environmental exposure levels, participants received an additional sampler to measure H_2S concentrations in their home, accompanied by an information sheet during the October trial (Appendix 6).

The home sampler was a strip of the Chemcassette® tape about the same length as the personal sampler, but without the key tag. It was marked on the reactive site of the tape with an 'H' and the ID number of the personal sampler and put in a snap-sealed plastic bag

In order not to confuse samplers with very low readings, with samplers that had not been exposed, participants who chose to opt out of this trial were asked to discard their sampler.

As almost all participants received their samplers at work or school during the morning of the trial, the exposure time of the home samplers was reduced to between 14 and 18 hours of the 24-hour period

3.2.6 Environmental control sampler

In order to get a better understanding of where exposure occurred and to compare personal vs. environmental exposure levels, environmental control samplers were placed at the colleges and at a further four locations where groups of participants worked together.

Environmental samplers were identical to personal samplers including the key tag. At each location, samplers were exposed at least in duplicate, inside and outside of a building. If H_2S concentrations above 2000 ppb were expected, a Gastec passive dosimeter tube was exposed concurrently, whenever possible. The Gastec passive dosimeter tube records cumulative exposure in a range of 10 to 200 ppm.
Again due to unforeseen circumstances, environmental samplers could not always be exposed at every location during every trial.

3.3 Influence of meteorological factors on H_2S air concentrations

To analyse the available meteorological data, the following observations collected by the New Zealand Meteorological Service were used from Rotorua Airport: wind direction, wind and gust speed, air pressure, relative humidity, rainfall, air temperature, dew-point and bulb temperature. Wind directions were reported in 16 categories, which were reduced to four to constrain the number of variables for the statistical analysis. The groupings were as follows: NE (NNE, NE, ENE, E), SE (ESE, SE, SSE, S), SW (SSW, SW, WSW, W), NW (WNW, NW, NNW, N).[10]

Due to the suspension of routine air H_2S monitoring in Rotorua during 2008, H_2S data were collected from outside air by the H_2S monitor, which was calibrated to read in the 0 to 90 ppb range and located at the NIWA office on Te Ngae Street (see Figure 2-1). Outside air samples were used rather than the data from personal samplers, because the former had a wider range of H_2S concentration than the latter (75% of H_2S levels below 5ppb). Furthermore, using outside air samples allowed analysing data over 1-hour intervals instead of 24-hour intervals as with the personal samplers. H_2S levels were recorded in 15-minute intervals which were converted to hourly averages to align with the hourly recordings of the meteorological data. If more than 2 recordings were above the upper detectable limit in an hour, the hourly H_2S concentration was classified as >90ppb.

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[10] Please note that the northerly wind direction is not included in the NE group

The data only incorporated readings from June (9-11.6.2008) and October 2008 (11-13.10.2008), because in April 2008 the monitor malfunctioned and in November 2008 the monitor was moved inside the NIWA office to facilitate the calibration study.
Additional H_2S recordings were taken in December 2007 (11.12.2007 from 07.45-13.00 hrs) during the first validation study, but the observation period was only five hours short and the monitor was calibrated to read in the higher 50 to 1500 ppb range. The December data were not used in the statistical analysis, because of the different measurement range. However, it was included in the descriptive statistics as H_2S concentrations were much higher (137-482 ppb), potentially providing further information on any associations between H_2S levels and meteorological factors. The December 2007 data recordings were taken in one-minute intervals and also converted to hourly averages. None of the observations were below the monitor's minimum detectable limit of 50 ppb.

The data were analysed by multiple regression, using STATA® 10 software.
Data from June and October 2008 were combined to have an adequate number of observations for the statistical analysis and all recordings were converted to New Zealand Standard Time. Readings above the upper detectable limit of 90 ppb were given a value of 150 ppb as in the analysis of the personal sampler. The H_2S levels were log-transformed and used as the dependent variable, while the meteorological observations were the independent variables. All independent variables were continuous except for wind direction, which was grouped into four categories, as described previously. SW winds were used as the reference variable since they had the lowest H_2S concentrations.

Before starting the multiple regression analyses, univariate analyses were completed for each independent variable and only independent variables with p-values ≤ 0.05 were entered into the multiple regression models, beginning with the variable with the smallest p-value and the largest standardised beta coefficient. Additionally the independent variables were tested for collinearity.

3.4 Health survey

In 1999, the Public Health Unit in Rotorua under Dr Phil Shoemack conducted a health survey asking participants about health symptoms and recording where people lived and worked as well as their residence time. Data collection and entry had been completed but the analyses of the data were still outstanding. These have been completed as part of this study to examine any possible association between the findings of the H_2S personal exposure study and the health survey.

The health survey was based on 370 completed questionnaires. Participants were randomly selected within the CAU areas by selecting every third house in a road and were approached by an interviewer, who assisted with the completion of the questionnaires. The questionnaire is reproduced in Appendix 7, while the selection process of participants is explained in more detail in the instruction sheet for the interviewer (Appendix 8).

Participants had been grouped into three H_2S exposure categories (high, medium, and low) by giving each Rotorua CAU an exposure category according to the zones established by Horwell *et al.* (2005).

In population based studies, the occurrence of disease may be influenced by a multitude of factors. The most common factors are age, sex, ethnicity and smoking status. The distribution of these factors in the three exposure groups were tabulated in the population statistics of the study and tested for differences between the exposure groups by using the t-tests for continuous variables (age and residence time) and the chi-square tests for categorical variables (sex, ethnicity and smoking status).

In order to assess a possible association between exposure levels and health effects, logistic regression analysis was applied. Using the current residential address for the exposure classification, crude and adjusted (controlled for age, sex, ethnicity and smoking status) odds ratios (OR)[11] and confidence intervals (CI)[12] were calculated for

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[11] Odds ratio: in logistic regression analysis an odds ratio of 3 is interpreted as participants in the exposure group being 3 times as likely to suffer a disease as participants in the low exposure group, while an odds ratio of 1 is interpreted as a lack of difference between two groups. A value below 1 is attributed with a protective effect.

[12] The confidence interval is an indicator of statistical significance and gives the range of values, which include the true value of the odds ratio. For the logistic regression analysis a CI including the 1 is deemed not to be statistically significant, as the effect of the exposure could either be protective or harmful (see odds ratio).

the following diseases: asthma, hypertension, epilepsy, other neurological conditions, cancer, sinus disorders, and cataract and skin disorders. Asthma was further categorised by the severity of disease into the 'Hospitalisation for asthma' and 'On medication for asthma' groups.

Notably higher odds ratios, although without statistical significance, were obtained for asthma and cataract. For these diseases the statistical analyses were repeated, refining the exposure models as follows:

- Participants who had resided for less than two years at their current address were given the exposure classification of their previous residential address.
- Participants who had resided for less than two years at their current address were excluded from the analysis, if their exposure category had changed.
  This model was introduced as it was unknown for how long participants had resided at their previous residence; however it reduced the number of observations
- Exposure categories from the home and work address of each participant were time-weighted and used to create a combined overall exposure category.
- The combined exposure category was further modified, like the residential model, by reclassifying or excluding participants who had changed home or work address in the previous two years.

In order to determine whether the length of residence time in Rotorua was associated with asthma, residence time was analysed for differences between the exposure groups. Then logistic regression analyses were performed separately for observations having a residence time above 3, 5, 7 and 10 years and their ORs compared.

In order to compare the findings of the personal exposure study with the findings of the health survey on a more detailed spatial level, asthma occurrence were mapped using ArcGIS. The different exposure zones in Rotorua used by the health survey were marked on the map, and the current residential address of participants was added by using different symbols for asthmatics and non-asthmatics. Participants living at their current address for less than 2 years were excluded. The resulting map was compared with the personal exposure maps.

Note that the observations used in the statistical analyses based on the previous residential address and the mapping data vary slightly from each other, because in the statistical analysis, participants with missing entries for age, sex, ethnicity and smoking status were excluded, but included in the mapping.

Furthermore, in the statistical analyses, participants were only excluded if their exposure category had changed in the last two years, but in the mapping all participants who had changed address in the last two years were excluded.

All statistical analyses were conducted using STATA $9^{®}$/ STATA $10^{®}$.

Chapter 4: Results

4.1 Validation and calibration of the personal sampler

4.1.1 Validation study

4.1.1.1 Precision of the sampler

While scanning samplers with varying degrees of discolouration it became apparent that the standard deviation of the grayscale histogram increased with increasing discolouration (decreasing grayscale value). Thus the precision of the grayscale readings declined with increasing discolouration. The readings of the grayscale histogram for various values are given in Appendix 9.

4.1.1.2 Upper and lower detectable limits of the sampler

With increasing H_2S concentrations, the samplers changed colour from white to beige to brown, but then to silver. The silver discolouration caused problems with the grayscale scanning as the colour change from white to brown matched a decrease in grayscale values, but the silver discolouration produced a lighter colour. Hence the grayscale value increased representing an erroneous low H_2S concentration. Furthermore, as the scanning produced a black and white image, the silver discolouration was not always detectable on the image. Therefore the upper detectable limit of the sampler was set to the level where silver discolouration started to occur between the grayscale values of 80 to 70, corresponding to a H_2S value of 90 ppb (section 4.1.2.2) and samplers were visually inspected for silver discolouration before scanning.

The different stages of silver discolouration are shown in Figure 4-1, while Table 4-1 shows the effect of silver discolouration on the statistics of the grayscale values. The displayed samplers and statistics are from the December, 2007 trial and had been exposed at three different sites in Rotorua.

The silver samplers from the waste-water plant site had clearly higher grayscale values than the other two sites which showed browner colours. The samplers from the other two sites showed similar mean and median values, but the standard deviation and maximum value were larger in the samplers from the Polytechnic site due to a silver hue.

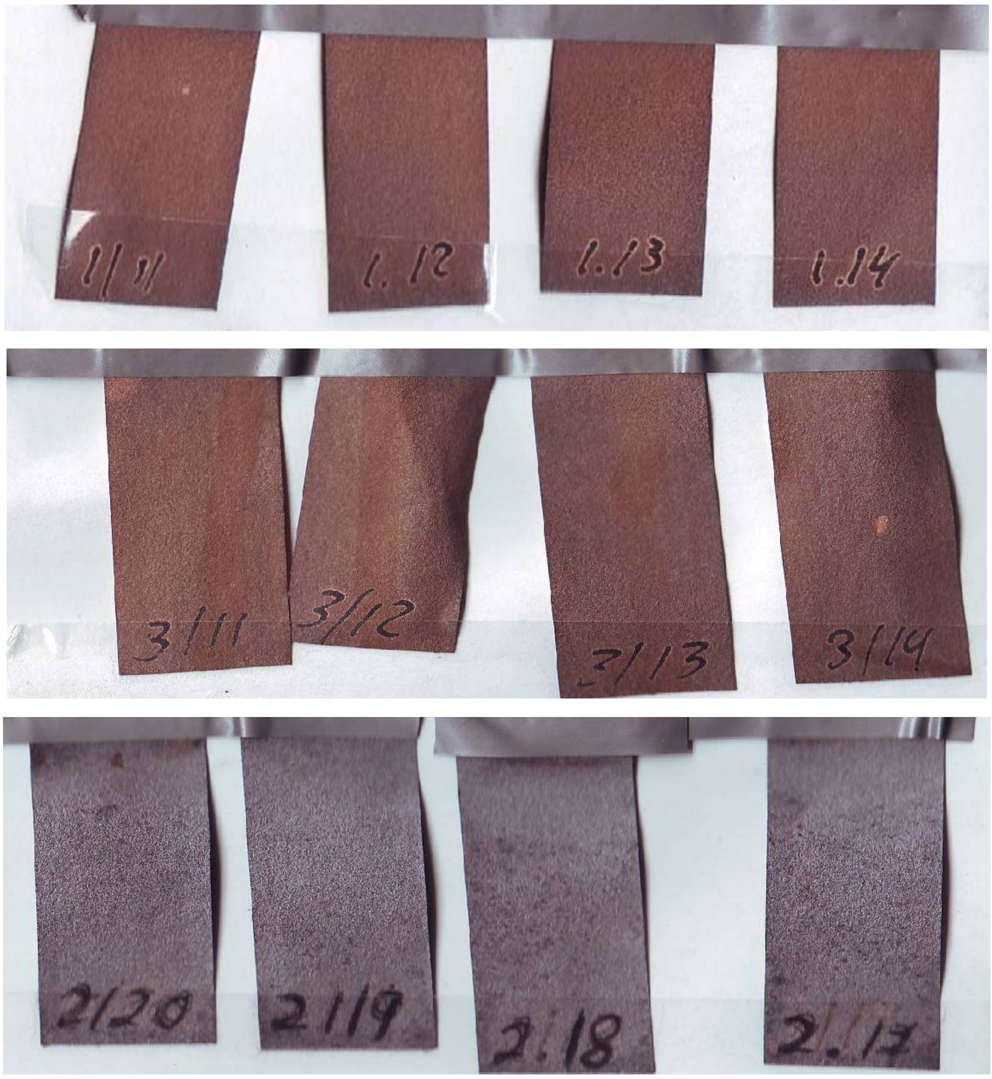

Figure 4-1: Enlarged photo of samplers with varying stages of silver discolouration during the validation trial, December 2007.

The top row (Te Ngae Road)[13] shows an even dark brown discolouration, while the middle row (Polytechnic) shows the beginning of silver discolouration and the bottom row (waste water treatment plant) shows a very strong silver discolouration.

Table 4-1: Statistics of grayscale values during the validation trial, December 2007

Location	mean	median	sd[1]	min	max	N[2]
Te Ngae Road	85.7	86.0	2.1	81	88	20
Polytechnic	85.2	85.5	7.7	75	100	20
Waste water plant	104.9	110.0	15.5	74	124	20

[1] standard deviation

[2] number of observations

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[13] Please note that samplers at Te Ngae Rd were only exposed for 6 hours instead of 24 hours as at the other locations.

The lowest H_2S recording taken by the gas analyser was 2.55 ppb with corresponding grayscale readings of 233 to 231, while the grayscale value of blanks was 255. Thus a concentration of 2.55 ppb represented a drop of 20 on the grayscale, which was substantial for this grayscale range indicating that the accuracy of the sampler is high at this grayscale range. Hence it is likely that the sampler would record values as low as 1 ppb and the lower detectable limit was set at 1ppb.

4.1.1.3 Susceptibility of the sampler to environmental influences and uniformity of discolouration

Because the validation samplers had shown silver discolouration for all trials except the November 2008 trial, only the results of this trial are discussed below.

In order to ascertain whether the samplers were sensitive to direct sunlight and humidity, groups of samplers were exposed to the environment either directly or sheltered by a plastic cup, half of them covered to block out sunlight. The difference in grayscale readings between the groups was larger than in each group. However considering the accuracy of the sampler is reduced at this degree of discolouration, the differences in grayscale values between the groups were still relatively small and it was thought to be acceptable to use the samplers without further protection. The statistics of the grayscale readings are given in Table 4-2, while Figure 4-2 shows the discolouration of the samplers.

In each group the discolouration of the samplers was relatively uniform. For example, the samplers exposed directly to the environment had grayscale values between 179 and 168 (Table 4-2). A difference of 11 on the grayscale is relatively small for this stage of discolouration, where the standard deviation of the grayscale histogram in each sampler is above 20. Thus the samplers discoloured reasonably uniformly.

Table 4-2: Statistics of grayscale values of uncovered and covered samplers, validation trial November 2008.

Exposure type	mean	median	sd	min	max	N
clear cups	191.3	189.0	6.7	186	201	4
covered cups	176.8	176.5	2.8	174	180	4
direct to the environment	176.2	178.0	4.7	168	179	5

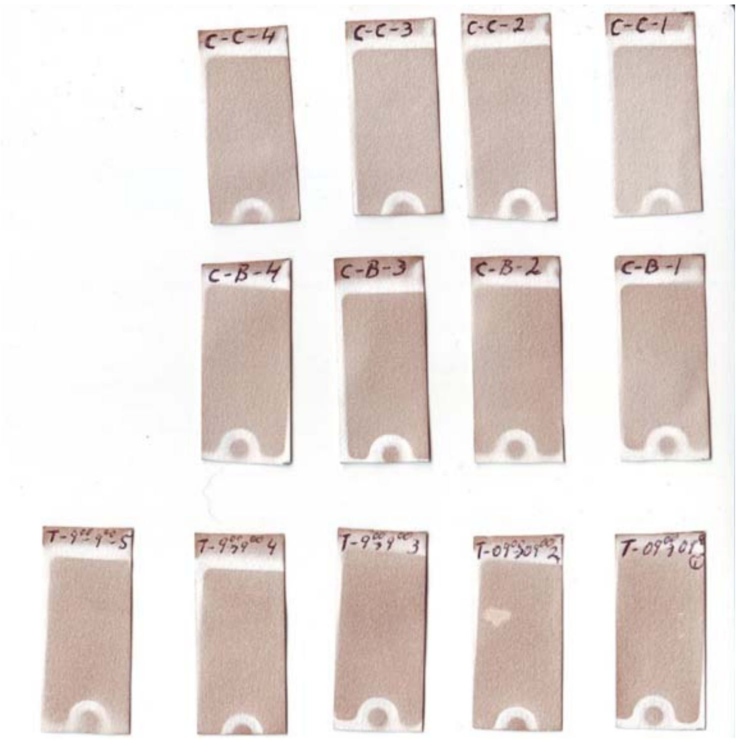

Figure 4-2: Photo of uncovered and covered samplers, validation trial, November 2008.

The top row shows samplers protected by a clear cup, the middle row samplers protected by a darkened cup and the bottom row samplers without cover.

In order to ascertain whether the samplers were sensitive to other pollutants, three samplers each were exposed inside and outside in Wellington. The inside samplers were very close to a wood burner and the outside samplers were exposed to the emission from the chimney. For the inside and outside group, the difference in the grayscale values before and after exposure were minimal (1 and 2 respectively), indicating a suitable degree of specificity to H_2S in the sampler. The statistics from the grayscale readings of the samplers are given in Table 4-3.

Table 4-3: Grayscale statistics of samplers exposed in Wellington, 10-11.10.2008.

Wellington	exposure	mean	median	sd	min	max	N
inside	pre-exposure	255.0	255	0	255	255	3
	post-exposure	253.7	254	0.6	253	254	3
outside	pre-exposure	255.0	255	0	255	255	3
	post-exposure	253.0	253	0	253	253	3

4.1.1.4 Storage of the sampler

In order to ascertain whether the storage of the samplers was appropriate, blanks were left in jars in Rotorua during each trial. All samplers had grayscale values of 255 before being placed in the jar, and values between 255 and 253 after being taken to Rotorua. However during the October 2008 trial, one sampler returned a reading of 250; it was then discovered that the lid of the jar had not been completely tightened causing unintentional exposure. For comparison a jar with five samplers was also left in Wellington during the October 2008 trial and when scanned four days later, all samplers had a reading of 255.

Disregarding the sampler with a grayscale reading of 250, all samplers placed in the jars and taken to Rotorua had a difference in grayscale values of 2 or less. This difference was small enough to find the jars an acceptable mode of storage. The statistics of the samplers kept in jars for the October 2008 trial are given in Table 4-4.

Table 4-4: Statistics of blank samplers kept in airtight jars in Rotorua and Wellington, October 2008 trial.

Jar	pre-/post exposure	mean	median	sd	min	max	N
Rotorua	pre-exposure	255	255	0	255	255	5
	post-exposure	253.2	254	1.8	250	254	5
Wellington	pre-exposure	255	255	0	255	255	5
	post-exposure	255	255	0	255	255	5

4.1.1.5 24-hour exposure length

Although the high number of outside samplers showing silver discolouration in the December 2007 trial suggested that an exposure length of 24 hours may be too long, it was decided to use this duration, as exposure levels in the majority of personal samplers were expected to be significantly lower. The exposure time of 24 hours was found to be of suitable length in the later trials.

4.1.2 Calibration study

4.1.2.1 Precision and accuracy of the sampler

As already mentioned, the precision of the samplers may decline with increasing H_2S concentrations due to the way the paper tape discolours. The following observations from the calibration study (Table 4-5) may indicate a further reduction in precision and accuracy of the sampler for higher H_2S concentrations:

- The sets of 24-hour samplers with grayscale values above 200 (low H_2S exposure) have a low standard deviation and a small difference between the minimum and maximum value, compared to the sets of 24-hour samplers with grayscale values below 200.
- The sets of 24-hour samplers with grayscale values below 190 ppb had readings above the upper detectable limit of the gas analyser for up to 5 hours, while samplers above a grayscale value of 190 did not have any such recordings. Thus the actual H_2S concentration of the former is not known.
- Silver discolouration of the samplers started to occur at grayscale values between 80 and 70. The grayscale values available from the calibration samplers ranged from 255 to 110. Consequently grayscale values from 110 to 85 could only have an H_2S concentration allocated by extrapolation.

The above findings suggest that the accuracy of the sampler begins to decline at grayscale values between 200 and 180, approximately equivalent to a H_2S concentration of 10 ppb. The grayscale readings from the 24-hour sampler sets and the corresponding H_2S concentrations are listed in Appendix 10, while the summary statistics (Table 4-5) and the scatter plot (Figure 4-3) are shown below.

Table 4-5: Statistics of grayscale readings for each 24-hour trial, the corresponding H_2S concentration, and the number of readings above the maximum detectable limit (>90 ppb).

Date	**Time**	**mean**	**median**	**sd**	**min**	**max**	**H_2S (ppb)**	**>90ppb**	**N**
24.11.2008	09.00	255	255	0	255	255	0	0	6
24.11.2008	11.00	255	255	0	255	255	0	0	6
25.11.2008	09.00	232	232	0.9	231	233	2.55	0	6
25.11.2008	11.00	218	218	1.0	217	220	4.67	0	6
25.11.2008	13.00	199	200	3.9	195	204	8.87	0	6
25.11.2008	15.00	181	183	6.0	173	187	15.03	2	6
26.11.2008	09.00	125	122	6.3	119	134	44.77	19	6
26.11.2008	11.00	117	118	5.0	111	123	44.26	16	6
09.05.2008	13.00	174	175	7.8	158	184	24.15	5	19

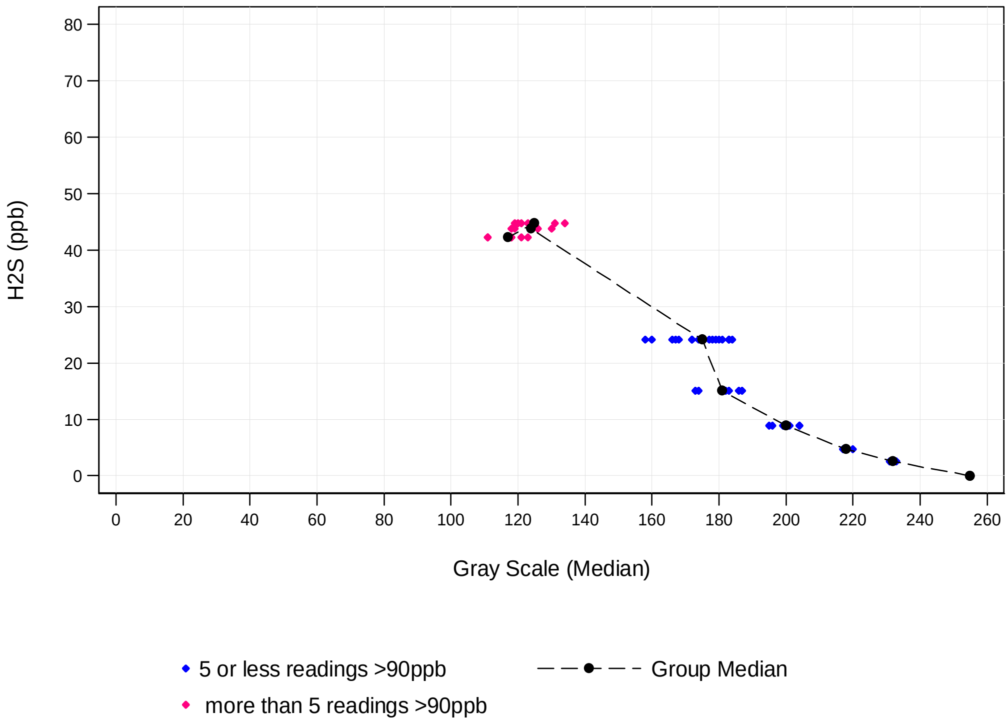

Figure 4-3: Graph showing grayscale values versus H_2S concentrations.

The group median denotes the median from each 24-hour sampler set.
Please note that points with the same grayscale value overlie each other in the graph.

4.1.2.2 Mathematical modelling

For the mathematical modelling the H_2S concentrations were log transformed. The scatter plot for the log transformed values and the fitted linear regression curve with confidence interval are displayed in Figure 4-4.

A variety of mathematical models were tested to correlate the H_2S concentrations as closely as possible to the grayscale values and it was found that quadratic and spline[14] regression improved on the linear regression fit. The R^2 statistics of these models are given in Table 4-6.

For the spline model only one knot per graph was used, as additional break points did not improve the fit of the model notably. For closer comparison, three different spline models were run using knots at 180, 190 and 200 on the grayscale, as the slope of the scatter plots (Figure 4-3) changed in the area between grayscale values 200 and 180, and this is also the area where the accuracy of the sampler started to decline.

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[14] In linear spline regression, knots (break points) are introduced into the line to give it the freedom to bend.

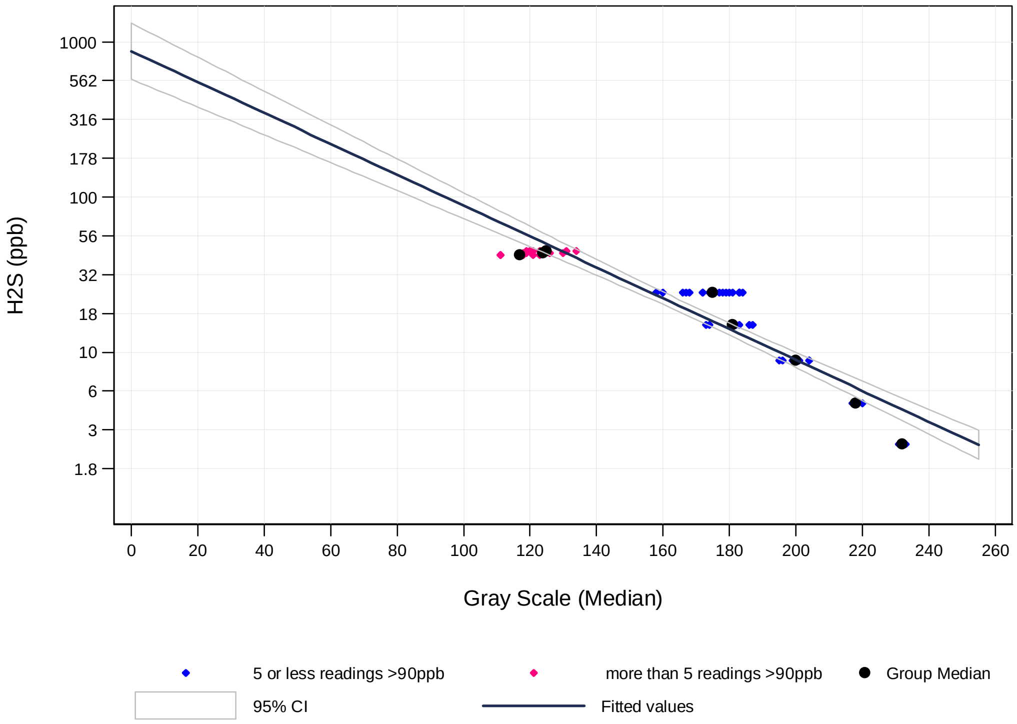

Figure 4-4: Graph showing grayscale values versus log H_2S concentrations and the linear regression fit with confidence interval.

Table 4-6: R^2 statistics for the regression models.

Model	**R^2 (%)**	**Adjusted R^2 (%)**
Linear	86.47	86.24
Quadratic	97.23	97.13
Spline (grayscale value 200)	95.50	95.35
Spline (grayscale value 190)	97.04	96.94
Spline (grayscale value 180)	97.70	97.62
Number of observations: 61		p<0.001 for all models

All models had areas of specific high association with the corresponding H_2S concentrations, but overall differences between the models were relatively small. The table of predicted H_2S values by the different models is given in Appendix 2.

The quadratic regression was excluded because it predicted H_2S values to drop for some lower grayscale values.

From the remaining spline models, the function with a knot at grayscale value 190 was selected, because grayscale values just above and below 190 had different H_2S concentrations (15 and 9 ppb respectively), while at the other two knots H_2S

concentrations were the same above and below the knots. Furthermore the accuracy of the grayscale readings changed at 190, as samplers with a grayscale value above 190 did not have any recordings over the upper detectable limit of the gas analyser, while the samplers with grayscale readings below 190, all had recordings over the upper detectable limit. However the average 24-hour H_2S concentrations recorded for grayscale values below 190 still had enough accuracy to be used for calibration because over half of these values had only 5 or less out of 96 recordings above the upper detectable limit (Figure 4-3).

The recorded and predicted H_2S concentrations and the corresponding grayscale values for the spline 190 model are shown in Table 4-7, while Figure 4-5 shows the calibration graph using log H_2S concentrations and Figure 4-6 shows the final calibration graph using H_2S concentrations in ppb.

Table 4-7: Recorded and predicted H_2S concentrations and the corresponding range of grayscale values for the spline 190 calibration model.

Grayscale values	H_2S (ppb) - model	H_2S (ppb) - gas analyser
255	0.84	0
233 - 231	2.33 - 2.56	2.55
220 - 217	4.26 - 4.90	4.67
204 - 194	8.95 - 13.58	8.87
187 - 173	17.84 - 21.60	15.03
160 - 184	18.59 - 26.52	24.15
118 - 130	38.89 - 45.83	43.76
134 - 119	36.82 - 45.21	44.77

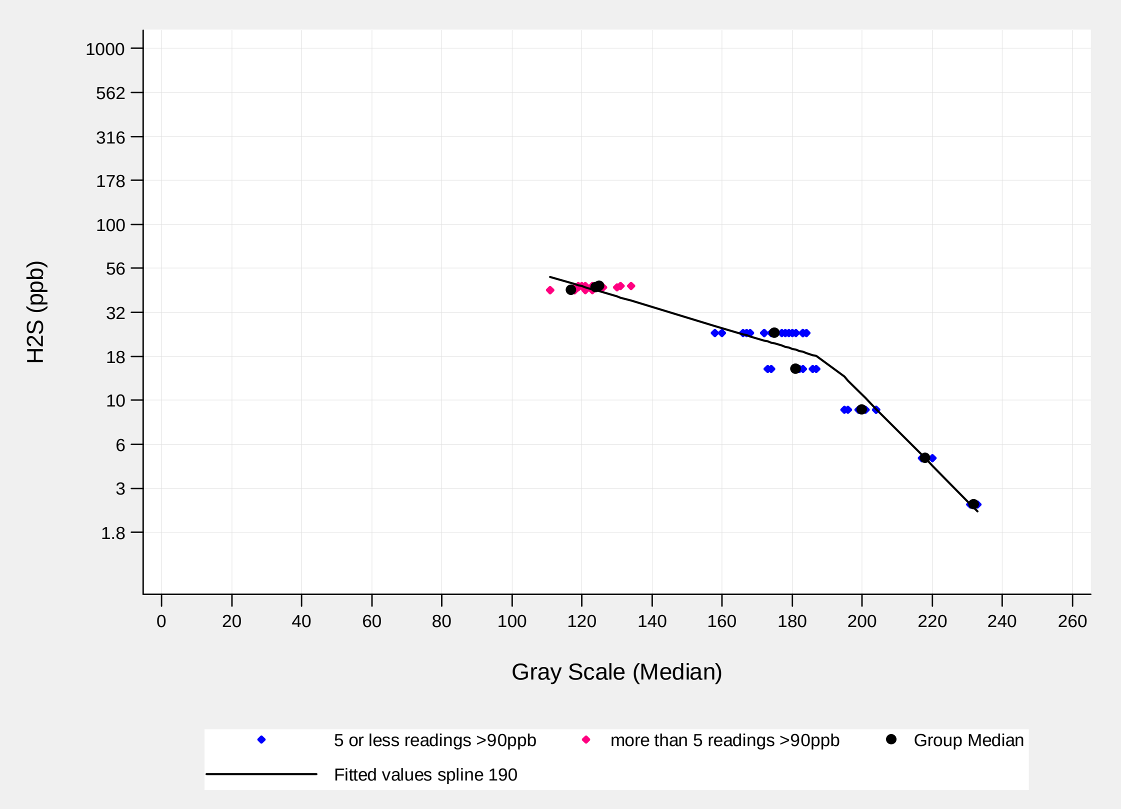

Figure 4-5: Graph showing grayscale values versus log H_2S concentrations and the fitted curve of the spline 190 calibration model.

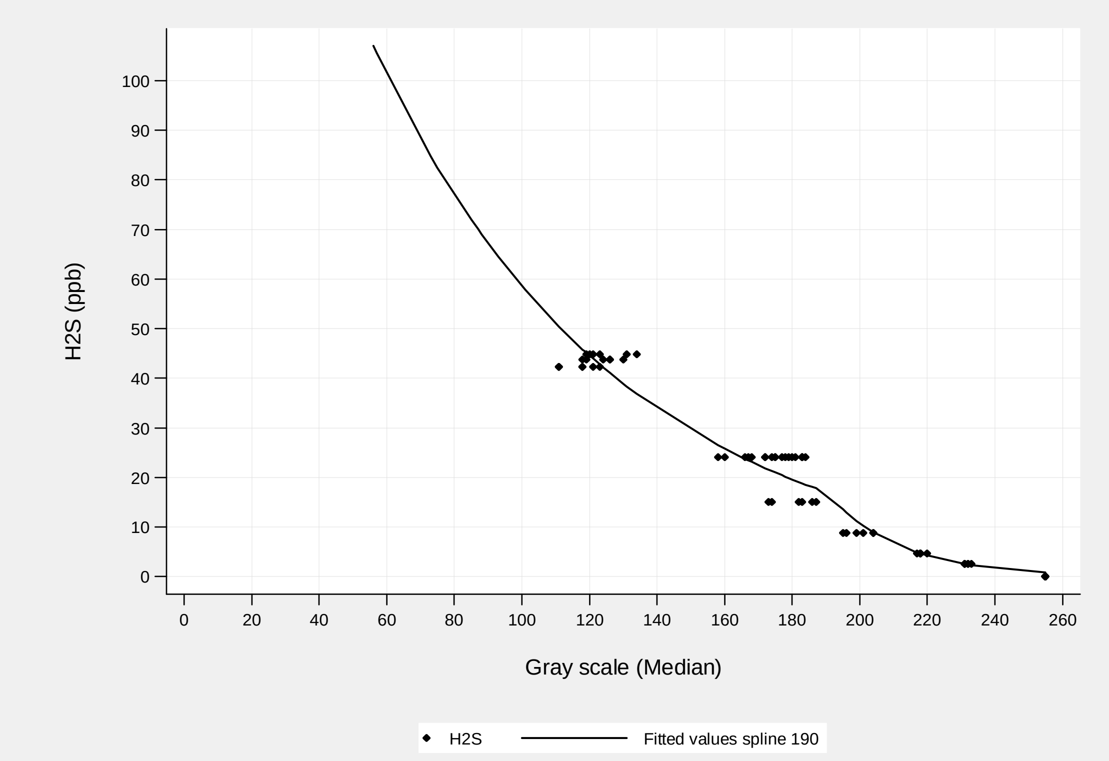

Figure 4-6: Graph showing grayscale values versus H_2S concentrations and the fitted curve of the spline 190 calibration model.

The model is relatively accurate in the grayscale range of 255 to 220, corresponding to H_2S concentrations of up to 5 ppb which covers 75% of the personal samplers, while the accuracy for grayscale values below 220 decreases.

For recordings of H_2S concentrations above 40 ppb it is likely that the model underestimates the actual H_2S concentration because recorded H_2S levels of almost 44 and 45 ppb correlated with predicted values ranging from 39 to 46 ppb. Furthermore both recordings had 4½ to 5 hours of exposure above the upper detectable limit of the analyser and thus the actual 24-hour average H_2S concentration would be even higher.

The upper detectable limit for the model was set to the grayscale value of 70 (90 ppb). Although a few samplers showed the beginning of silver discolouration at a grayscale level of 80, most samplers did not, while at a grayscale value of 70 almost all samplers showed silver discolouration.

4.2 Personal exposure study

4.2.1 Variation in H_2S concentrations in ambient air during the trials

Outside air monitoring data were not available for the April and November trials, and during the other two trials, readings above 90 ppb were frequent; thus the actual H_2S concentrations for these recordings were unknown.

However, environmental samplers were also distributed at the Te Ngae site, making it possible to assign relative H_2S levels to the trials with respect to each other. The environmental samplers for the April, June and October trials all showed silver discolouration (>90 ppb), while the November samplers had a mean of 21 ppb and a median of 20.5 ppb. Hence H_2S concentrations were markedly lower in November.
Figure 4-7 below shows one sampler from each of the remaining trials and it is apparent that silver discolouration is only beginning in the April sampler compared to the other two samplers.

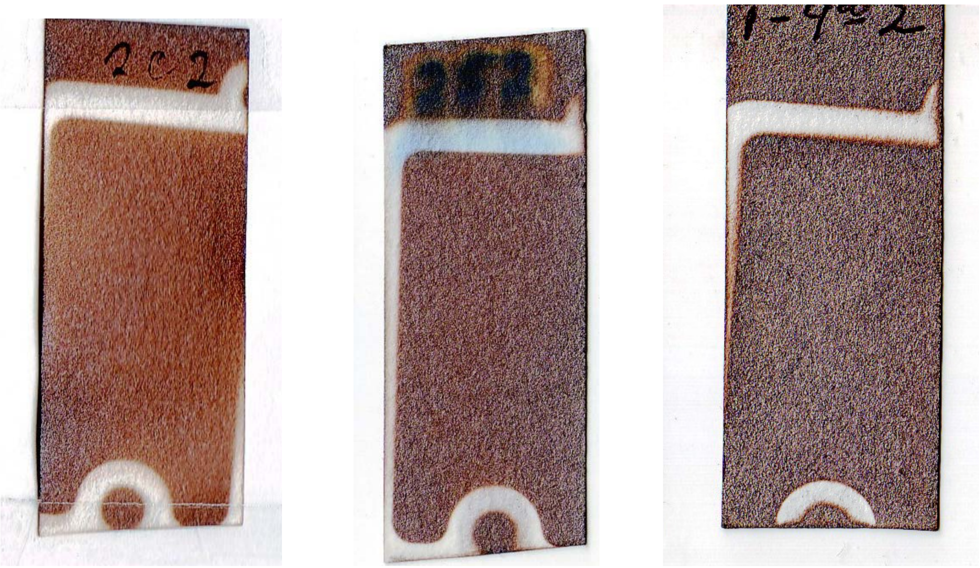

Figure 4-7: Scanned images of 24-hour environmental control samplers at Te Ngae Road, April, June and October 2008.

From left to right: samplers from the April, June and October 2008 trial.

Hence it is likely that the H_2S concentrations in April were lower than in June and October.

For the remaining two trials the discolouration of the samplers was similar, but monitor readings were available for these trials to estimate H_2S concentrations. The June recordings had 22 readings above 90 ppb with an average H_2S concentration of 44 ppb, while the October readings had 64 readings above 90 ppb with an average H_2S concentration of 72 ppb[15]. Hence it is probable that ambient air H_2S concentrations were higher in the October trial than in the June trial.

In conclusion, the lowest air H_2S concentrations occurred at the Te Ngae site in November with approximately 20.5 ppb followed by April, June and October.

4.2.2 Descriptive statistics of personal samplers

In the descriptive statistics the data were analysed by combining all readings from the personal samplers (overall results), followed by an analysis of the data with respect to the group and trial variables. The readings from the home samplers were analysed separately. Table 4-8 provides the descriptive statistics.

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[15] In order to compare the relative H_2S concentrations of the four trials, readings above 90 ppb were allocated a value of 90 ppb for the calculation of the average value

Table 4-8: Descriptive statistics of H_2S concentrations from personal and home samplers.

Personal samplers		mean	median	sd	p10	p25	p75	p90	G-mean[#]	G-sd[#]	N
Overall	**H_2S**	12.04	2	28.22	1	1	5	34	3.20	4.03	377
Group	**RGH**	4.98	2	10.05	1	1	3	13.5	2.09	2.94	180
	RLH	3.87	2	8.20	1	1	3	5	2.15	2.32	99
	RDC	33.29	8	47.06	1	2	50	>90	10.45	5.22	98
Trial	**04.2008**	10.26	2	25.34	1	1	4	21	2.96	3.65	101
	06.2008	13.06	3	25.27	1	2	9	39	4.55	3.75	102
	10.2008	14.93	2	30.87	1	1	17	51.5	3.30	5.08	90
	11.2008	9.87	2	31.86	1	1	3	11	2.21	3.42	84
Home[1]	**Home**	6.23	1	20.82	0.25	1	1	5	1.18	3.99	82

[#] Geometric mean and standard deviation respectively, which are the mean and sd of the log-transformed data converted back to a base 10 number.

[1] Home sampler were exposed for less than 24 hours

The overall distribution of H_2S concentrations from personal samplers was skewed towards the lower concentrations, with 50% of the samplers having H_2S levels of 2 ppb or below, 75% of 5 ppb or below and only 3% having H_2S concentrations above 90 ppb. The distribution pattern is displayed in the histogram below (Figure 4-8).

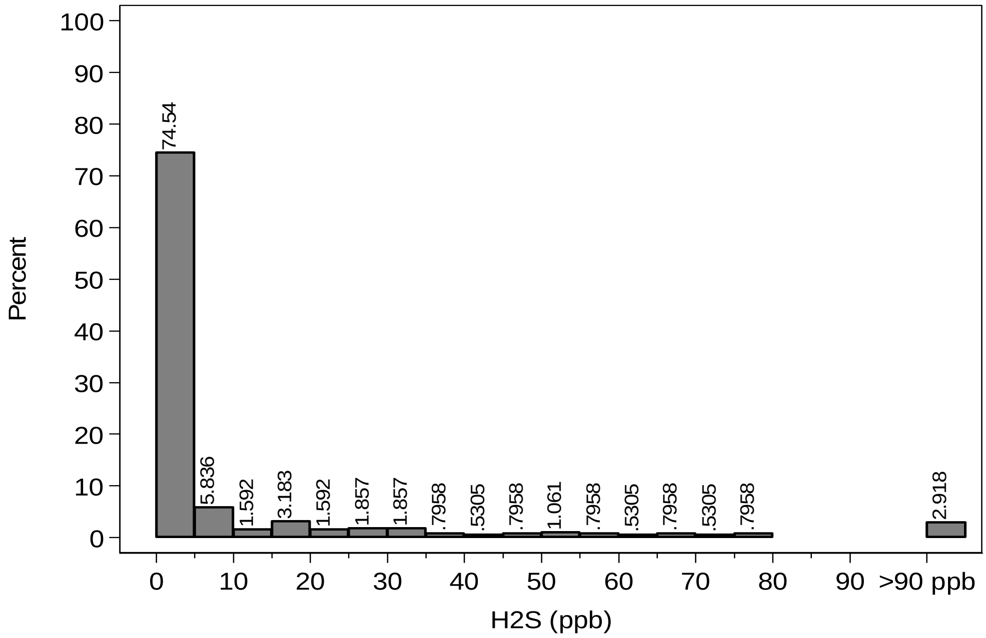

Figure 4-8: Histogram of H_2S concentrations from personal samplers (overall results).

Comparing the distribution patterns between the groups does not show much difference between RGH and RLH groups (Figure 4-9). In contrast, H_2S concentrations in the RDC group were higher with a median value of 8 ppb, which is four times higher than in the other groups. The 75 percentile was 50 ppb compared to 3 in the other two groups, and 11% of the samplers were above 90 ppb compared to none in the other two groups. Although still skewed towards the lower H_2S concentrations, the number of RDC samplers in the lower range (< 5 ppb) was halved and H_2S concentrations of the samplers were more evenly spread over the range, indicating that exposure levels vary in the RDC group.

When comparing the statistics of the personal samplers over the trials (Figure 4-10) with the statistics between the groups, differences are less pronounced. Median and mean values vary only slightly and the major differences are in the 75 and 90 percentiles. Hence variation of H_2S concentrations in the personal samplers were predominantly found in the highest 25% of readings, suggesting that variation over time may be larger in the RDC group.

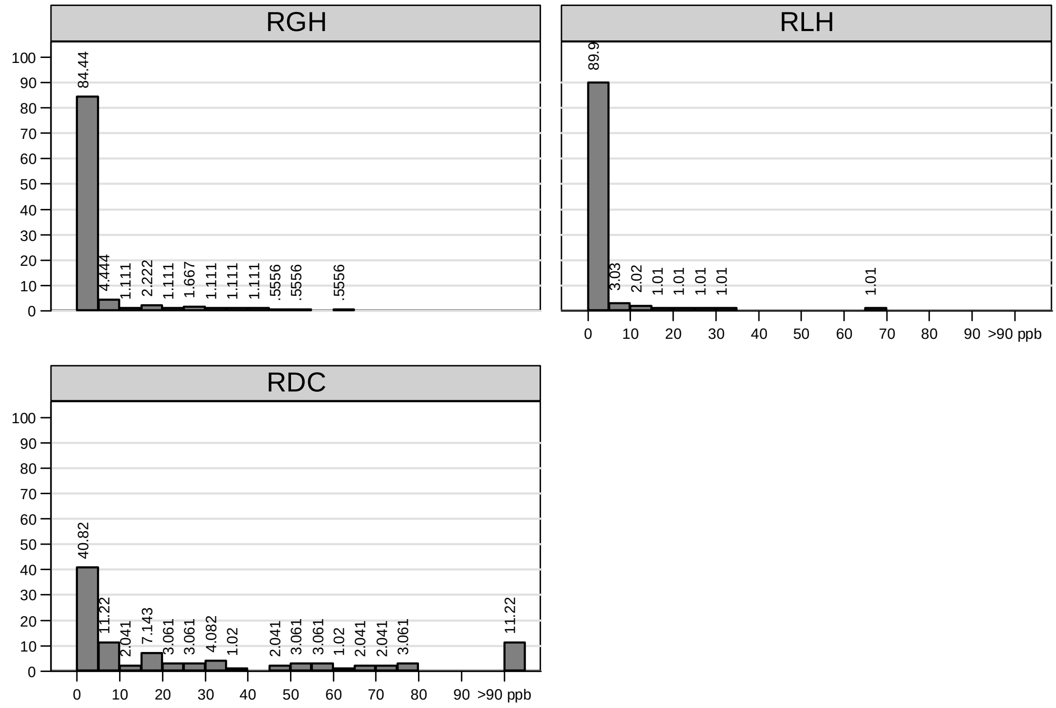

Figure 4-9: Histograms of H_2S concentrations from personal samplers by exposure group.

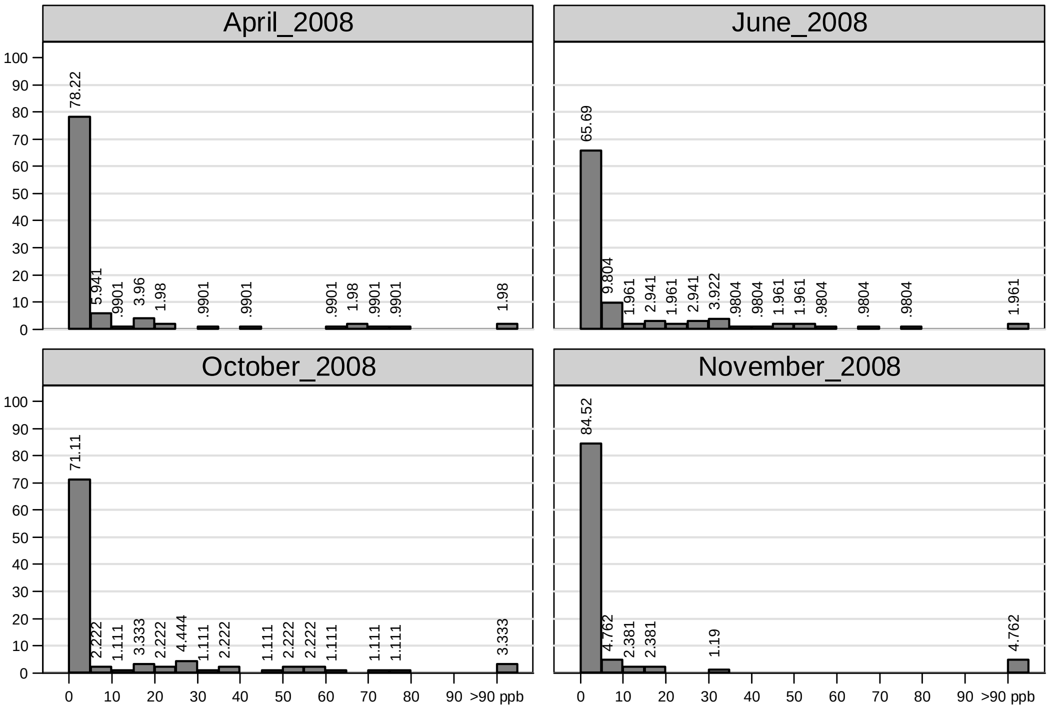

Figure 4-10: Histograms of H_2S concentrations from personal samplers by trial.

4.2.3 Regression analysis

The distribution of the H_2S concentrations in the personal samplers did not follow a normal distribution (Table 4-8), but strongly skewed towards the lower concentrations. Log transformation of the data reduced skewness from 3.73 to 1.22 and the mean value from 12.04 to 3.20 in the geometric mean. Thus the geometric mean approached the median value of 2, representing a more normal distribution pattern.

The results of the univariate analysis showed the same trend as observed in the descriptive statistics. Group and thus location in Rotorua explained 25% of the variance in H_2S levels compared to fewer than 3% explained by the different trials (Table 4-9).

The H_2S concentrations of the RLH group were not significantly different from those of the RGH group (beta: 1.03, partial R^2: 0.01%). The H_2S concentrations of the RDC group on the other hand, were substantially higher (4.99 fold: CI: 3.71-6.73) and this explained 23% of the variance in H_2S concentrations.

Only the June trial showed a statistically significant difference with a 2.06 fold increase compared to the November trial and (explained variance R^2: 3.29%).

Table 4-9: Univariate regression analysis of H_2S concentrations from personal samplers.

Trial/Group	**Ratio(10^B)**[16]	**95% Confidence Interval**	**Partial R^2 (%)**[17]
April 2008	1.33	0.90-1.99	0.54
June 2008	2.06^{***}	1.38-3.06	3.29^{***}
October 2008	1.49	0.99-2.25	0.98
Number of observations: 377		**Adjusted R^2 (%) Model: 2.62^{**}**	
RLH	1.03	0.76-1.38	0.01
RDC	4.99^{***}	3.71-6.73	23.19^{***}
Number of observations: 377		**Adjusted R^2 (%) Model: 25.03^{***}**	

$^{*}p \leq 0.05$, $^{**}p \leq 0.01$, $^{***}p \leq 0.001$ Reference groups: November 2008 trial and RGH respectively

In the multivariate regression model, the explained percentage of variance in H_2S concentrations for the model increased to 29%. The effect of the groups remained similar to the ones observed in the univariate analysis, with RLH not having any considerable effect, while the effect size and percentage of explained variation in the RDC group increased slightly (Table 4-10).

The effect of the trials also remained similar to the ones observed in the univariate analysis, but the results for all trials gained statistical significance (Table 4-10).

Table 4-10: Multivariate regression analysis of H2S concentrations from personal samplers.

Trial/ Group	**Ratio(10^{B})**	**95% Confidence Interval**	**Partial R^2 (%)**
April 2008	1.55^{*}	1.11-2.19	1.71^{*}
June 2008	2.30^{***}	1.63-3.23	5.84^{***}
October 2008	1.69^{**}	1.19-2.41	2.30^{**}
RLH	1.05	0.79-1.41	0.03
RDC	5.22^{***}	3.90-6.99	25.18^{***}
Number of observations: 377		**Adjusted R^2 (%) Model: 28.88^{***}**	

$^{*}p \leq 0.05$, $^{**}p \leq 0.01$, $^{***}p \leq 0.001$

Therefore when both variables were entered into the regression model, being in the RDC group remained the strongest determinant of elevated H_2S concentration in the personal samplers, but differences over the trials gained in importance, although on a smaller scale.

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[16] The effect estimate (coefficient beta) represents the change in H_2S for a change in one measurement unit of the independent variable. Because the data were log transformed the coefficient beta represents a ratio. *E.g.* a coefficient beta of 3.2 indicates a 3.2 fold increase in H_2S concentrations compared to the reference group (based on the geometric mean).

[17] partial R^2: correlation between H_2S and one independent variable, when the effects of the other independent variables are removed. Hence it is an indication of the unique contribution of that independent variable to the model.

4.2.4 Analyses using stratification by trial and group

In order to analyse the data in more detail, stratification by group and trial was applied. The descriptive statistics of the data are given in Table 4-11 and the distribution pattern is displayed in the following box plot (Figure 4-11), while Tables 4-12 and 4-13 show the results of the regression analyses.

Table 4-11: Descriptive statistics of H_2S concentrations from personal samplers stratified by group and trial.

Group	Trial	mean	median	sd	p10	p25	p75	p90	G-mean[#]	G-sd[#]	N
RGH	April 2008	4	1	7.35	1	1	3	12	1.95	2.70	50
	June 2008	6.61	2	11.30	1	2	4	28	3.15	2.81	51
	October 2008	6.28	1	13.76	1	1	2	27	1.79	3.66	44
	November 2008	2.35	1	3.45	1	1	2	4	1.54	2.21	35
RLH	April 2008	4.50	2	6.72	1	2	3.5	14	2.77	2.30	28
	June 2008	5.56	2	13.53	1	1	3	9	2.51	2.66	25
	October 2008	2.71	2	4.83	1	1	2	4	1.74	2.08	24
	November 2008	2.41	1.5	3.65	1	1	2	2	1.64	2.03	22
RDC	April 2008	30.87	4	46.57	1	2	65	79	7.89	5.90	23
	June 2008	32.92	21	39.97	3	6	47	78	16.63	1.14	26
	October 2008	45.55	27.5	48.12	2	13	57	150	22.49	4.21	22
	November 2008	25.70	2	53.20	1	2	5	150	4.53	5.37	27

[#] Geometric mean and standard deviation respectively, which are the mean and sd of the log-transformed data converted back to a base 10 number.

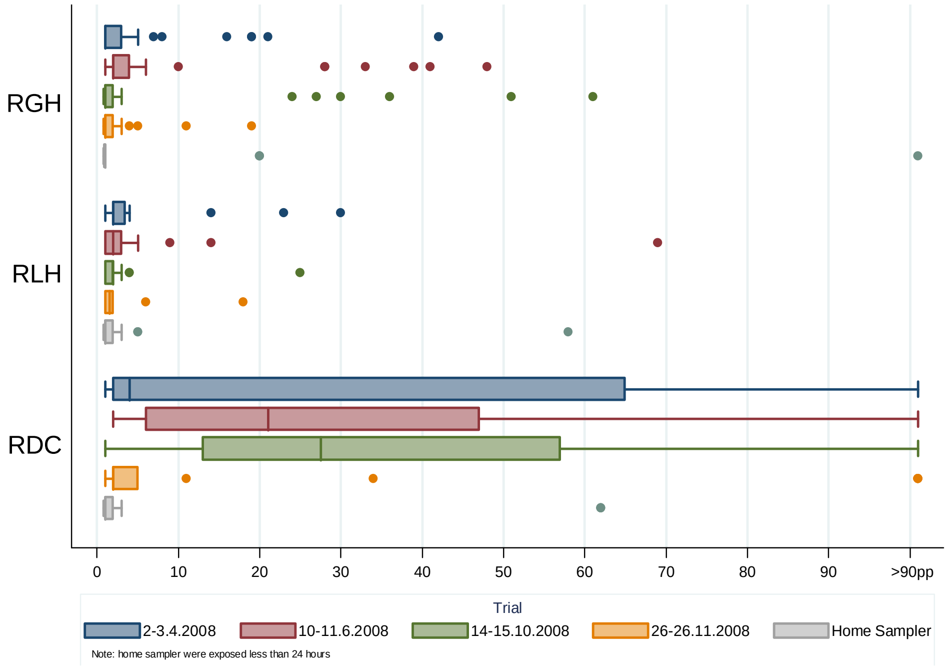


Figure 4-11: Box plot showing the H_2S distribution from personal samplers by exposure group and trial, and the H_2S distribution of the home samplers.

Table 4-12: Regression analysis of H_2S concentrations from personal samplers stratified by trial.

Trial	Group	Ratio(10^B)	95% Confidence Interval	Partial R^2 (%)
April 2008	**RLH**	1.42	0.82-2.47	1.60
	RDC	4.05***	2.24-7.30	18.41***
Number of observations: 101			**Adjusted R^2 (%) Model: 16.83*****	
June 2008	**RLH**	0.08	0.47-1.35	0.74
	RDC	5.28***	3.14-8.88	29.01***
Number of observations: 102			**Adjusted R^2 (%) Model: 32.42*****	
October 2008	**RLH**	0.97	0.53-1.79	0.01
	RDC	12.52***	6.67-23.48	42.27***
Number of observations: 90			**Adjusted R^2 (%) Model: 44.32*****	
November 2008	**RLH**	1.06	0.58-1.98	0.05
	RDC	2.94***	1.65-5.25	14.44***
Number of observations: 84			**Adjusted R^2 (%) Model: 14.19*****	

$^{*}p \leq 0.05$, $^{**}p \leq 0.01$, $^{***}p \leq 0.001$ Reference groups: RGH

Table 4-13: Regression analysis of H_2S concentrations from personal samplers stratified by group.

Group	Trial	Ratio(10^B)	95% Confidence Interval	Partial R^2 (%)
RGH	**April 2008**	1.27	0.80-2.00	0.58
	June 2008	2.05**	1.30-3.23	5.17**
	October 2008	1.17	0.73-1.87	0.24
Number of observations: 180			**Adjusted R^2 (%) Model: 4.7****	
RLH	**April 2008**	1.69*	1.06-2.69	4.95*
	June 2008	1.53	0.95-2.46	3.14
	October 2008	1.06	0.65-1.72	0.06
Number of observations: 99			**Adjusted R^2 (%) Model: 4.3**	
RDC	**April 2008**	1.74	0.73-4.18	1.44
	June 2008	3.67**	1.58-8.56	8.45**
	October 2008	4.96***	2.05-12.02	11.72***
Number of observations: 98			**Adjusted R^2 (%) Model: 12.1****	

$^{*}p \leq 0.05$, $^{**}p \leq 0.01$, $^{***}p \leq 0.001$ Reference groups: November 2008 trial

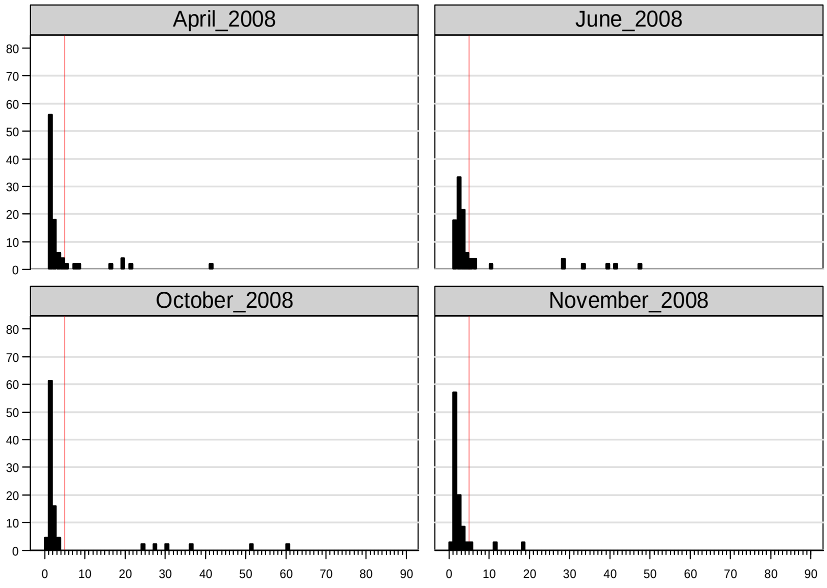
Stratification by group and trial corroborated the previous findings that the distribution patterns of the RGH and RLH were very similar with H_2S concentrations strongly skewed towards the lower H_2S levels, while H_2S concentrations in the RDC group were higher and more evenly spread (Figure 4-11). Belonging to the RDC group remained the most important determinant of elevated personal exposure levels (Table 4-12) and most of the variation in personal exposure between the trials occurred in the RDC group (Table 4-13).

The statistical analysis stratified by trial provided the following additional findings: In the regression analysis stratified by trial (Table 4-12), the importance (Beta and Partial R^2 values) of belonging to the RDC group as a determinant of elevated personal exposure increased when air H_2S concentrations increased at the Te Ngae Road monitoring site, where the lowest concentrations were recorded in the November trial followed by the April, June and October trials. Hence personal exposure levels in central Rotorua were linked to air H_2S concentrations at Te Ngae Road. Such a link was not observed for the RLH group.

In the regression analysis stratified by group (Table 4-13), statistically significant trials varied between groups, possibly suggesting that the factors driving elevated personal exposure vary between the groups.

For the RGH and RLH groups personal exposure levels in the statistically significant trials varied little from the levels of the other trials, and seem to have occurred in the range below 5 ppb (Figure 4-11). In order to examine whether there were noteworthy changes in the distribution patterns between the trials in the college groups, the histograms for the RGH group were redone using a bar width of 1 ppb (Figure 4-12). RGH was chosen, because in the statistical analyses the effect size (Beta and partial R^2 value) and the p-value of the statistically significant trial were greater than the values of RLH trial.

Figure 4-12: Histograms showing the distribution of H_2S concentrations from personal samplers for the RGH group using a bar width of 1 ppb, April, June, October and November 2008.



The red reference line is located at 5 ppb.

The June trial varied from the other trials, which were similar in their distribution in the reduction of samplers with an H_2S concentration of 2 ppb (from between 50% to 60% to just above 30%), and in the increase in samplers with a H_2S concentration of 3 ppb (from just below 20% to above 30%) plus a small increase in samplers of 4 ppb.
Overall the differences seem relatively small and hence it is unlikely that variations in personal exposure levels between the trials had an important effect on personal exposure in the RGH and RLH group.

4.2.5 Home sampler

Overall H_2S concentrations in the homes were very low and the distribution was strongly skewed towards the lower concentrations, with 75% being 1 ppb or below, and 90% being 5 ppb or below. Mean and the median values were lower than in the personal samplers. Descriptive statistics on the home sampler, stratified by group were not represented, as the home location did not always correspond to the group allocation[18]. The mapping will provide a more precise picture of the distribution of H_2S concentrations in the home samplers. However Figure 4-11 shows the distribution of the H_2S levels in the home stratified by group, and clearly indicates that H_2S concentrations were lower in the home samplers compared to the personal samplers for all groups.

4.2.6 Environmental control samplers

Environmental control samplers had been placed at the sites where groups of participants were exposed. The table below lists the sites and the results from the environmental control samplers. The results show the median value from all samplers exposed at each site. Results from Gastec Dosimeter tubes are given in brackets. Please note that the Gastec readings are cumulative H_2S concentrations over 24 hours.

Environmental samplers from RGH and RLH, which were the only sample sites not located in the central corridor, had low H_2S concentrations with little variation between the trials and between inside and outside concentrations, with the exception of the November trial at RLH.

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[18] Group classification was either by the location of the college or for the RDC group by working or residing in the central corridor. Many of the RDC participants lived outside central Rotorua

Table 4-14: H_2S concentrations (ppb) from environmental control samplers.

Group	April 2008		June 2008		October 2008		November 2008	
Outside/inside	**out**	**in**	**out**	**in**	**out**	**in**	**out**	**in**
RGH	2	2	3	3.5	1	2	1	1
RLH	3	2	2	2	2	3	2	10
RDC		51.5	70 (0)	70	51 (0)	47	25.5	8
Government Gardens	>90 (8-10000)	73	>90 (7-10000)	>90 (0)	65 (0)	30.5 (0)	>90	
Te Ngae Street	>90		>90	45.5	>90 (0)	50	20.5	
Ngapuna[19] **Site A**	>90 (5-8000)	>90 (200000)	>90	>90		>90 (200000)	>90	>90
Ngapuna Site B	>90		>90	56.5		79.5	>90	25

Readings from Gastec tubes are displayed in brackets.

During the November trial at RLH, two outside and two inside locations were used for environmental control samplers which were exposed in duplicate. The H_2S concentrations of the samplers were as follows: (2 ppb, 2ppb) and (2ppb, 11ppb) for the outside and (11 ppb, 9ppb) and (8ppb, 15 ppb) for the inside locations. The cause of the elevated readings is uncertain and is not reflected in the statistics of the personal samplers. As the inside measures were all taken in the science classroom, contamination is a possibility, but would not explain the elevated reading in one of the outdoor samplers.

In contrast to the college samplers, outside environmental samplers from the central city had H_2S concentrations largely above 90 ppb, except for the RDC site where H_2S concentrations were always below 90 ppb. Comparing the outside readings with those from the personal samplers of participants who worked all day in these buildings, suggests that personal exposure was considerably lower, except for the Ngapuna site A where no conclusion could be drawn because both personal and environmental samplers had readings above 90 ppb.

Inside readings for the Government Gardens, the Te Ngae Road and the Ngapuna site B locations were lower than the corresponding outdoor readings, while at the RDC site

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[19] On this site, H_2S concentrations were monitored and exposure managed by the RDC and the company concerned.

inside readings were equal to or lower than the outside ones. At the Ngapuna site A, readings inside were substantially higher than outside during the first trial. However inside and outside H_2S concentrations were only measured concurrently on one occasion.

4.2.7 Mapping of personal samplers

Compared to the statistical analyses which had categorised participants into groups, the mapping examined exposure with respect to locations frequented by participants.
The number of personal samplers analysed in the mapping section was smaller than in the statistical analyses, as only 55% to 87% of participants returned useable maps with their samplers.

The results section of the mapping will focus on the October 2008 trial, as additional information was available from the home samplers, allowing for the exclusion of more locations as potential sources of exposure.

4.2.7.1 Home sampler

The map below (Figure 4-13) shows the location and H_2S concentration of the home samplers. Diamonds at the ends of roads exiting the map show H_2S concentrations of personal samplers from participants, who live outside the map area. When looking at the home sampler map, it has to be remembered that exposure time was about 2/3 of the exposure time for personal samplers, potentially reducing H_2S readings.

The map shows that H_2S concentrations in the west were very low (1 ppb or below) or absent, while the east had a mixture of samplers from below 1 to 5 ppb. Only 7 home samplers were returned from central Rotorua as it is predominantly a commercial rather than a residential area, especially at the northern part. However H_2S concentrations above 5 ppb only occurred in the central city. Compared to the environmental sample from Te Ngae Street which was >90 ppb, the home samples from central Rotorua were all below 90ppb, with the exception of one sampler.

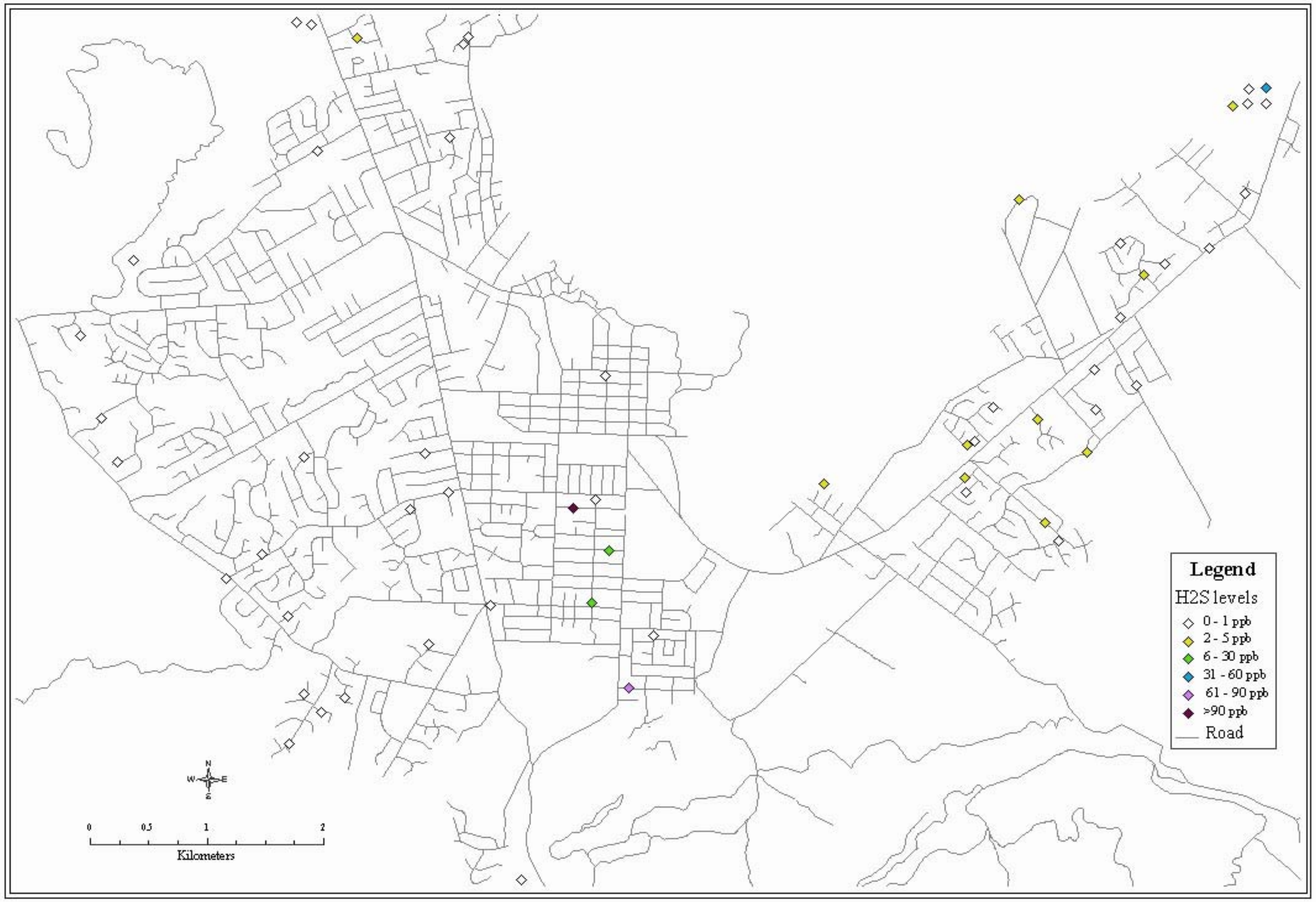


Figure 4-13: Map showing locations and H_2S concentrations of the home samplers, October 2008.

Home samplers were exposed for less than 24 hours.

The home sampler with a reading above 90 ppb had a unique discolouration pattern, not observed in any other home or personal sampler. Below is a photo (Figure 4-14) of the home sampler and its corresponding personal sampler.

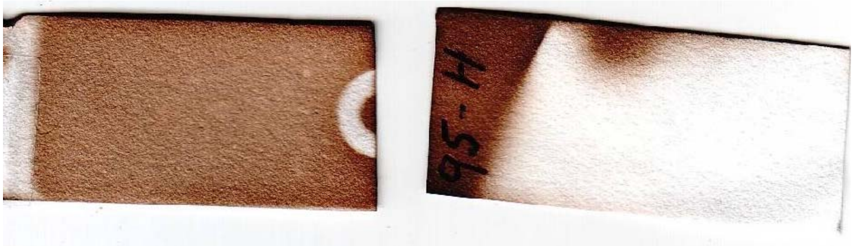


Figure 4-14: Photos showing the home sampler (right) with a reading above 90 ppb and the correlated personal sampler.

The discolouration pattern of the home sampler would suggest that most of the sampler had been protected from exposure somehow, leaving only a small corner on the top left for scanning. Although the numbers of pixels scanned was heavily reduced, it was decided to include the results of this sampler in the study because the corresponding personal sampler had a reading of 51 ppb and the personal samplers of this participant had shown elevated readings throughout all the trials (42, 48, 11 ppb).

It is possible that the H_2S concentration of this home sampler was artificially elevated because the scanning area may have included the edges of the sampler where discolouration is more intense.

4.2.7.2 Map of personal exposure October 2008

The next map (Figure 4-15) shows all the locations frequented by the participants during the trial. All locations frequented by the same participant were given the H_2S concentration of the corresponding personal sampler. Locations frequented by several people were marked in a red box. Additionally 33 locations were removed as they were unlikely sources of exposure for the following reasons:

- Because not all participants had returned a home sampler, the home locations were given the H_2S concentration of the personal samplers, as was done for all the other locations. Home locations were removed when the H_2S concentration of the home sampler was ≤ 3 ppb and the H_2S concentration of the corresponding personal sampler was at least double the concentration of the home sampler, because in these

cases, control samplers (home samplers) had indicated that the location did not considerably contribute to the higher personal exposure levels (30 locations).
The value of 3 ppb was chosen because 75% of the personal samplers were below 5 ppb, but the exposure times of the home samplers were only approximately 2/3 of the personal samplers and hence 5ppb was reduced to 3ppb.

- The school locations were removed from the map, because they were unlikely sources of exposure due to the low readings of the environmental control samplers (see Section 5.2.5). Furthermore 66% of the pupils attending RGH and 46% from RLH returned a personal sampler of 1 ppb or less. (2 locations)
- One location frequented by a participant whose personal sampler had a higher H_2S concentration was removed, because a control sampler exposed for exactly the same time did not show any exposure. (1 location)

There were two exceptions where home locations in central Rotorua were not excluded, although both home samplers had readings of 1 ppb. In both cases, the personal samplers had elevated H_2S readings (30 ppb and 36 ppb), but the participants had only been at school and at home. Therefore either the home sampler had been exposed in a very sheltered place or the exposure occurred on the way from school to home, which in both cases was predominantly through central Rotorua. Hence exposure must have occurred in central Rotorua and the home locations received the H_2S concentration of the personal samplers.

After the exclusion of unlikely locations of exposure, all locations with H_2S concentrations above 5 ppb were found in central Rotorua. In the east and west of Rotorua, all H_2S concentrations were between 0 and 5 ppb. The only exception was one sampler in the east leading out of Rotorua. This sampler was associated with living close to a geothermal area outside to the east of Rotorua.

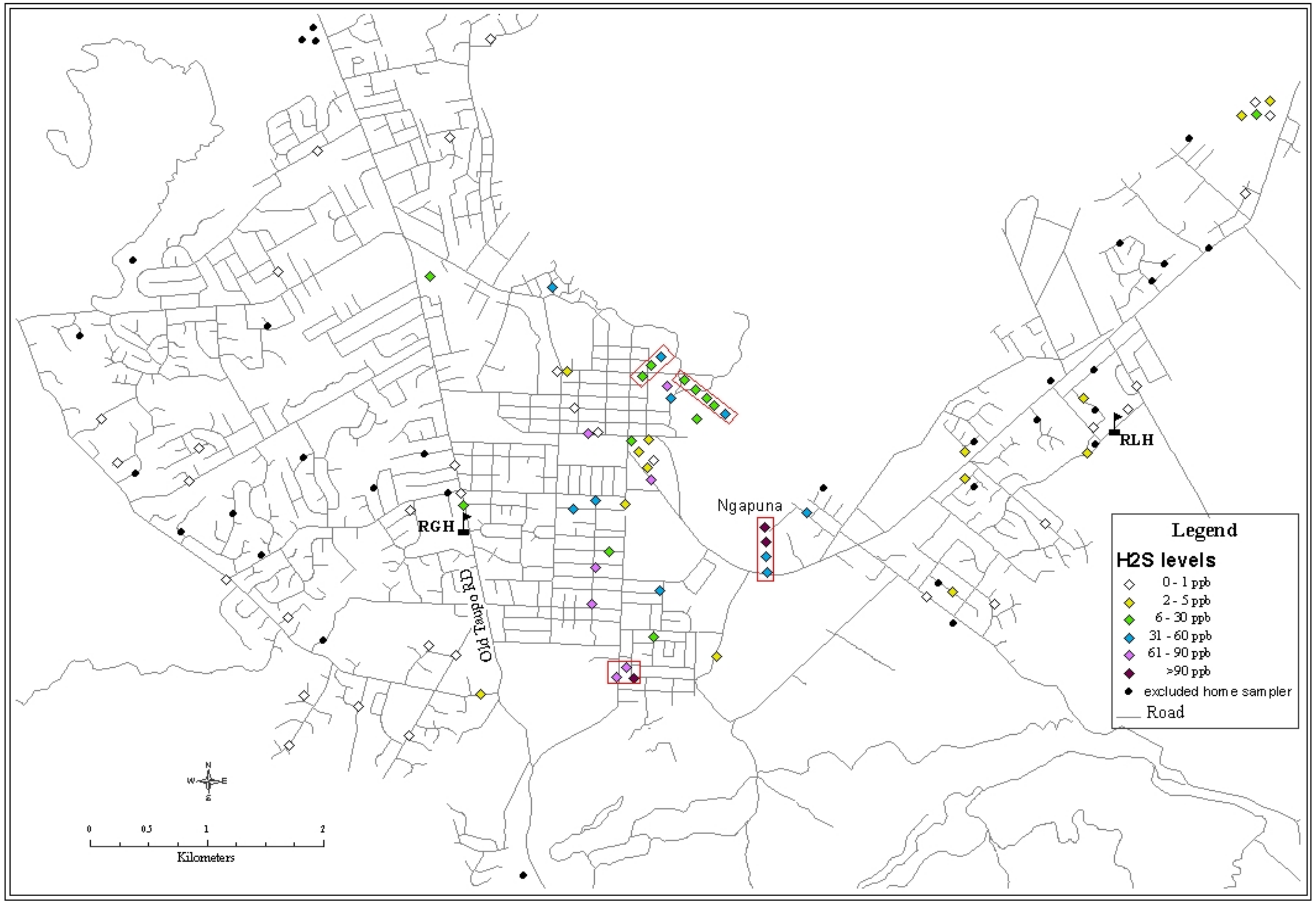


Figure 4-15: Adjusted map showing locations and H_2S concentrations of the personal samplers, October 2008.

4.2.7.3 Map of personal exposure in central Rotorua October 2008

The following map (Figure 4-16) is an enlargement of central Rotorua, east of Old Taupo Road and west of Ngapuna, and will show personal exposure in the central city in more detail.

Participants who stayed at more than one location in the central city had the location with the longest residence time marked with a number, while subsequent locations were marked with an additional letter following the number.

4.2.7.3.1 Personal exposure and exposure length

When the locations were inspected for exposure times, all locations in central Rotorua with a personal sampler reading of ≤ 5 ppb were associated with participants who had stayed for 2 hours or less in the central city. The actual readings of these samplers were ≤3 ppb. The only exceptions are the samplers marked 11 close to Kuirau Park, where the samplers had readings of 1 ppb and 2 ppb, but the participants had stayed at the location for 6.5 and 8 hours respectively. The remaining samplers in central Rotorua all had actual readings of 17 ppb or above and exposure times of 6.5 hours or more in the central city, showing that exposure time was an important determinant of H_2S concentrations in personal samplers.

4.2.7.3.2 Locations of uncertain exposure levels in central Rotorua

Locations 1c, 4a and 5b are unlikely sources of exposure as locations nearby showed low H_2S concentrations during the other trials and the corresponding participants had been to other locations where higher exposure was evident.

Due to a lack of observations in the October data, it is uncertain whether elevated exposure occurred in the area north of Amohau Street and west of Fenton Street including Kuirau Park and in between Ranolf Street and Old Taupo Road. Whether the small residential area to the north-east of the Ngapuna site (Location 1a) is a source of exposure is undetermined, as the participant from this location had elevated H_2S readings during all trials, but had also frequented other sites where exposure was evident. In contrast, the home sampler from this area had only returned an H_2S concentration of 2 ppb. Due to this uncertainty the two samplers from this area were not classified as eastern Rotorua, but included in the central Rotorua area.

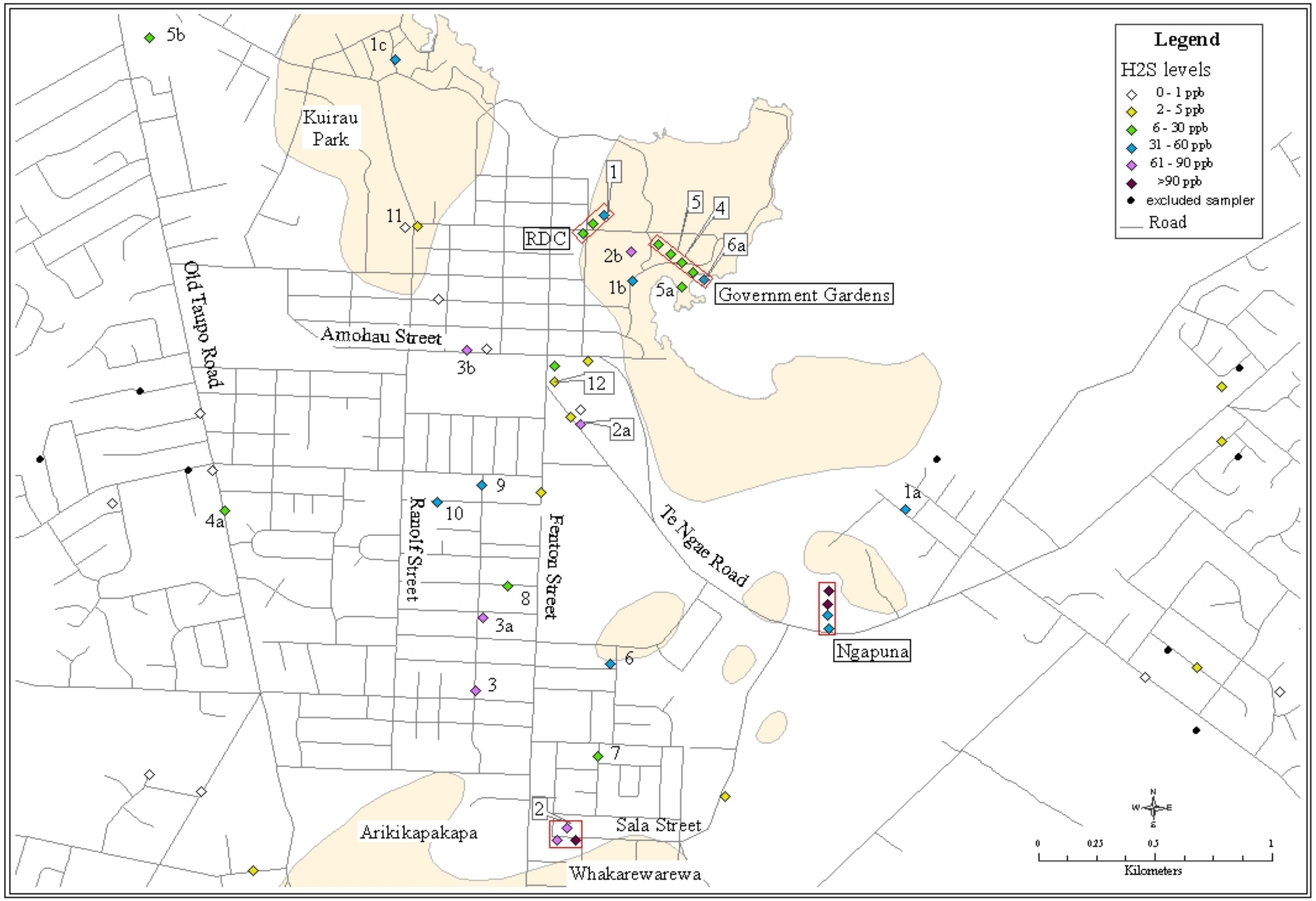


Figure 4-16: Enlarged map of central Rotorua showing locations and H_2S concentrations of the personal samplers and active geothermal areas, October 2008.

4.2.7.3.3 Possible sources of exposure

Elevated exposure occurred only along a corridor in central Rotorua, which is close to the active geothermal areas. Looking at the distribution of samplers with elevated H_2S concentrations and possible sources of exposure, the RDC site, the Government Gardens site and probably location 2a and 12 would be affected by the geothermal areas of upper Sulphur Bay including the Government Gardens active geothermal area, while the Ngapuna site would be affected by the lower Sulphur Bay area. Interestingly a rapid colour change in the personal samplers was observed by some participants when visiting the above mentioned areas.

The area of locations 2, 3 and 7 is close to three geothermal areas: lower Sulphur Bay to the north-east, Arikikapakapa to the west and Whakarewarewa to the south. Furthermore leakage of H_2S from disused bores had been reported in this area (Brownbridge 2009b). A rapid colour change in the samplers was observed by two participants when visiting Whakarewarewa. Both visits occurred on the same occasion and exposure was clearly identified with being in very close proximity to a geothermal feature.

The area of locations 3, 3a, 6, 8, 9 and 10 could be affected by any or all of the four geothermal areas, although the distance to upper Sulphur Bay area seems substantial. In addition, smaller areas of geothermal activity are present between Fenton Street and Te Ngae Road, which possibly affect H_2S concentrations at these sites.

The Kuirau Park geothermal area was not associated with higher personal exposure levels.

4.2.7.3.4 Variation in H_2S exposure over short distances

In two instances H_2S exposure varied markedly (20 ppb or more) between participants, although they had been in locations very close to each other, for approximately the same length of time, and other sites of exposure could be excluded in all cases. The H_2S concentration of the sampler at location 12 at Te Ngae Street was 2 ppb and the exposure time was 2 hours, while the participant at the location just to the north (green diamond) had spent 2.5 hours at this location, but had a H_2S reading of 24 ppb. In both instances most of the time was spent indoors, therefore it is possible that building structures influenced H_2S exposure.

The other instance was at the Ngapuna site and occurred throughout all trials. The two participants with readings above 90 ppb worked in one building, while the other two participants worked in a different building 50 to 100 metres away. Building structure may have caused the differences in H_2S exposure levels, as during two trials the inside environmental samples from Site B showed lower H_2S concentrations compared to the ones from Site A. However small geothermal features such as ground vents have been observed in this location and proximity to a geothermal feature may be another cause of differences in personal exposure.

4.2.7.4 Mapping of personal exposure during the remaining trials

To investigate whether the findings of the October trial were also evident in the remaining trials, the following procedures were applied to the maps:

- All locations to the east (east of Ngapuna) and west (west of Old Taupo Road) were selected respectively on the map
- Locations marked by participants from the RDC group were removed from the east and west as the October data suggested that exposure was more likely to occur in central Rotorua
- Locations marked in the east or west by participants who had spent more than two hours in the inner city and had a personal sampler reading above 5 ppb were removed, as exposure was more likely to have occurred in central Rotorua
- Locations marked in the east or west by participants who had clearly indicated on their maps that exposure had occurred somewhere else, were removed
- Locations in central Rotorua visited by participants of the RGH or RLH group, who stayed for two hours or less and whose personal sampler had a reading of 5 ppb or below, were removed
- Locations associated with participants living close to geothermal areas outside of Rotorua were disregarded.

Statistics of H_2S concentrations were obtained by using the personal ID number, in order to avoid including the same participant multiple times, if that person had frequented several locations. However, if a participant from the east had stayed in the west or vice versa, the personal sampler was included in both the western and eastern statistics. The descriptive statistics are displayed in Table 4-15 below, followed by the adjusted maps of the remaining trials (Figures 4-17 to 4-19).

The results of the remaining trials reiterated the findings of the October trial and the statistical analyses. Personal samplers of participants who lived in east or west Rotorua and who had not been to the central city for more than two hours, had H_2S concentrations of 5 ppb or below over all trials, except for one personal sampler in the east during the November trial, which had a reading of 6 ppb. The median and mean values would suggest that most of these samplers had an H_2S concentration in the range of 0 to 3 ppb and that there was little variation in exposure levels over the trials.

In contrast, locations in central Rotorua had markedly elevated H_2S concentrations during all trials. Median values of H_2S concentrations varied more noticeably between the trials than in the statistical analyses and were correlated to air H_2S concentrations at Te Ngae Road.

Table 4-15: Descriptive statistics of H_2S concentrations from personal samplers by locations in east, west and central Rotorua.

Trial	Location	mean	median	min	max	sd	N
April 2008	east	2.19	2	1	4	1.06	27
	west	1.48	1	1	4	0.78	27
	central	22.75	5.50	1	>90ppb	31.78	32
June 2008	east	2.47	3	1	4	1.04	17
	west	2.00	2	1	3	0.73	22
	central	24.42	15.50	2	>90ppb	26.46	38
October 2008	east	1.59	1	1	4	0.77	17
	west	1.20	1	1	3	0.51	20
	central	40.00	32	1	>90ppb	30.71	18
November 2008	east	2.90	2	1	6	1.51	10
	west	1.25	1	1	2	0.43	12
	central	20.68	3	1	>90ppb	36.50	25

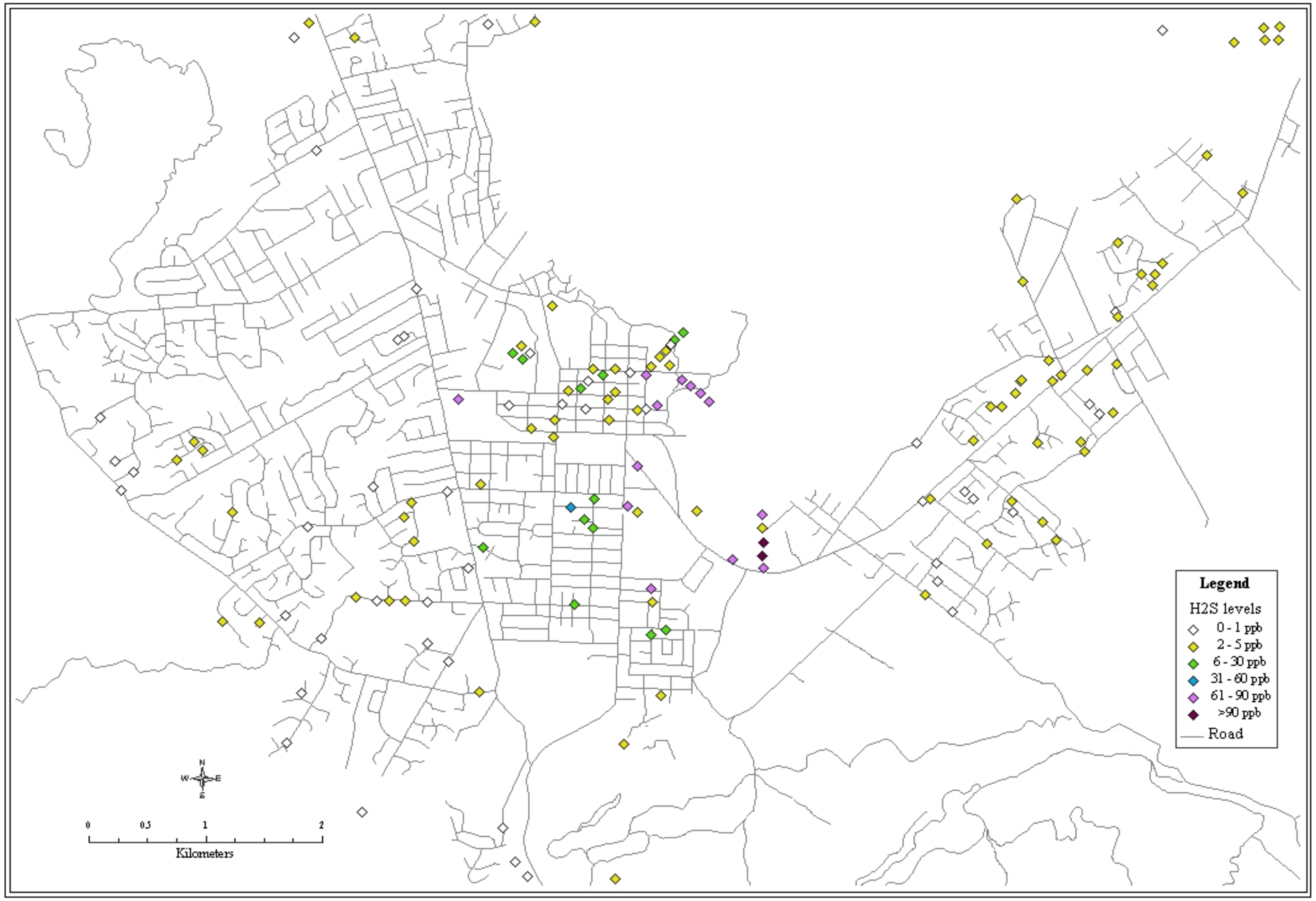


Figure 4-17: Adjusted map showing locations and H_2S concentrations of the personal samplers, April 2008.

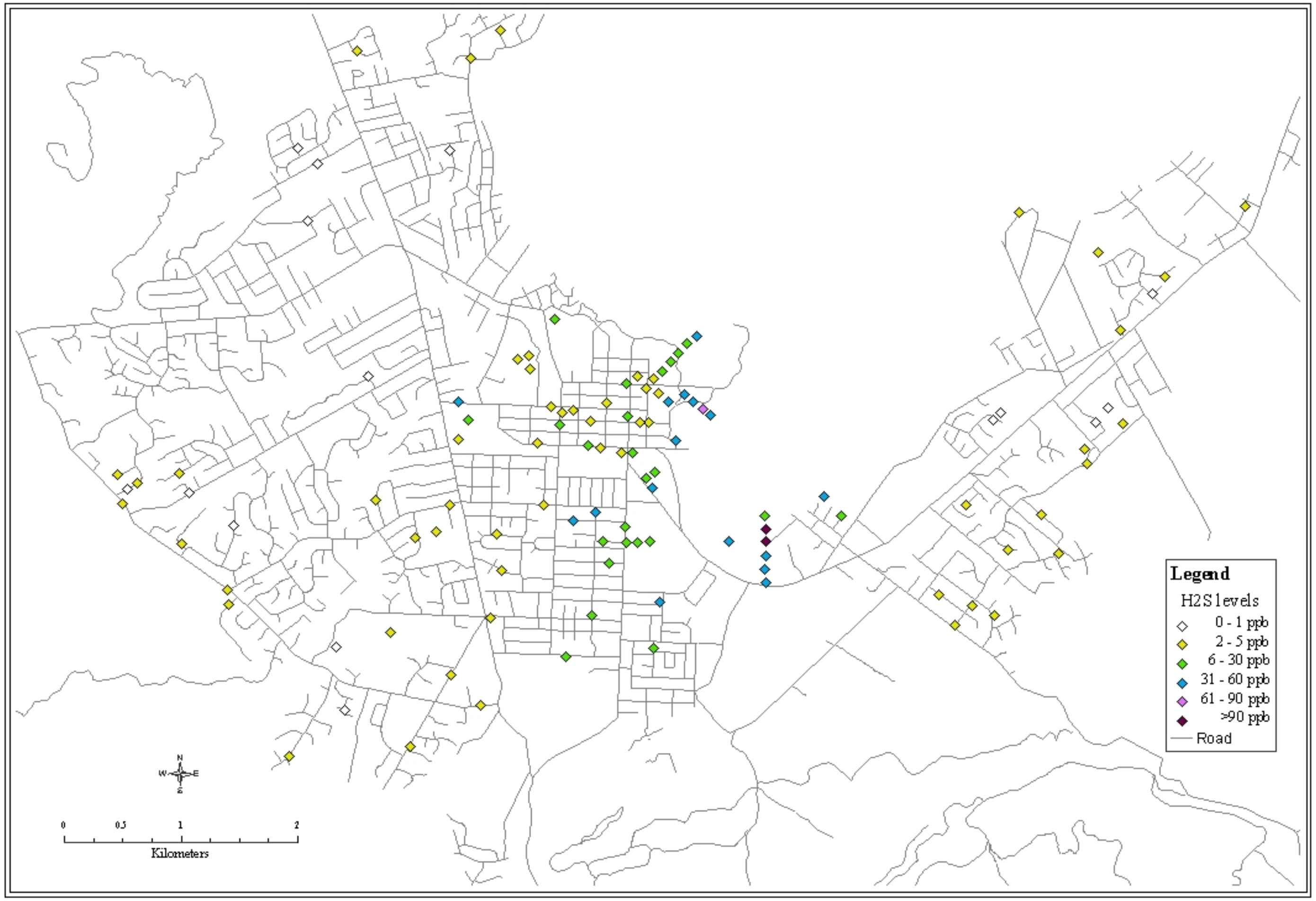


Figure 4-18: Adjusted map showing locations and H_2S concentrations of the personal samplers, June 2008.

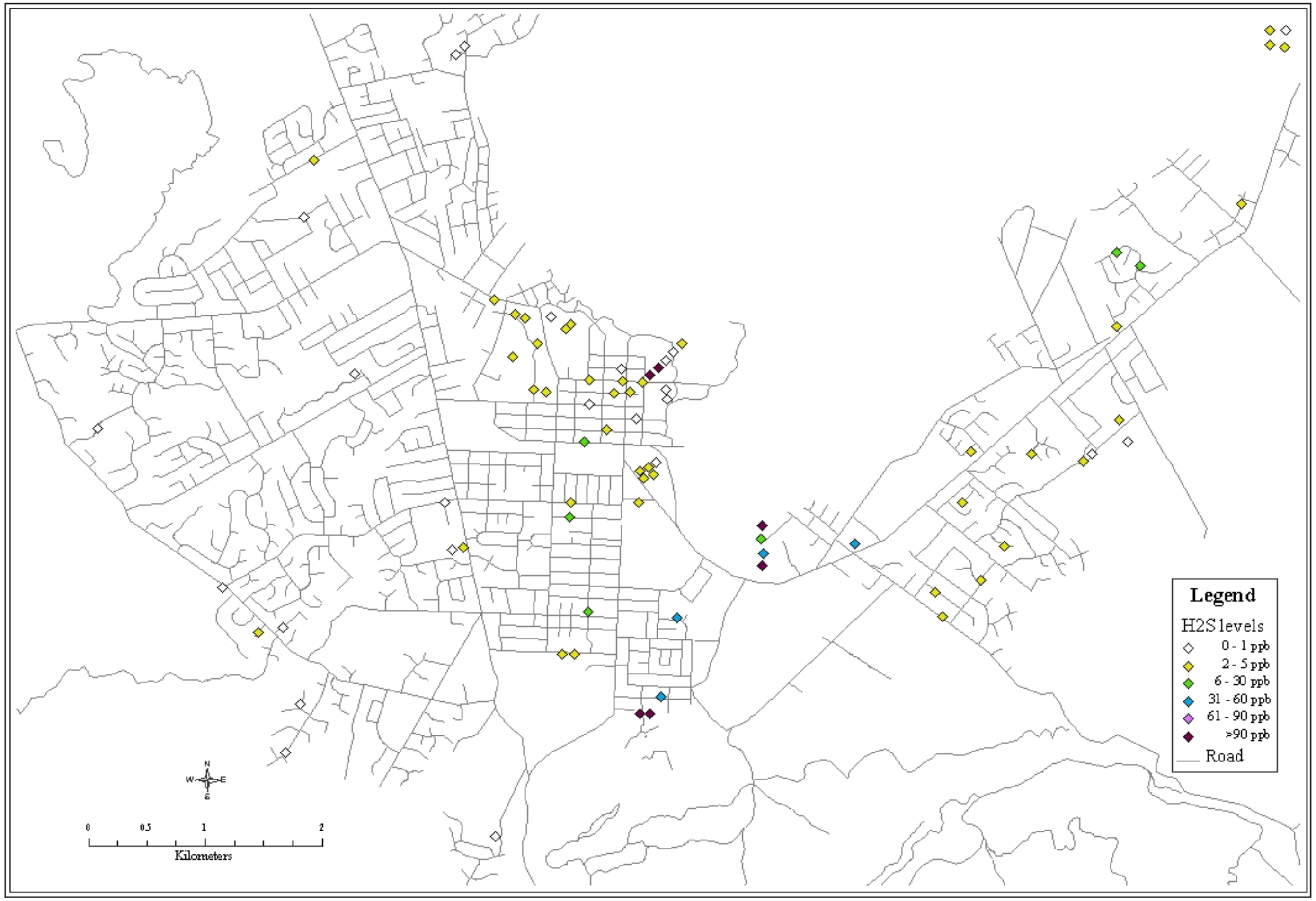


Figure 4-19: Adjusted map showing locations and H_2S concentrations of the personal samplers, November 2008.

Please note that the two exposures > 90ppb in the RDC location, were associated with a geothermal feature at the Whakarewarewa geothermal area, but as the RDC location was frequented later, additional exposure there could not be excluded.

Readings of personal samplers in the RDC group varied over a wide range of H_2S concentrations, indicating that exposure may be very localised or further influenced by other factors such as mobility of participants.

The area of elevated exposure levels in central Rotorua, east of Fenton Street and between Fenton, Ranolf and Amohau Streets remained constant for all trials. Although H_2S concentrations in ambient air varied over the trials, the size of the area of exposure remained unchanged, but personal exposure levels varied in this area, most noticeably for the November 2008 trial.

Compared to the geothermal areas in the east, Kuirau Park was not associated with markedly higher exposure levels. The two locations with readings above 5 ppb in the April trial had actual readings of 7 ppb and 8 ppb and exposure times of 8 hours.
Thus even for exposure times of 8 hours, H_2S concentrations of personal samplers in Kuirau Park remained relatively low.

Whether elevated exposure occurred in the area between Ranolf Street and Old Taupo Road and in the small residential area east of the Ngapuna site, remains uncertain because numbers of observations were low. Some personal samplers in this area had readings above 5 ppb, but in all cases the participants had also been to the area where higher exposure levels were evident.

Compared to the remainder of central Rotorua, exposure levels seemed lower in the area north of Amohau Street and west of Fenton Street. Moreover all samplers with readings above 5 ppb were associated with other areas of exposure. However, exposure time was mostly short (3 hours and below), and the small number of participants (2-4 participants) who had exposure times of up to 8 hours were consistently mobile inside this area. Therefore it is uncertain if exposure is lower in this area or if the lower exposure levels could be attributed to lower residence time and higher mobility of participants.

4.2.8 Regression analysis using map locations for the classification of groups

Using the colleges as a proxy for location resulted in the allocation of some participants into the wrong group. For example in the box plot (Figure 4-11) five of the outliers from RGH group were participants who lived in the central city and all the outliers in the RLH group were participants associated with a geothermal area outside of Rotorua. Hence these participants had been placed wrongly into the eastern and western Rotorua groups. In order to avoid the misclassifications, participants were regrouped in accordance to their map locations and the regression analyses were redone. The results showed the same trends as for the original regression analyses except that the effect (beta and partial R^2) of belonging to the RDC group increased considerably, *e.g.* exposure levels increased 7 fold for the RDC group compared to the levels of the RGH group. The results of the multiple regression analysis are shown in Table 4-16, while Table 4-17 shows the results of the regression analyses stratified by trial before and after reclassification for the RDC group and the remaining results of the regression analyses are reported in Appendix 11.

It should be noted that not all misclassifications were removed because some participants had not returned maps with their samplers.

Table 4-16: Multivariate regression analysis of personal samplers using reclassified groups.

H_2S 1-hour average	Ratio(10^B)	95% Confidence Interval	Partial R^2 (%)
RLH	1.29	0.98-1.68	0.93
RDC	7.20***	5.63-9.19	40.78***
April 2008	1.40*	1.83-1.90	1.30*
June 2008	2.07***	1.53-2.80	5.76***
October 2008	1.60**	1.17-2.19	2.38**
Number of observations: 369		**Adjusted R^2 (%) Model: 44.21*****	

*p=<0.05, **p=<0.01, ***p=<0.001

Table 4-17: Results of the regression analyses by trial for the RDC group before and after reclassification of the groups.

Trial	N		Ratio(10^B)		95% Confidence Interval		Partial R^2 (%)	
	before	after	before	after	before	after	before	after
April 2008	101	99	4.05***	6.04***	2.24-7.30	3.73-9.72	18.41***	36.15***
June 2008	102	100	5.28***	6.61***	3.14-8.88	4.32-10.11	29.01***	44.48***
October 2008	90	88	12.52***	19.05***	6.67-23.48	12.00-30.23	42.27***	65.45***
November 2008	84	82	2.94***	3.59***	1.65-5.25	2.05-6.29	14.44***	20.60***

*p≤ 0.05, **p≤ 0.01, ***p≤ 0.001 Reference group: RGH

4.3 Influence of meteorological factors on H_2S air concentrations

4.3.1 Descriptive statistics

Because the gas analyser did not take outside H_2S measurements during the April and November 2008 trials, only the data from the June and October 2008 trials and the December 2007 trial are available. Table 4-18 below only shows the statistics of the H_2S distribution for the combined June and October 2008 data, for the trials separately and for the December 2007 trial, followed by the corresponding histograms. The histogram for the December 2007 trial was omitted because it only had six data points.

Table 4-18: Descriptive statistics of H_2S concentration from air monitoring data (1-hour average) overall and by trial

H_2S (ppb)	mean	median	min	max	p5	p25	p75	p95	sd	>90[1]	N
June and October 2008	74	47	3	>90	6	22	>90	>90	59	38	106
June 2008	47	28	4	>90	5	10	60	>90	49	8	51
October 2008	100	>90	3	>90	11	44	>90	>90	57	30	55
December 2007[2]	246	224	193	347	193	200	265	347	63	n/a	5

[1] Number of readings above 90 ppb

[2] The air monitor was calibrated to read in the higher 50 to1500 ppb range

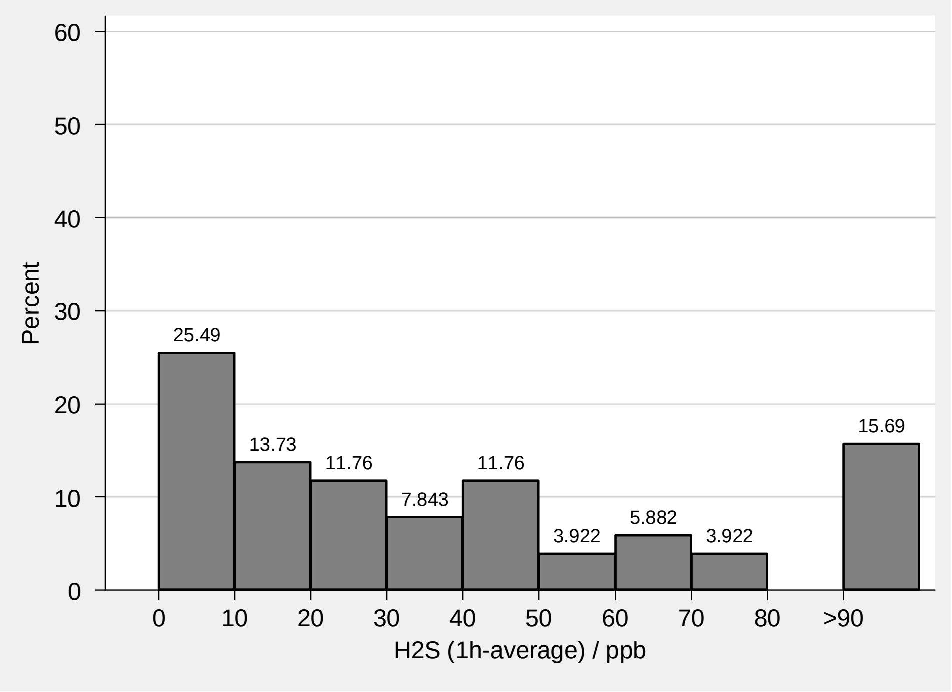


Figure 4-20: Histogram of H_2S distribution for the June 2008 trial (N = 51).

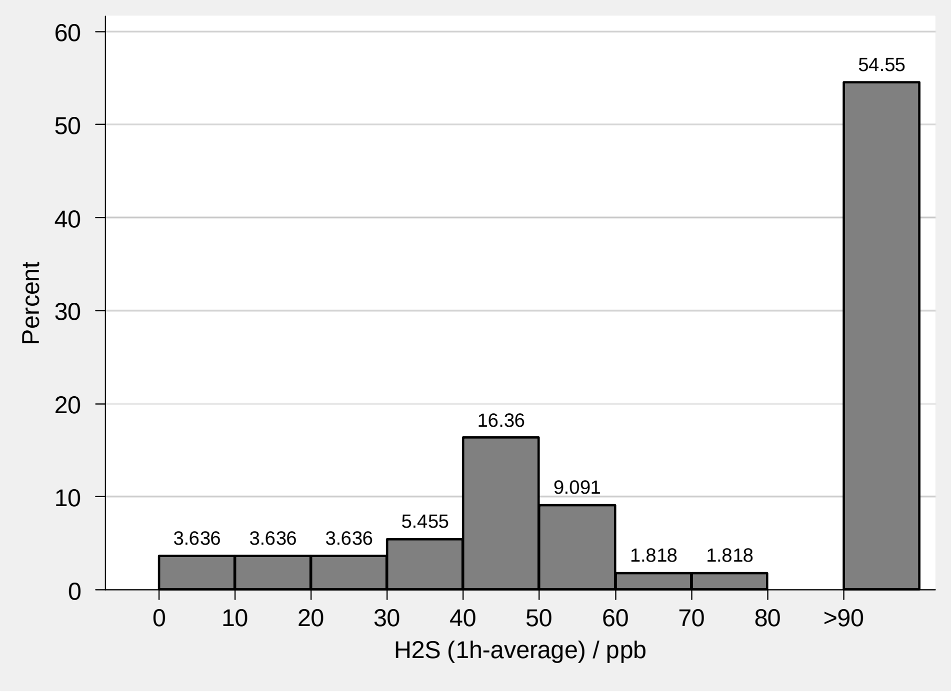


Figure 4-21: Histogram of H_2S distribution for the October 2008 trial (N = 55).

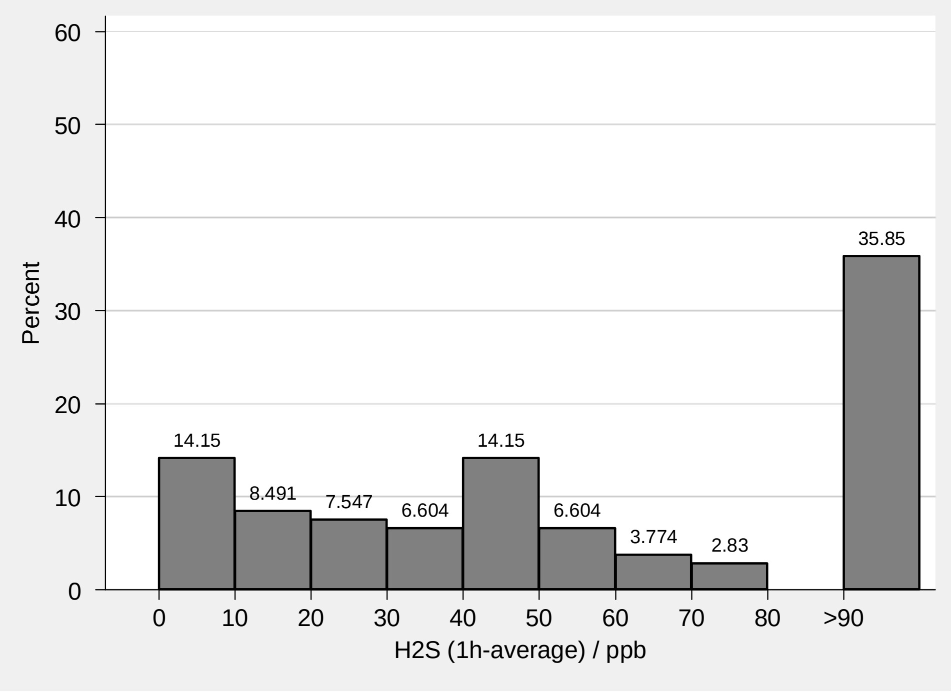


Figure 4-22: Histogram of H_2S distribution for the combined data from the June and October 2008 trial (N = 106).

The October and the combined data showed marked differences between the mean and the median. These data were skewed towards higher H_2S concentrations, while the June data were skewed towards lower concentrations. The December data which had the highest H_2S concentrations were more evenly distributed, probably due to the low number of recordings.

The number of readings above the upper detectable limit account for 60% of the observations in the October data and for 36% of the observations in the combined data. For the statistical analyses these readings were allocated a value of 150 ppb as was done in the personal exposure analyses. It is possible that the actual H_2S concentrations in the air could be higher, as indicated in the December data where all readings (1-minute interval) were above 150 ppb. However as it was impossible to estimate the actual concentrations, the value of 150 ppb was retained, as it also provided consistency between the personal exposure analysis and the analysis of the influence of meteorological factors.

Table 4-19 below shows the descriptive statistics of the meteorological data from the June and October 2008 combined trials based on hourly averages. Several meteorological observations in this study have a narrower data range than previous meteorological recordings in Rotorua, probably due to the limited amount of data collected in this study.

Table 4-19: Descriptive statistics of meteorological data combined from the June and October 2008 trials

Meteorological variables June and October 2008	mean	median	min	max	p5	p25	p75	p95	sd	N
Pressure (hPa)	1028.7	1029.9	1017.7	1033.6	1018.7	1027.3	1031.5	1033.2	4.1	107
Temperature air (ºC)	10.0	11	1	17	3	8	12.4	15	3.8	107
Temperature dew (ºC)	7.6	8.3	0.5	12.1	2.1	5.7	10.1	11.5	3.0	107
Temperature bulb (ºC)	8.8	9.7	0.8	13.3	2.7	7.4	11	12.7	3.2	107
Relative Humidity (%)	86.2	90.8	48	99.3	59.1	81	96	98	11.9	107
Rain (mm)	0.1	0	0	4.2	0	0	0	0.4	0.4	107
Wind Speed (m/sec) **(km/h)**	2.5 9.0	2.1 7.6	0 0	6.2 22.3	0.5 1.8	1 3.6	4.1 14.8	5.7 20.5	1.7 6.1	107
Gust Speed (m/sec) **(km/h)**	4.6 16.6	3.6 13.0	1 3.6	11.3 40.7	1.5 5.4	2.6 9.4	6.7 24.1	9.3 33.8	2.6 9.4	107

Compared to the national range of air pressure (960-1040 hPA), the range in this study (1017.7-1033.6 hPA) was narrower and skewed towards the higher values.

Historical data (1992-2005) on temperature in Rotorua showed a range from -5 to 29º C with a mean of 12.4º C and a median of 12.5º C (Ellery, 2007), while the range for this study is 1 to 17º C, with a mean and median of 10º C and 11º C respectively.

Little rainfall was recorded over the study period with only 12 one-hour periods in the October data. The three highest recordings were 4.2, 1.2 and 1mm; all other recordings were below 1mm.

Historical wind data (1992-2005) showed a range for wind speed from 0-70 km/h with a mean of 13 km/h and a median of 11 km/h (Ellery, 2007). This study recorded lower values with a range of 0 to 22.3 km/h, a mean of 9 km/h and a median of 7.6 km/h. Thus distribution in this study was skewed towards the lower end of the wind speed scale. Previous data (Ellery, 2007) had recorded wind speeds between 20 and 30 km/h, 17.3% of the time, and wind speeds above 30 km/h 3.1% of the time. Such wind speeds were rarely observed during this study. Historical data on gust speeds were not available but it is likely that a similar trend as for wind speed would be observed with the observations in this study lying in the lower range of gust recordings in Rotorua.

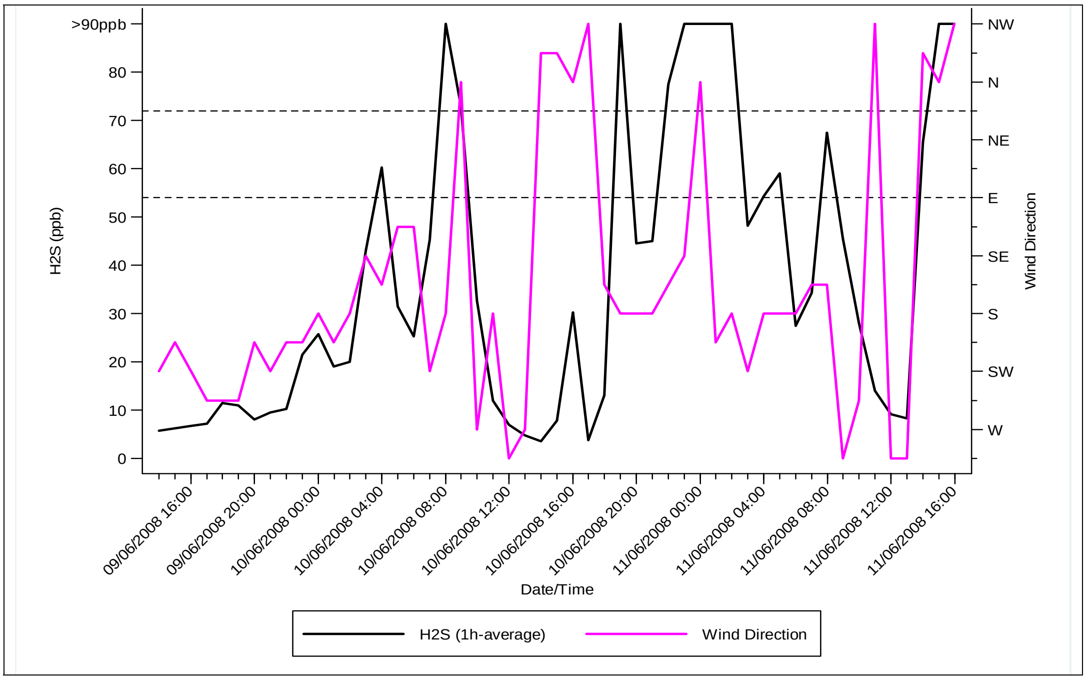
4.3.1.1 H_2S concentrations and wind direction

Table 4-20 gives the descriptive statistics of H_2S concentrations for the 4 categories of wind directions using the combined data from the June and October 2008 trials. Higher concentrations were observed during NE winds, while concentrations were notably lower during SW winds.

Table 4-20: Statistics of H_2S concentration by wind direction June and October 2008 data.

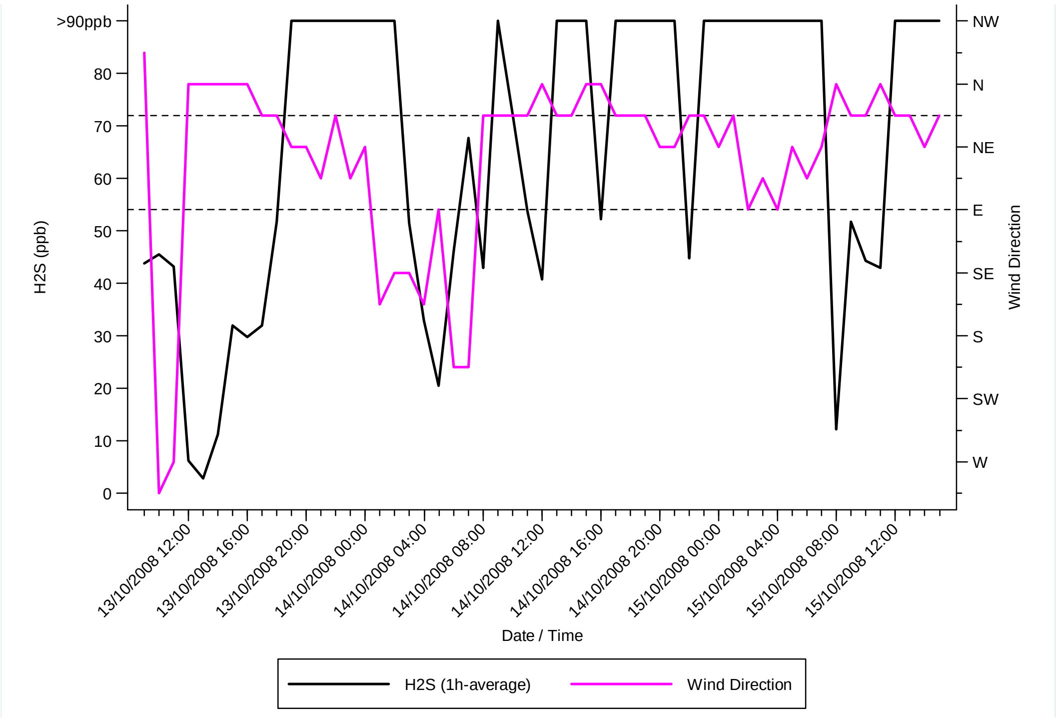
wind direction/ H_2S levels (ppb)	mean	median	min	max	p5	p25	p75	p95	sd	N
SW	29.2	15.3	4.8	>90	5.3	7.6	44.3	108.9	33.9	20
NW	45.7	31.2	2.8	>90	3.5	8.3	52.3	>90 .0	49.5	26
NE	124.0	>90 .0	20.5	>90	32.0	111.1	>90 .0	>90 .0	46.2	36
SE	67.7	48.3	12.0	>90	13.0	29.5	113.8	>90 .0	51.1	24

The following 3 graphs (Figure 4-23 - 4-25) display H_2S concentrations and wind directions in 1-hour intervals for the June and October 2008 trials and for the six-hour period during the December 2007 trial.



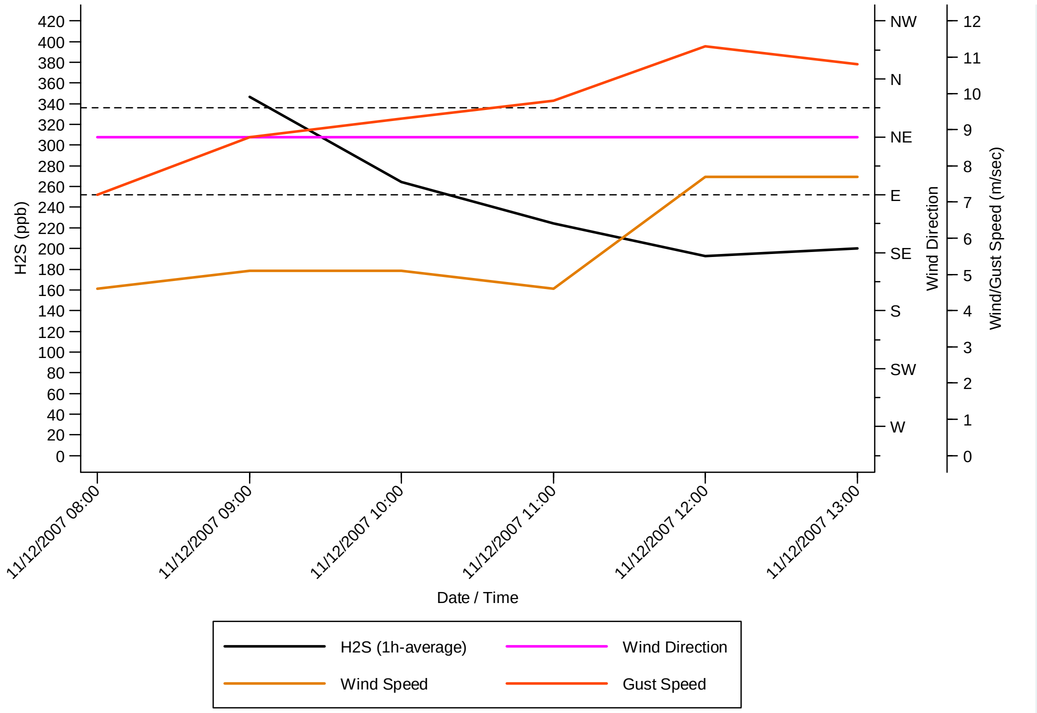
The wind directions between the dashed lines denote the group classified as NE winds in this study

Figure 4-23: Graph showing H_2S concentration and wind direction, June 2008.



The wind directions between the dashed lines denote the group classified as NE winds in this study

Figure 4-24: Graph showing H_2S concentration and wind direction, October 2008.



The wind directions between the dashed lines denote the group classified as NE winds in this study

Figure 4-25: Graph showing H_2S concentration, wind direction, wind and gust speed, December 2007.

During the June 2008 trial, which had recorded lower H_2S concentrations, NE winds were not observed, whereas during October 2008 north-easterlies were the prevailing winds. Additionally the October 2008 graph shows an association between higher H_2S concentrations and NE winds. During the December 2007 trial, which recorded high H_2S concentrations (130-480 ppb) the wind came consistently from a NE direction.

Several authors (Horwell *et al.*, 2005; Iremonger, 2008; Petersen *et al.*, 1998) observed higher H_2S concentrations during night time in Rotorua. This increase was also evident in parts of the June and October 2008 graphs, but once the NE winds became prevalent in the October 2008 graph, daytime H_2S levels rose and obscured the night time effect.

Thus these findings would indicate an association between higher H_2S concentrations and NE winds.

4.3.1.2 H_2S concentrations, gust and wind speed

Higher wind and gust speed have been implicated in having an inverse effect on H_2S concentrations by increasing dispersion of H_2S (Petersen *et al.*, 1998; Rogie *et al.*, 2001; Viveiros *et al.*, 2008; Viveiros *et al.*, 2009). Such an inverse association was observed in the December 2007 graph (Figure 4-25) and in the first 10 hours in the June 2008 graph (Figure 4-26), but subsequently not in the June 2008 graph or in the October 2008 graph (Figure 4-27).

It is possible that wind and gust speed did not reach a threshold speed to show a dispersive effect during the June 2008 trial, whereas during the October 2008 trial the effect of the NE winds may have obliterated any association between H_2S concentrations and wind or gust speed.

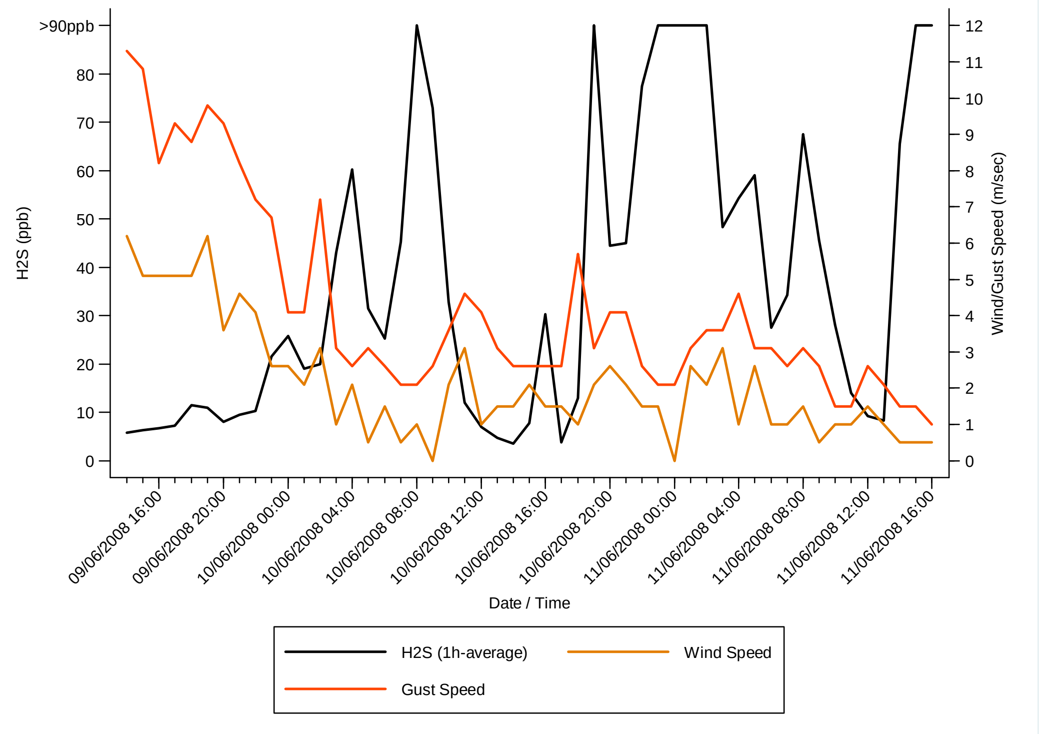


Figure 4-26: Graph showing H_2S concentration, wind and gust speed, June 2008.

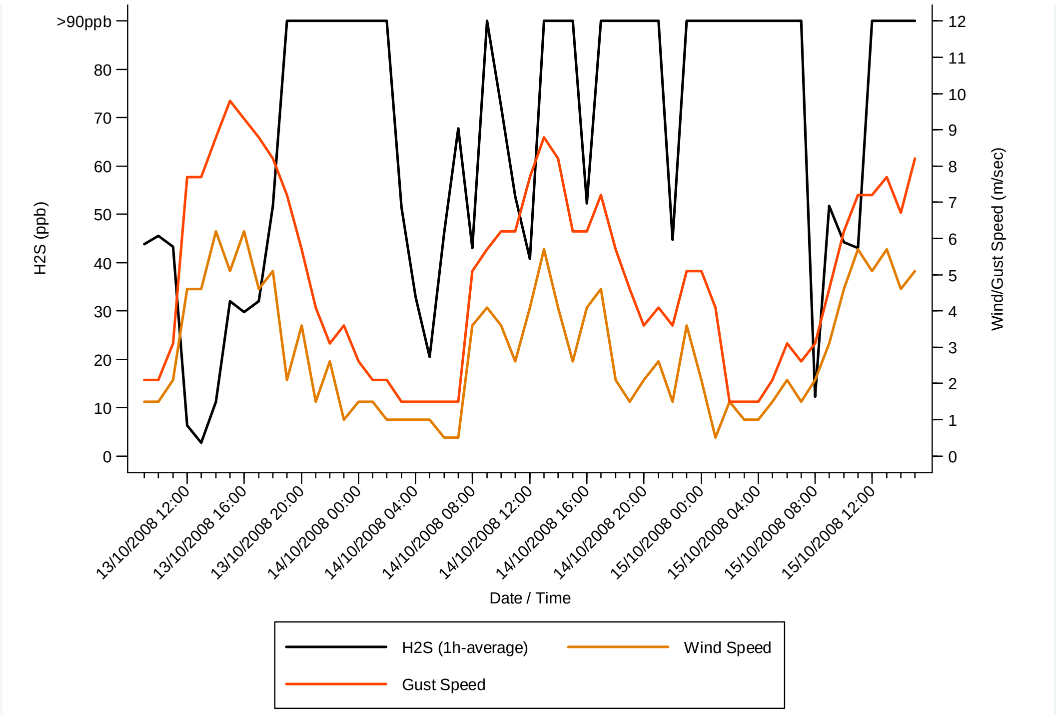


Figure 4-27: Graph showing H_2S concentration, wind and gust speed, October 2008.

4.3.1.3 H_2S concentrations, air pressure, relative humidity, and rain

Elsewhere in the world, air pressure and rainfall have also been implicated to have an inverse association with H_2S concentrations from soil gas emissions (Rogie *et al.*, 2001; Viveiros *et al.*, 2008; Viveiros *et al.*, 2009).

An association between air pressure and H_2S concentrations was not observed in the graphs in this study (Figure 4-28 - Figure 4-30). However as already mentioned air pressure readings in this study were skewed to the higher concentrations.

Relative humidity (RH) seemed positively correlated to H_2S concentration in the graphs except for the last 8 hours in June 2008 (Figure 4-28 to Figure 4-30).

An association between rainfall and H_2S concentrations could not be examined due to the low number of rainfall events and the small amount of rainfall during these events (Figure 4-28 - Figure 4-30).

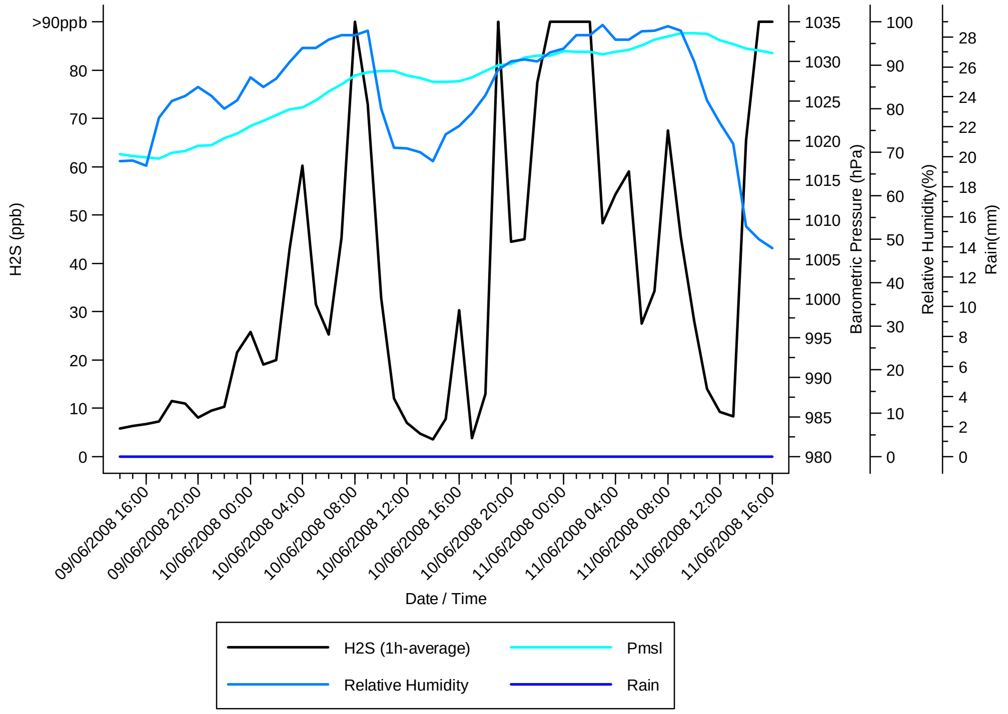


Figure 4-28: Graph showing H_2S concentrations, air pressure, relative humidity and rain, June 2008.

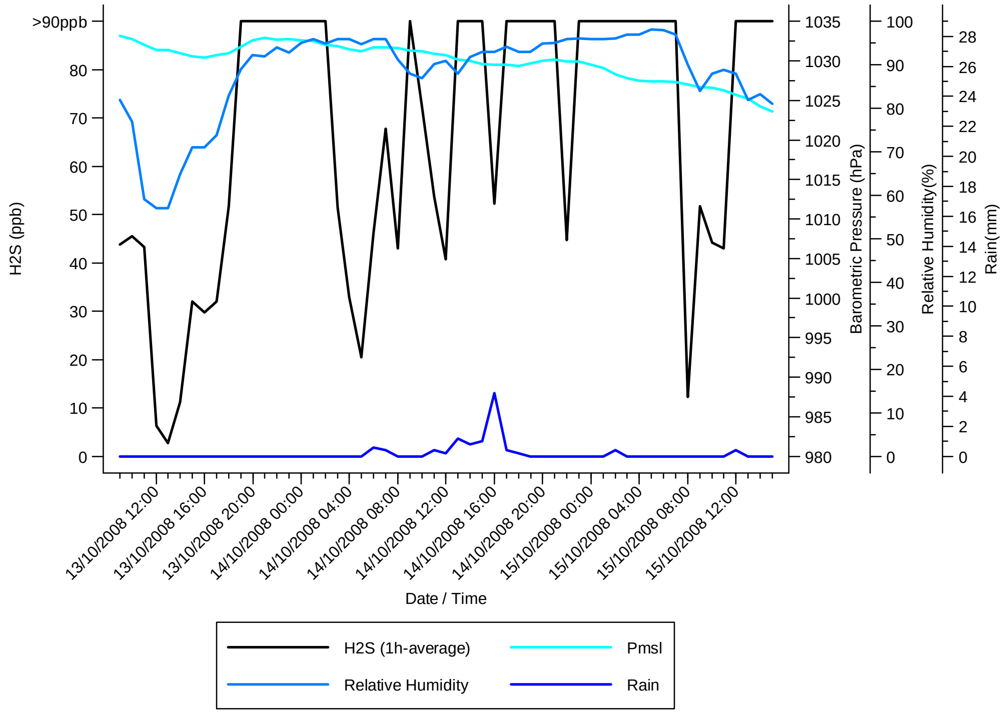


Figure 4-29: Graph showing H_2S concentration, air pressure, relative humidity and rain, October 2008.

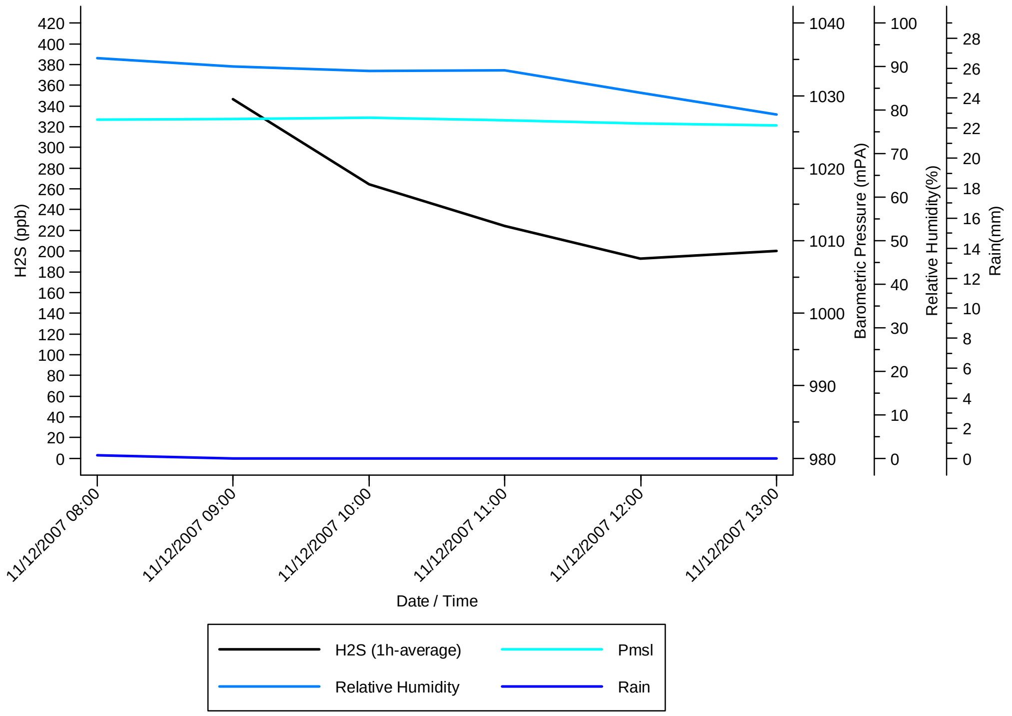


Figure 4-30: Graph showing H_2S concentration, air pressure, relative humidity and rain, December 2007.

4.3.1.4 H_2S concentrations and temperature

Air, dew-point, and wet temperature are inversely correlated with H_2S concentration in the June 2008 graph (Figure 4-31), but this relationship is obscured in the October 2008 graph (Figure 4-32), once the north-easterlies become the prevailing winds (approximately after the first 10 hours of observations). Air temperature and relative humidity were also inversely correlated during the June and October 2008 trial until the NE winds arrived. In the December 2007 graph (Figure 4-33) all temperatures remained constant throughout the trial and hence temperature variance conclusions could not be drawn.

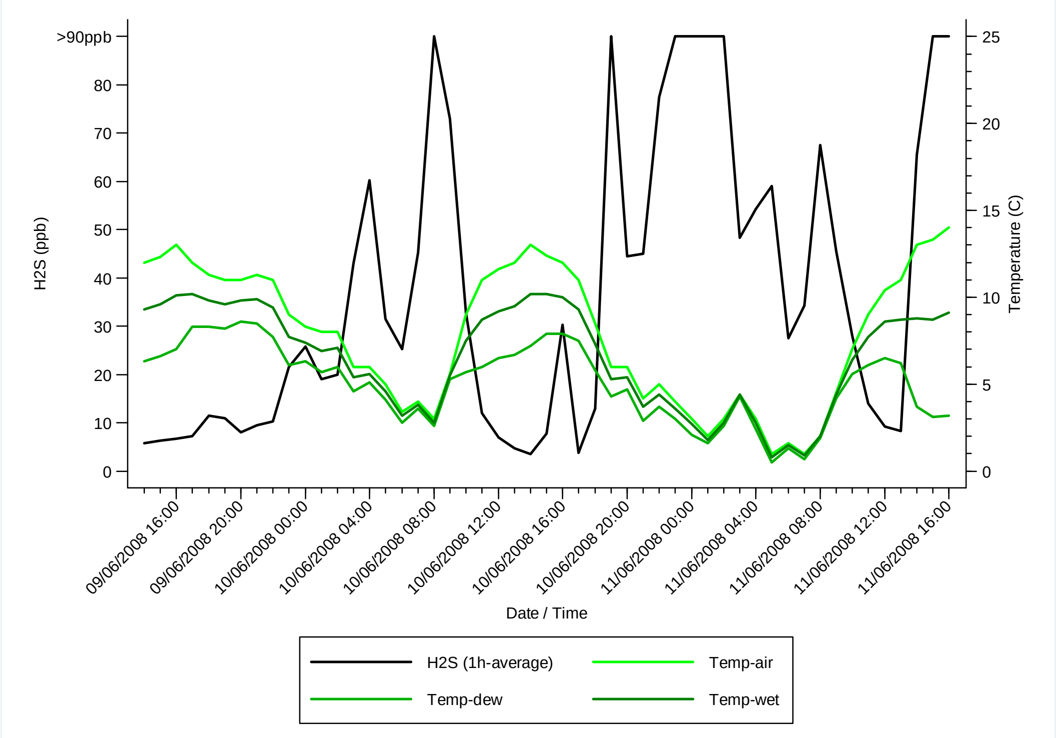


Figure 4-31: Graph showing H_2S concentration and temperature, June 2008.

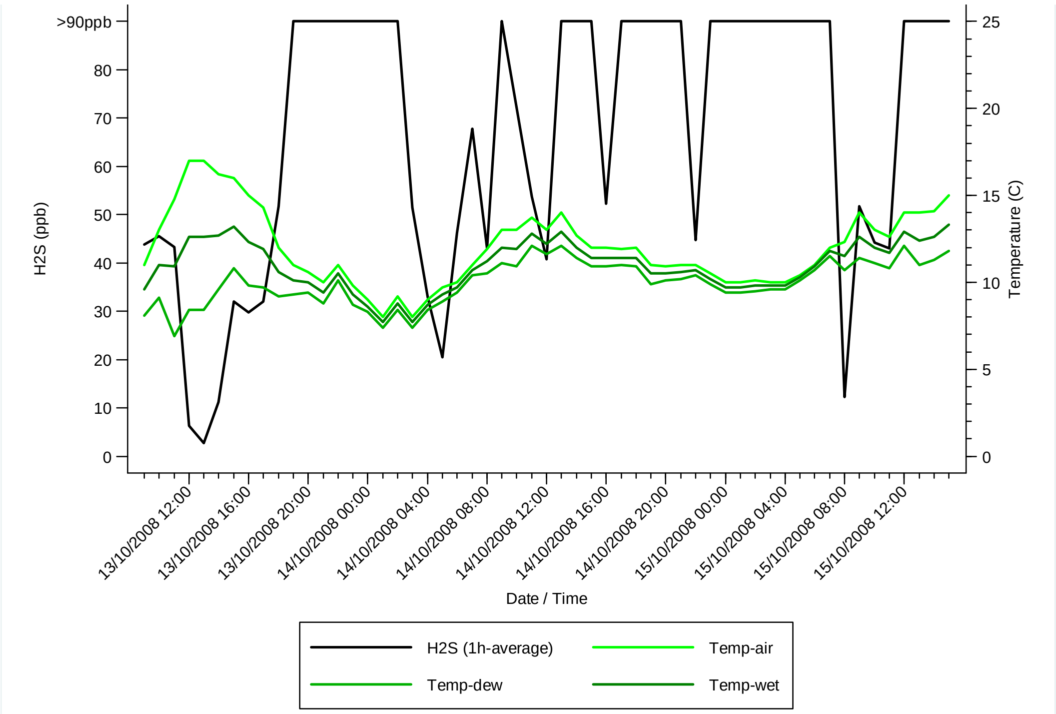


Figure 4-32: Graph showing H_2S concentration and temperature, October 2008.

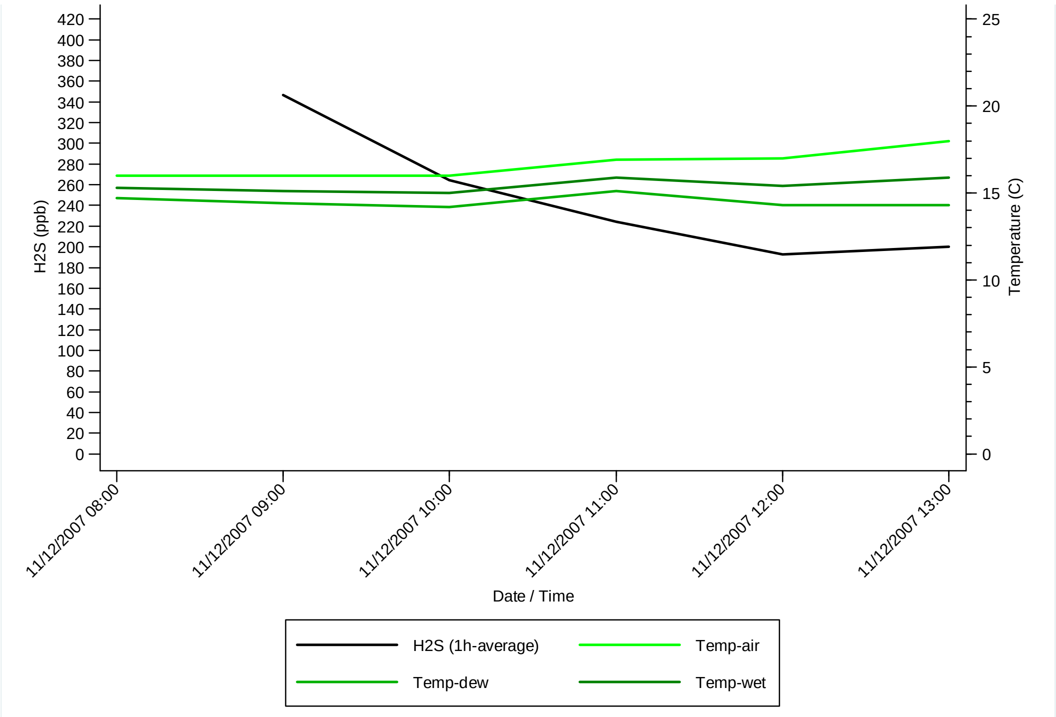


Figure 4-33: H_2S concentration and temperature, December 2007.

4.3.2 Multiple regression analysis

The multiple regression analysis was preceded by univariate analyses and by testing of the independent variables for collinearity.

4.3.2.1 Univariate analysis

Univariate analysis was performed to estimate the effect on H_2S concentrations in ambient air for each independent variable by itself. The results showed that relative humidity ($p \leq 0.001$), pressure ($p \leq 0.001$), wind ($p \leq 0.05$) and gust speed ($p \leq 0.001$) (Table 4-21) and wind direction ($p \leq 0.001$) (Table 4-22), had a statistically significant effect on H_2S concentrations.

Wind direction, relative humidity and pressure had a positive relationship with H_2S concentrations, while wind and gust speed had an inverse association with H_2S concentrations.

Table 4-21: Univariate analysis of H_2S concentration and meteorological data.

Meteorological variable	Ratio(10^{B})[20]	95% Confidence Interval	Ratio(10^{Beta})[21]	Adjusted R^2 (%) Model
Pressure (hPa)	1.12***	1.06-1.18	2.51	15.22***
Temperature air (°C)	0.95	0.89-1.00	0.66	2.39
Temperature dew (°C)	1.06	0.98-1.14	1.40	1.21
Temperature bulb (°C)	0.98	0.92-1.06	0.90	0.20
Relative Humidity (%)	1.05***	1.04-1.07	3.33	26.70***
Rain (mm)	1.33	0.81-2.19	1.30	0.3
Wind Speed (m/sec)	0.87*	0.76-0.98	0.61	3.67*
Gust Speed (m/sec)	0.89**	0.82-0.96	0.53	6.51**
Number of observations: 106				

$^{*}p\leq 0.05$, $^{**}p\leq 0.01$, $^{***}p\leq 0.001$

Table 4-22: Univariate analysis of H_2S concentration and wind direction

Wind direction	Ratio(10^{B})	95% Confidence Interval	Partial R^2 (%) [22]
NW	1.34	0.79 – 2.28	1.20
NE	6.10***	3.72–10.01	34.00***
SE	2.83***	1.65 – 4.84	12.63***
Number of observations: 106			**Adjusted R^2 (%) Model: 38.87*****

$^{*}p\leq 0.05$, $^{**}p\leq 0.01$, $^{***}p\leq 0.001$ Reference group: SW winds

Almost 39% of the variance in H_2S levels was associated with wind direction. NE winds explained most of the variance (34%, $p\leq 0.001$), followed by SE winds (13%, $p\leq 0.001$), while NW winds explained just 1% (not statistically significant). Thus the high explained variance in H_2S concentrations by NE winds and the increase in H_2S concentrations by a factor of 6.1 compared to the SW winds suggests that NE winds are a major determinant of ambient air H_2S concentrations at Te Ngae Road.

In contrast, the effects of the other meteorological factors which were statistically significant, were smaller. Relative humidity and pressure explained 27% and 15% of the variance in H_2S levels respectively, while wind and gust speed explained about 4% and 7% of the variance respectively. To compare the increase in H_2S concentration between wind direction and the other meteorological factors is more difficult as one makes comparison between categories (SW vs. NE) and the other is a continuous variable

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[20] The effect estimate (coefficient beta) represents the change in H_2S for a change in one measurement unit of the independent variable. Because the data were log transformed the coefficient beta represents a ratio. *e.g.* a coefficient beta of 1.9 indicates a 1.9 fold increase in H_2S concentrations for a one unit increase in the independent variable, while an increase in 3 units of the independent variable will increase H_2S concentrations $(1.9)^3 = 6.86$ times.
For categorical variables, a coefficient of 1.9 indicates a 1.9 fold increase in H_2S compared to the reference variable.

[21] The effect estimate (standardised Beta) represents the change in H_2S associated with a change of one standard deviation in the independent variables. Again due to log transformation the results are ratios.

[22] partial R^2: correlation between H_2S and one independent variable, when the effects of the other independent variables are removed. Hence it is an indication of the unique contribution of that independent variable to the model.

where the effect estimate relates to one unit increase of the variable of interest. However an increase in 10 units for relative humidity (10%) and pressure (10 hPa) would increase H_2S concentrations by a factor of 1.63 and 3.11 respectively compared to a 6.1 fold increase for the NE winds.

4.3.2.2 Tests of collinearity between the independent variables

Collinearity testing of the independent variables was done using the Variance-Inflation Factor (VIF)[23] and the Pearson Correlation Coefficient[24]. Only variables with a p-value ≤0.05 in the univariate analyses were tested for collinearity. The results are displayed in table 4-23 and table 4-24 respectively.

In both tests wind and gust speed showed collinearity: consequently only gust speed was entered into the multiple regression model, because its R^2 and unstandardized beta values were higher than the wind speed values.

Table 4-23: VIF collinearity test of independent variables.

Variable	VIF	1/VIF
Gust Speed	5.56	0.179825
Wind Speed	5.21	0.191958
NE	2.53	0.395017
NW	2.49	0.402037
SE	2.16	0.462296
Pressure	1.82	0.548937
Relative Humidity	1.69	0.592962
Mean VIF	3.07	

Table 4-24: Pearson collinearity test of independent variables.

Variable	NW	NE	SE	RH	Pressure	Gust Speed	Wind Speed
NW	1.000						
NE	-0.403***	1.000					
SE	-0.305***	-0.383***	1.000				
RH	-0.488***	0.308***	0.292**	1.000			
Pressure	0.230*	0.128	0.072	0.171	1.000		
Gust Speed	-0.073	0.127	-0.267**	-0.289**	-0.517***	1.000	
Wind Speed	-0.053	0.158	-0.282**	-0.291**	-0.451***	0.897***	1.000

*p=<0.05, **p=<0.01· ***p=<0.001 N=107

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[23] Variance-inflation factor (VIF): The 1/VIF is the tolerance $(1-R^2)$. A small value (<0.1) indicates that the variable under consideration is almost a perfect linear combination of independent variables already in a model and that it should not be added. The VIF is the inverse of the tolerance. Values >5 suggest a multicollinearity problem, but sometimes the cut-off is set higher.

[24] Pearson correlation coefficient: Pearson's r is a measure of correlation which varies from -1 to +1, with 0 indicating no relationship (random pairing of values); 1 indicates a perfect positive relationship and -1 indicates a perfect negative relationship. A factor of 0.75 or higher is often used as an indicator of multicollinearity.

4.3.2.3 Multiple regression analyses

Only variables with a p-value ≤0.05 in the univariate analyses were entered into the multiple regression models and wind speed was omitted. Variables were entered into the model one at a time to better judge the effect of each variable on the model.

For all variables entered into the multiple regression models the partial R^2 and the standardized Beta values dropped compared with the values from the univariate analysis, while the Model R^2 increased to over 50% (Table 4-25).

NE winds were again the most influential meteorological variable with partial R^2, beta and standardized Beta values being considerably larger than the values of the other variables.

When added to the model, relative humidity and pressure increased the adjusted R^2 of the model by about 7 and 5% respectively and their partial R^2 values were 8 and 5% respectively, indicating a small to moderate effect on H_2S concentrations.

Gust speed had little effect on H_2S concentrations as indicated by the small partial R^2 value (1.72), the low impact on the adjusted R^2 of the model, and the loss of statistical significance.

Table 4-25: Multiple regression analysis of H_2S concentrations and meteorological data.

H_2S 1-hour average	Ratio(10^B)	95% Confidence Interval	Ratio(10^{Beta})	Partial R^2 (%)
NW	1.34	0.79–2.28	1.29	1.20
NE	6.10^{***}	3.72–10.01	5.65	34.00^{***}
SE	2.83^{***}	1.65–4.84	2.41	12.63^{***}
Number of observations: 106			**Adjusted R^2 (%) Model: 38.87^{***}**	

H_2S 1-hour average	Ratio(10^B)	95% Confidence Interval	Ratio(10^{Beta})	Partial R^2 (%)
NW	1.66^{*}	1.00-2.74	1.55	3.76
NE	4.53^{***}	2.79-7.37	4.26	27.38^{***}
SE	2.01^{**}	1.19-3.42	1.81	6.37
Relative Humidity (%)	1.03^{***}	1.02-1.05	2.21	13.46^{***}
Number of observations: 106			**Adjusted R^2 (%) Model: 46.57^{***}**	

H_2S 1-hour average	Ratio(10^B)	95% Confidence Interval	Ratio(10^{Beta})	Partial R^2 (%)
NW	1.01	0.58-1.77	1.01	0
NE	3.23^{***}	1.98-5.35	3.08	17.59^{***}
SE	1.47	0.86-2.52	1.38	1.97
Relative Humidity (%)	1.03^{***}	1.01-1.04	1.87	10.18^{***}
Pressure (hPa)	1.08^{***}	1.03-1.13	1.93	10.14^{***}
Number of observations: 106			**Adjusted R^2 (%) Model: 51.51^{***}**	

H_2S 1-hour average	Ratio(10^B)	95% Confidence Interval	Ratio(10^{Beta})	Partial R^2 (%)
NW	1.01	0.57-1.76	1.01	0
NE	3.45^{***}	2.07-5.76	3.27	18.89^{***}
SE	1.44	0.84-2.46	1.36	1.79
Relative Humidity (%)	1.03^{**}	1.01-1.04	1.80	7.94^{**}
Pressure (hPa)	1.06^{*}	1.01-1.12	1.65	5.44^{*}
Gust Speed (m/sec)	0.95	0.88-1.03	0.77	1.72
Number of observations: 106			**Adjusted R^2 (%) Model: 51.86^{***}**	

$^{*}p \le 0.05$, $^{**}p \le 0.01$, $^{***}p \le 0.001$

Reference group (wind direction): SW

4.4 Health survey

4.4.1 Population Statistics

In order to establish whether there were any notable differences between the three exposure groups[25] with respect to age, sex, ethnicity, smoking and residence time, which could affect the results of the logistic regression analysis, the population statistics were obtained (Table 4-26) and analysed using the t-test for continuous variables and the Pearson chi-square test for categorical variables.

Table 4-26: Population statistics for the current residential exposure category.

Exposure category	low	medium	high
Age (n)	(140)	(133)	(70)
Mean (SD)	43.9 (15.6)	46.2 (16.3)	52.4 (21.2)
Sex (n)	(151)	(138)	(71)
Female %	67.6	76.1	66.2
Ethnicity (n)	(148)	(133)	(67)
NZ Maori/Pacific Islander %	54.1	32.3	23.9
Smoking (n)	(152)	(139)	(71)
Ex-smoker %	29.6	26.6	26.0
Smoker %	26.7	23.7	24.1
Residence time - years (n)	(142)	(127)	(66)
Mean (SD)	19.9 (14.5)	24.1 (14.5)	23.4 (14.1)

Table 4-26 shows that the number of participants in the high exposure group was about half the size of the other two groups and that 66% to 76% of the participants were female.

Statistically significant differences between the groups were found for the following factors:

- The mean age in the high exposure group was about 10 years older than in the median and low exposure groups (equal variance[26]: $p < 0.001$; unequal variance: $p < 0.05$).
- The percentage of Maori and Pacific Islanders in the low exposure group was notably higher than in the other groups ($p< 0.05$). For the statistical analyses, the four ethnicity categories (NZ Maori, NZ European, Pacific Islander, other) were reduced

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[25] The researchers, who originally conducted the health survey, had based the categorisation of the exposure groups on ambient air measurements by Horwell (1998).

[26] assuming equal standard deviations for all groups

to two, because only 9 participants identified as Pacific Islanders and 17 participants as ‘Other’. The Pacific Island group was included in the NZ Maori category and the ‘Other’ group in the NZ European category.

- In the low exposure group, the length of residence in Rotorua was about 4 years less compared to the other groups. This difference in the length of residence time was statistically significant between the low and the median exposure groups ($p<0.05$), but not between the low and the high exposure group.

4.4.2 Crude and adjusted odds ratios (OR) for all diseases

In contrast to the crude OR, the adjusted OR was calculated by controlling for differences between the groups with respect to age, sex, ethnicity and smoking status. Hence any differences between the crude and the adjusted OR may indicate that one of these factors had influenced the results of the crude OR.

In the logistic regression analyses, only the values of the crude OR for cataract had statistical significance, but not for its adjusted OR (Table 4-27). Furthermore the adjusted OR value had dropped to 1.7 compared to a crude OR value of 5. As the occurrence of cataract is mostly age related and the mean age was raised in the high exposure group, it is likely that the high value of the crude OR is due to differences in the age distribution rather than to differences in H_2S exposure between the groups.

Asthma and its severity-subcategories showed raised adjusted OR values (1.9-3.1) for the high exposure group. Although the CIs included the neutral value of 1 (not statistically significant), values were often close to 1, which may indicate that the lack of statistical significance could be due to the relatively small number of observations.

None of the other diseases showed statistical significance and all CI values deviated largely from 1. The same applied to the crude and adjusted OR values of the medium exposure group with the exception of cataracts.

Table 4-27: Crude and adjusted OR for diseases using the current residential exposure category

	1. crude OR (95% CI)		**2. adjusted OR** (95% CI)	
Exposure Category	**medium**	**high**	**medium**	**high**
Asthma 1. (n=362/ cases: 65) 2. (n=328)	1.2 (0.63-2.19)	1.2 (0.95-3.82)	1.1 (0.59-2.21)	2.1 (0.97-4.36)
Hospitalisation for asthma: all asthmatics 1. (n=361/cases: 20) 2. (n=327)	0.9 (0.31-2.87)	2.3 (0.76-6.73)	0.8 (0.23-2.62)	2.4 (0.71-7.73)
Hospitalisation for asthma:[2] 1. (n=317/ cases: 20) 2. (n=284)	1.0 (0.31-2.94)	2.4 (0.81-7.28)	0.9 (0.25-2.91)	3.1 (0.90-10.94)
On medication for asthma: all asthmatics 1. (n=362 /cases: 55) 2. (n=328)	1.2 (0.57-2.17)	1.8 (0.84-3.70)	1.1 (0.54-2.23)	1.9 (0.86-4.24)
On medication for asthma:[3] 1. (n=352/ cases: 55) 2. (n=318)	1.1 (0.57-2.19)	1.8 (0.87-3.83)	1.1 (0.55-2.26)	2.0 (0.90-4.49)
Epilepsy 1. (n=291/ cases: 7) 2. (n=262)	0.8 (0.18-3.71)	no cases	0.9 (0.20-4.38)	no cases
Other neurological condition 1. (n=349/ cases: 7) 2. (n=200)	1.6 (0.27-9.87)	2.2 (0.31-16.07)	0.8 (0.10-6.16)	1.4 (0.16-11.49)
Cancer 1. (n=359/ cases: 19) 2.n=325)	1.3 (0.44-3.56)	1.2 (0.35-4.31)	1.0 (0.33-3.07)	0.5 (0.11-2.10)
Cancer Skin 1. (n=349/ cases: 9) 2.(n=205)	1.1 (0.27-4.49)	0.5 (0.59-4.87)	0.7 (0.16-3.14)	0.2 (0.02-2.49)
Sinus problems 1. (n=360/ cases: 107) 2. (n=326)	1.2 (0.69-1.90)	1.1 (0.58-2.02)	1.1 (0.61-1.84)	1.1 (0.54-2.10)
On medication:[4] 1. (n=293/ cases: 39) 2. (n=266)	1.0 (0.49-2.11)	0.7 (0.28-1.98)	0.8 (0.34-1.79)	0.7 (0.25-2.17)
Cataract 1. (n=355/ cases: 23) 2. (n=323)	3.2 (1.00-10.33) *	5.0 (1.45-17.18) **	3.0 (0.66-13.76)	1.7 (0.34-13.76)
Skin problems 1. (n=356/ cases: 50) 2. (n=323)	1.3 (0.65-2.42)	0.8 (0.35-2.01)	1.2 (0.61-2.47)	0.8 (0.32-2.05)
Hypertension 1. (n=362/ cases: 54) 2. (n=328)	1.4 (0.72-2.68)	1.4 (0.65-3.12)	1.2 (0.55-2.45)	0.8 (0.35-2.05)

[2] excluding asthmatics who never been hospitalised for asthma
[3] excluding asthmatics who are not on asthma medication
[4] excluding participants who are not taking medication for sinus problems and those on herbal remedies

* p≤ 0.05; ** p ≤ 0.01

Please note that the number of observations used for the analysis of the crude and adjusted OR value vary, as the adjusted OR takes age, sex, ethnicity and smoking status into consideration. If an observation had a missing value for any of these factors it was excluded from the analyses.

In order to investigate a possible association between exposure to H_2S and asthma and cataract, the analyses were repeated for these diseases using the refined exposure models.

4.4.3 Refined exposure models for asthma and cataract

The refined exposure models used either only the residential exposure category or a combined exposure category created by incorporating the exposure category of the work place. These two models were further refined by using the exposure category of the previous home or work address, if these addresses had changed in the last 2 years. In the ensuing two models the exposure category was either adjusted or the observation removed, if the exposure category had changed in the last two years.

Table 4-28 gives the adjusted OR values for asthma and cataract for the refined exposure models. The population statistics for these models and the crude OR values are shown in Appendix 12. The population statistics of the refined models were similar to the ones shown in table 4-26 except for an increase in the percentage of ex-smokers in the high exposure group.

Refining the exposure model reduced the number of observations, possibly affecting the validity of the results from the statistical analyses. Such an effect was observed for two asthma severity groups ('Hospitalisation for asthma') in the combined exposure model, which excluded observations with a change in exposure category over the last two years (Table 4-28). The number of cases in this model had reduced to 6 and none was observed in the medium exposure group and all were female participants. Consequently the software removed all of the observations in the medium exposure group and all observations from male participants in the other two exposure groups from the analysis. The number of observations was reduced to 94 and 82 respectively and the adjusted OR values for these categories deviated markedly from the OR values of the other asthma categories. Thus these OR values should be disregarded and the 'Hospitalisation for asthma' categories were excluded from further analyses.

Table 4-28: Adjusted OR for asthma and cataract using the refined exposure models.

Exposure Category	**medium** OR (95% CI)	**high** OR (95% CI)	**medium** OR (95% CI)	**high** OR (95% CI)	**medium** OR (95% CI)	**high** OR (95% CI)
Exposure Model	**1. current residential exposure**		**2. previous residential exposure[1]**		**3. observation excluded if residential exposure category changed**	
Asthma (1.n=328 , 2.n=319, 3.n=279)	1.1 (0.59-2.21)	2.1 (0.97-4.36)	0.6 (0.31-1.28)	2.4 (1.11-5.00)*	0.8 (0.35-1.71)	2.4 (0.98-5.69)
Hospitalisation all asthmatics (1.n=327 , 2.n=318, 3.n=279)	0.8 (0.23-2.62)	2.4 (0.71-7.73)	0.5 (0.12-1.72)	1.5 (0.41-5.41)	0.6 (0.14-2.76)	1.4 (0.29-7.02)
Hospitalisation for asthma[1] (1.n=284 , 2.n=275, 3.n=248)	0.9 (.25-2.91)	3.1 (0.90-10.94)	0.5 (0.12-1.79)	2.0 (0.53-7.70)	0.7 (0.15-2.84)	1.8 (0.35-9.61)
On medication all asthmatics (1.n=328 , 2.n=319, 3.n=279)	1.1 (0.54-2.23)	1.9 (0.86-4.24)	0.6 (0.29-1.39)	2.9 (1.34-6.39)**	0.7 (0.28-1.64)	3.0 (1.21-7.39)*
On medication for asthma[2] (1.n=318 , 2.n=309, 3.n=273)	1.1 (0.55-2.26)	2.0 (0.90-4.49)	0.6 (0.29-1.36)	2.9 (1.30-6.26)**	0.7 (0.28-1.66)	2.9 (1.17-7.18)*
Cataract (1.n=323 , 2.n=314, 3.n=275)	3.0 (0.66-13.76)	1.7 (0.34-8.34)	2.4 (0.57-9.93)	1.0 (0.19-4.86)	2.5 (0.54-11.63)	1.3 (0.23-6.98)
Exposure Model	**1. current combined exposure**		**2. previous combined exposure**		**3. observations excluded if combined exposure category changed**	
Asthma (1.n=281, 2.n=272, 3.n=212)	1.1 (0.53-2.19)	1.9 (0.85-4.20)	0.6 (0.25-1.21)	2.0 (0.90-4.53)	0.6 (0.21-1.62)	1.9 (0.70-5.35)
Hospitalisation all asthmatics (1.n=281, 2.n=272, 3.n=94)	0.5 (0.11-1.88)	1.4 (0.36-5.11)	0.2 (0.02-1.19)	0.6 (0.10-2.98)	no cases	0.7 (0.08-6.42) $^{\#}$
Hospitalisation for asthma[1] (1.n=242, 2.n=233, 3.n=82)	0.5 (0.12-2.06)	1.8 (0.45-7.03)	0.1 (0.02-1.19)	0.7 (0.12-3.97)	no cases	0.9 (0.98-7.97) $^{\#}$
On medication all asthmatics (1.n=281, 2.n=272, 3.n=212)	1.0 (0.47-2.20)	1.8 (0.74-4.15)	0.5 (0.21-1.25)	2.6 (1.11-6.09)*	0.4 (0.13-1.53)	2.8 (0.95-8.07)
On medication for asthma[2] (1.n=271 , 2.n=263, 3.n=206)	1.0 (0.47-2.22)	1.8 (0.77-4.35)	0.5 (0.21-1.23)	2.5 (1.07-5.93)*	0.5 (0.13-1.55)	2.7 (0.91-7.79)
Cataract (1.n=277, 2.n=268, 3.n=208)	2.2 (0.41-12.13)	1.8 (0.31-10.55)	1.6 (0.32-7.66)	0.8 (0.14-4.81)	1.6 (0.29-9.21)	1.1 (0.17-7.86)

[1] excluding asthmatics who never been hospitalised for asthma

[2] excluding asthmatics who are not on asthma medication

$^{\#}$ invalid result see section 4.4.3

* $p \leq 0.05$, ** $p \leq 0.01$

Disregarding the categories of ‘Hospitalisation for Asthma’ in the refined models, which use the residential address, the OR values for asthma in the high exposure group were larger (2.4 for ‘Asthma’ and 2.9 for ‘On medication for asthma’) than in the model which used the current residential address only. Furthermore all OR values gained statistical significance except for one, however the CI value was close to 1. These trends indicate that the association between asthma and the high exposure group became stronger as the exposure model became more refined and the diagnosis of asthma more tightly defined, supporting the hypothesis of an association between asthma and H_2S exposure. It is unclear whether the higher percentage of ex-smokers in the high exposure group would have had an additional effect on the increase in OR values.

In the models using the combined exposure a similar trend was observed, but the evidence was weaker with slightly lower OR values and a lack of statistical significance, especially in the ‘Asthma’ category. It is uncertain whether these differences between the residential and combined exposure models were due to the more precise classification of exposure or to the lower number of observations in the combined exposure models.

In all models, the CIs for the statistically significant OR values were wide with values ranging from 1.1 to 7. Hence there is uncertainty about the actual effect size H_2S exposure has on the occurrence of asthma. In all models, an association between asthma and exposure levels was not observed for the medium exposure group.

For cataract, the OR values in the high exposure group were predominantly close to 1 and without statistical significance. In the medium exposure group OR values were relatively high but again without statistical significance and the CI values deviated largely from 1. Thus there was little evidence supporting an association between cataract and H_2S exposure in the refined exposure models.

4.4.4 OR for asthma using different lengths of residence time

In order to investigate whether the length of residence in Rotorua affected the association between exposure to H_2S and asthma, the adjusted OR values were recalculated using only observations with a residence time above 3, 5, 7 and 10 years.

The results for the asthma severity group “asthmatics who are on medication, excluding asthmatics, who are not on medication”, are given in Table 4-29. The results for the other asthma severity groups were similar and are reproduced in Appendix 13.

The results of this analysis should be treated with some caution because about 75% of the observations had a residence time above 10 years and the number of observations decreased with increasing residence time as more observations were excluded.

In 5 of the 6 exposure models the ORs increased with the length of the residence time for the high exposure group, but only 2 were statistically significant. The exposure model using the previous residential address did not show such an increase, and the OR values remained constant at 2.5 with statistical significance ($p<0.05$).

In the combined exposure model excluding participants who had changed exposure category in the last two years, an OR value from the medium exposure group was 0.2 (indicating a protective effect) with statistical significance ($p<0.05$). It is very likely that this is an erroneous finding as the CI was very wide and similar OR values with statistical significance were not observed in any other analyses.

Table 4-29: Adjusted OR for asthmatics on medication using the residential and combined exposure models and a residence time longer than 3, 5, 7, 10 years.

Exposure Category	**medium** OR (95% CI)	**high** OR (95% CI)	**medium** OR (95% CI)	**high** OR (95% CI)	**medium** OR (95% CI)	**high** OR (95% CI)
Exposure Model	**1. current residential exposure**		**2. previous residential exposure**		**3. observation excluded if residential exposure category changed**	
Residence time over 3 years (1.n=283, 2.n=277, 3.n=246)	0.9 (0.42-1.94)	1.8 (0.77-4.30)	0.6 (0.24-1.29)	2.5 (1.10-5.76)*	0.5 (0.20-1.36)	2.2 (0.83-5.63)
Residence time over 5 years (1.n=255, 2.n=249, 3.n=222)	0.7 (0.30-1.69)	2.1 (0.85-5.19)	0.5 (0.18-1.16)	2.5 (1.01-6.23)*	0.4 (0.13-1.17)	2.5 (0.89-6.85)
Residence time over 7 years (1.n=237, 2.n=232, 3.n=206)	0.8 (0.32-1.92)	2.2 (0.86-5.55)	0.5 (0.18-1.27)	2.5 (1.00-6.42)*	0.4 (0.14-1.37)	2.6 (0.91-7.54)
Residence time over 10 years (1.n=217, 2.n=212, 3.n=189)	0.9 (0.36-2.21)	2.2 (90.82-5.73)	0.5 (0.16-1.25)	2.6 (1.01-6.72)*	0.5 (0.16-1.61)	3.0 (1.01-8.86)*
Exposure Model	**1. current combined exposure**		**2. previous combined exposure**		**3. observations excluded if combined exposure category changed**	
Residence time over 3 years (1.n=241, 2.n=238, 3.n=189)	0.9 (0.37-1.99)	1.7 (0.65-4.23)	0.5 (0.19-1.28)	2.3 (0.90-5.62)	0.3 (0.07-1.24)	1.7 (0.53-5.45)
Residence time over 5 years (1.n=217, 2.n=215, 3.n=174)	0.7 (0.28-1.90)	2.0 (0.75-5.48)	0.5 (0.17-1.32)	2.6 (0.95-6.93)	0.2 (0.04-0.98)*	1.6 (0.47-5.69)
Residence time over 7 years (1.n=202, 2.n=200, 3.n=161)	0.9 (0.31-2.30)	2.2 (0.79-6.22)	0.5 (0.18-1.47)	2.7 (0.96-7.37)	0.2 (0.04-1.34)	2.0 (0.51-7.60)
Residence time over 10 years (1.n=185, 2.n=182, 3.n=147)	1.0 (0.34-2.67)	2.2 (0.75-6.62)	0.5 (0.16-1.51)	2.9 (1.01-8.17)*	0.3 (0.05-1.78)	2.6 (0.64-10.92)

Asthmatics who are not on medication have been excluded.

* $p \leq 0.05$, ** $p \leq 0.01$

4.4.5 OR for cataract in the 50+ and 60+ age groups

In order to examine whether the elevated crude OR values for cataract were indeed due to differences in the age distribution between the groups, the logistic regression analyses were repeated without controlling for age, but excluding participants younger than 50 and younger than 60 years (Table 4-30). Limiting the observations to the 50+ and 60+ age group reduced the number of observations noticeably.

An association between cataract and high exposure group was not observed in the results (Table 4-30). OR values were not consistently elevated nor did they follow any trend, and all values were without statistical significance.

Thus the findings of this analysis support the assumption that elevated crude OR values for cataract in the high exposure group were attributable to differences in the age distribution between the exposure groups.

Table 4-30: Adjusted OR for cataract in the 50+ and 60+ age groups.

Exposure Category	**medium** OR (95% CI)	**high** OR (95% CI)	**medium** OR (95% CI)	**high** OR (95% CI)	**medium** OR (95% CI)	**high** OR (95% CI)
Exposure Model	**1. current residential exposure**		**2. previous residential exposure**		**3. observation excluded if residential exposure category changed**	
Cataract age>50 years (1.n=116, 2.n=114, 3.n=101)	2.6 (0.51-13.23)	1.5 (0.29-8.10)	1.9 (0.41-8.90)	0.8 (0.15-4.46)	2.0 (0.37-10.34)	1.0 (0.17-6.40)
Cataract age >60 years (1.n=71, 2.n=76, 3.n=70)	1.1 (0.18-6.88)	1.1 (0.16-7.44)	0.6 (0.09-3.86)	0.4 (0.04-2.81)	0.6 (0.08-4.23)	0.5 (0.05-4.43)
Exposure Model	**1. current combined exposure**		**2. previous combined exposure**		**3. observations excluded if combined exposure category changed**	
Cataract >50 years (1.n=103, 2.n=98, 3.n=83)	1.6 (0.26-10.20)	1.4 (0.22-9.62)	1.0 (0.17-6.02)	0.6 (0.08-3.95)	1.0 (0.14-6.76)	0.7 (0.09-6.26)
Cataract age >60 years (1.n=73, 2.n=72, 3.n=66)	1.2 (0.18-8.80)	1.5 (0.20-11.37)	0.6 (0.08-4.75)	0.5 (0.05-4.09)	0.7 (0.08-5.51)	0.7 (0.06-7.00)

4.4.6 Mapping of exposure areas and asthma cases

In order to establish whether there were any associations between asthma occurrence and the findings from the personal exposure maps, asthma cases and non-asthmatics were mapped at their current residential address, if they had not changed address in the last two years. Additionally the exposure zones used in the health survey were mapped (Figure 4-34).

The southern part of the central corridor in Rotorua had the highest density of asthma cases with respect to non-asthmatics (Table 4-31, Figure 4-34) and was also identified as an area of elevated personal exposure, supporting the assumption of an association between asthma and exposure to H_2S. However the number of cases used in the analyses and the mapping was low.

Table 4-31: Frequency table of asthma using mapping data.

exposure category	asthma on medication	asthma not on medication	non-asthmatics
low	11	4	72
medium	13	3	99
high	11	2	38
total n= 253	35	9	209

Even though the southern part of the central corridor had the highest density of asthma cases its area size was small compared to the low and medium exposure zones.

Probably due to a lack of residential areas in the northern part of the central corridor the southern part was the only area surveyed and it is uncertain whether the findings apply to the remainder of the central corridor.

The absence of asthma cases at Whakarewarewa was most likely due to the low number of observations (7). However personal exposure measurements were not available for this area and it is possible that these participants had experienced lower personal exposure levels than in the remainder of the high exposure zone, although air measures nearby would suggest otherwise (Horwell, 1998).

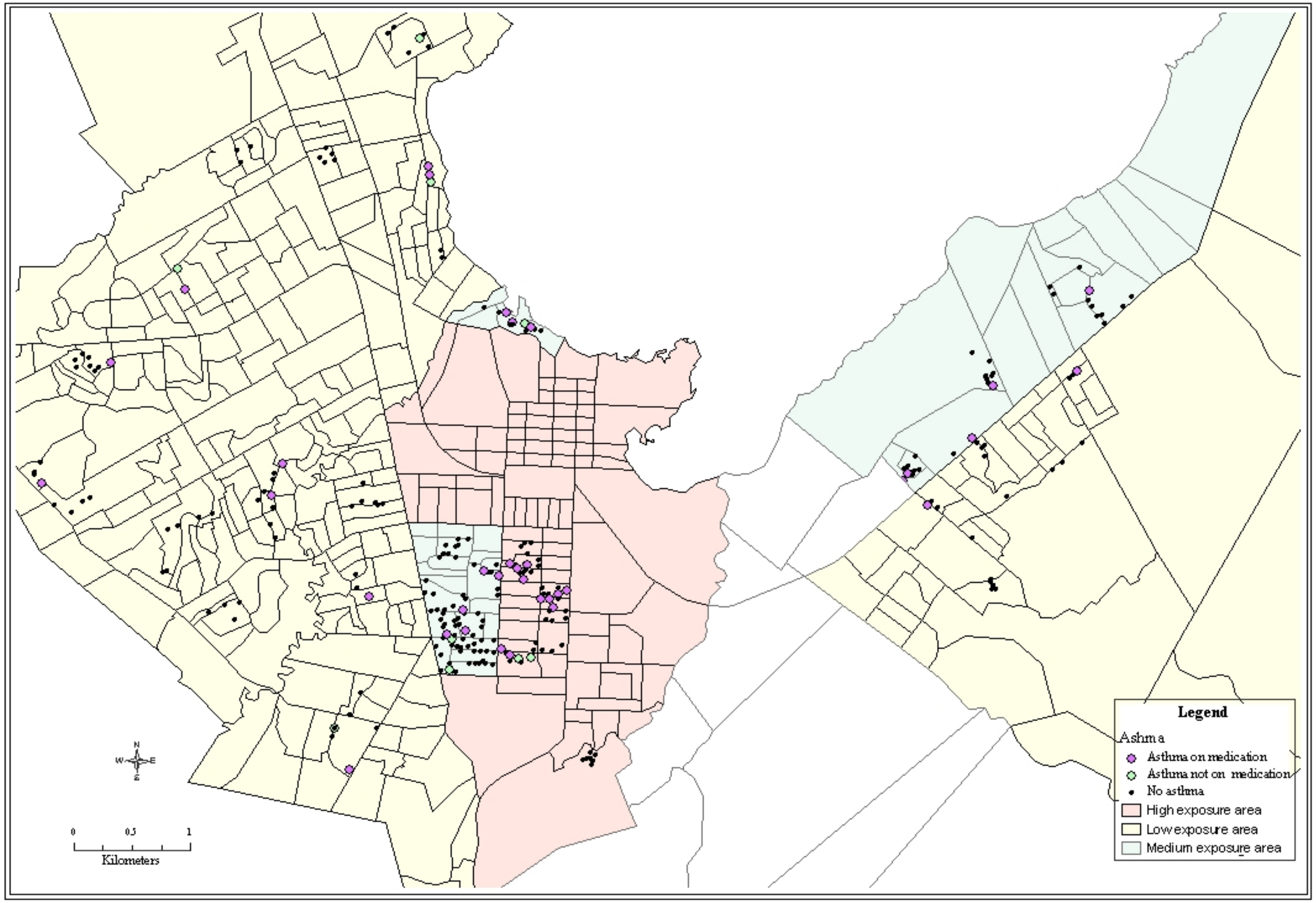

Figure 4-34: Map showing the distribution of asthmatics and non-asthmatics from the health survey using the residential address.

Excluding participants who had changed residential address in the past 2 years.

Chapter 5: Discussion

5.1 Validation and calibration of the personal sampler

The Chemcassette® tape proved to be suitable for use as a personal sampler. The discolouration of the tape followed a consistent pattern over all trials and was shown to be highly specific to H_2S, as the effect on discolouration by sunlight, humidity and other pollutants was minimal.

The precision of the sampler decreased for H_2S concentrations above 10 ppb as observed by the increase in the coefficient of variation and the increase in the standard deviation for groups of samplers exposed at the same place for the same length of time. The accuracy of the sampler also decreased with increasing H_2S concentrations due to some limitations of the calibration model, namely the small number of calibration points and the inability to quantify H_2S concentrations for readings above 90 ppb. Hence higher H_2S concentrations especially above 40 ppb should be viewed as an estimate rather than an actual value. The maximum detectable limit of the sampler before silver discolouration was around 90 ppb. For H_2S concentrations of 5 ppb or below, the precision and accuracy of the Chemcassette® tape and the mathematical model were relatively high and 75% of the personal sampler readings were in this range.

The exposure duration of 24 hours was long enough to reduce the time-dependent variations in discolouration, which mainly occur in the first 8 hours. The 24-hour period was still short enough to link exposures to specific locations and to achieve a high level of compliance from the participants.

Preparation and storage methods of the samplers as well as some delay in scanning did not produce any notable effects on the discolouration of the sampler.

In conclusion, although relatively crude, the sampler and the mathematical model were compatible with the aim of this study to provide a first overview of personal exposure levels in the population of Rotorua. Furthermore, the sampler did not inconvenience participants and was discreet to wear, as well as being cost-efficient and easily deployed to a larger number of participants.

5.2 Personal exposure study

In this section H_2S concentrations are discussed in general terms of higher and lower concentrations rather than using an actual value, because the accuracy of the sampler decreased with increasing H_2S concentrations, hence higher values are an estimate rather than an exact figure.

When considering the findings of this chapter, some caution is advised as only four 24-hour trials were conducted. The small number of observations does not provide enough evidence to draw definite conclusions about areas of higher exposure and the levels of personal exposure in Rotorua, but provides a basis for further research.

Before the start of the discussion the following factors and issues need to be considered as they may have affected the readings of the personal samplers or the statistical analyses:

- Start time of exposure, and exposure length, varied between participants potentially affecting H_2S concentrations. Times differed mainly between pupils depending on their classes, but were consistent for each class over the trials. As both colleges had very low exposure levels during this study, it is not expected that the impact of this issue was substantial.
- Wearing the sampler underneath clothing or with the reactive side facing the clothing may have decreased H_2S readings. It is not expected that this affected results considerably as participants were made aware of the issue.
- Exposing the home sampler in a sheltered area may have decreased H_2S readings. It is possible that several samplers were affected by this issue, but the actual number is unknown, and therefore the impact of this issue on the results of the home sampler readings is uncertain.
- Environmental samplers were predominantly exposed on buildings, which could have affected H_2S concentrations, but because personal samplers showed similar trends to the environmental samplers it is suggested that the effect was small to moderate.

- In the college groups, between 18% and 30% of the samplers were not returned, which may have led to different pupils participating in the trials, creating some variance in the results of the different trials from the RGH and RLH group. As the variance only occurred in the 0-5 ppb range, the impact on the general results is likely to be small.

5.2.1 Personal H_2S exposure – overall results

Looking at the results of the analyses for the overall population, 75% of the personal samplers had H_2S concentrations of 5 ppb and below. It is expected that the actual percentage of the Rotorua population in this lower exposure range is larger and that the percentage in the higher exposure range is smaller, because the RDC group was not randomly selected, but being expected to be subjected to higher exposure levels.

5.2.2 Personal exposure levels compared to air monitoring data

Comparison of environmental H_2S measurements with the results from the personal samplers is difficult for west and east Rotorua because the environmental samples from the colleges and the personal samplers were both low, in the narrow range of 0 to 5 ppb, and little air monitoring data were available for these areas.

In the central corridor, only a small number of personal samplers had readings above 90 ppb compared to the environmental samplers from central Rotorua and previous air monitoring data which frequently showed H_2S concentrations above 90 ppb. (Fisher *et al.*, 1996; Horwell *et al.*, 2005; Iremonger, 2008; Petersen *et al.*, 1998; Siegel *et al.*, 1986). Mobility of the participants is a possible explanation for the low H_2S concentrations in the personal samples, because most participants had only spent part of their day in the central city and consequently exposure length was reduced.

Personal exposure levels may have been further reduced by the sheltering effect of buildings, as many participants had spent most of their time indoors. This idea is supported by the following findings:

- Compared to the personal samples H_2S concentrations were lower in home samples. On the other hand, it is possible that the low H_2S concentrations recorded in the homes were due to their shorter exposure time (2/3 of personal exposure time) and/or the small number of samples collected in the central city.
- In the environmental control samples from central Rotorua, indoor readings were often lower than outdoor readings. However all these buildings were commercial or public differing in size, air circulation and foot traffic to residential housing. Hence the findings may not apply to private homes.
- The regular nightly increases in H_2S concentrations in ambient air (Iremonger, 2004; Iremonger, 2008) were not observed in the personal samples by the participants.

Furthermore, even if buildings provide shelter, this may not apply to all buildings as the previous investigation on indoor pollution had suggested (Durand and Scott, 2005) and building structure was a possible cause of elevated H_2S exposure in two instances in this study.

5.2.3 Location as a determinant of H_2S exposure in Rotorua

The statistical analyses and the mapping indicate that being in central Rotorua was the major determinant of elevated personal H_2S exposure, while exposure levels in western and eastern Rotorua were consistently low (5 ppb or below). Mapping showed that the area of elevated exposure in central Rotorua was restricted to a 1 to 2 km wide north-south trending corridor, which was consistent with the findings from previous air monitoring studies (Horwell *et al.*, 2005; Wegműller and Peterson, 1998).

In this study, fluctuations in the personal exposure levels in the central corridor (RDC group) were related to variations in air H_2S concentrations, observed at Te Ngae Road. However, an increase in ambient air H_2S concentrations did not affect the size of the central corridor, which remained consistent in extent over all trials, as personal exposure levels between the trials varied little in west and east Rotorua in contrast to the variations in exposure levels observed in central Rotorua.

Nonetheless some uncertainties of the exact extent of the central corridor remain.

Although the personal sampler readings from the residential area east of the Ngapuna site were inconclusive because the participant had also frequented other sites of possible exposure, the low H_2S concentrations of the only home sampler in this area and the absence of gas complaints from this area (Brownbridge, 2009b) would suggest a lower level of exposure than in central Rotorua.

The area between Fenton Street and Kuirau Park, north of Amohau Street, showed lower personal exposure levels than the remainder of the central corridor. The high mobility of participants working in this area is a possible explanation. However higher air H_2S concentrations have been recorded at the eastern and southern margins of the area, and gas complaints from a wider area are reported when the wind is coming from a north to north-easterly direction (Brownbridge, 2009b). Hence this area may experience higher exposure levels only occasionally when H_2S is carried in by the wind. For this to happen, wind direction and speed need to be favourable and it is likely that such an event was not captured during this study.

Intermittent higher exposure levels due to weather conditions may also affect the area between Ranolf Street and Old Taupo Road. Air monitoring data (Horwell *et al.*, 2005; Wegműller and Peterson, 1998) had shown higher H_2S levels in this area, but still considerably lower than in the central corridor. Unfortunately personal exposure data were missing from this area.

Intermittent higher exposure levels due to weather conditions may also be experienced in the east of Rotorua where Horwell *et al.* (2005) observed higher air H_2S concentrations during the winter trial compared to the summer trial and attributed it to differences in the prevailing wind direction. Furthermore occasional gas complaints have been received from the airport area in the east of Rotorua (Brownbridge, 2009b).
It is also worth noting that in this study, small increases in H_2S concentrations have been observed in an environmental sampler and a personal sampler from the east during the November trial. However a general rise in personal H_2S exposure in the east was not observed in this study.

5.2.4 Possible geothermal sources of higher exposure levels

As H_2S concentration in ambient air drops sharply with distance from the source (Vasilakos *et al.*, 2005), proximity to active geothermal areas, which are all located in central Rotorua, is the most apparent cause of elevated personal exposure levels. However it has to be remembered that the effect of distance to a geothermal source can be altered by a multitude of factors such as variations in the amount of H_2S emissions, weather conditions and exposure length which was implicated in the mapping. Furthermore in an active geothermal area venting of H_2S does not occur evenly all over the area but is restricted to smaller point sources. Consequently distance to the actual source and the number of emission points per area unit will affect H_2S exposure, too.

The Sulphur Bay geothermal area was clearly associated with elevated personal exposure levels, while the southern geothermal areas of Whakarewarewa and Arikikapakapa lack data from personal samplers. However higher air H_2S concentration (Petersen *et al.*, 1998) and higher soil gas emissions (Finlayson, 1992) were reported from these areas, so they could be potential sources of elevated personal exposure, at least for participants in the southern part of the central corridor.

Exposure levels associated with Kuirau Park in the north-west were noticeably lower, being the same or slightly above the levels of western Rotorua. This difference in exposure levels between the south-eastern and north-western geothermal areas is consistent with the geological findings that these are two chemically distinct geothermal fluid/gas emanations (Finlayson, 1992; Giggenbach and Glover, 1992; Mroczek *et al.*, 2004).

Whether H_2S is emitted from the lake and whether the amount of emission would be large enough to affect air H_2S concentrations is undetermined. Studies of the Rotorua lake bed are further complicated by the additional existence of methane gas below the lake floor. However some observations raise the possibility of H_2S discharges from the lake. Most recently, depressions likely to be hydrothermal explosion craters actively discharging water and gas have been observed north of Sulphur Point and to the east of Mokoia Island (Pearson, 2007). It is plausible that weather and lake water conditions have to be favourable for noticeable H_2S emissions to occur.

5.2.5 Localised exposure to high concentrations of H_2S

Although this study showed relatively low personal exposure levels compared to air concentrations, personal exposure can reach substantial levels near geothermal sources of H_2S emission, on seepage points and at defunct bores. At these places concentrations above 100 ppm have been recorded, but they commonly drop rapidly away from the source, even reaching $\leq$ 10 ppm at a distance of only 1 to 5 metres (Brownbridge, 2009b; Durand, 2006). Thus the risk of high personal exposure diminishes quickly in these areas, too. In this study, a rapid increase in personal exposure levels was observed by two participants when being very close to a geothermal source. As the upper detectable limit of the personal sampler was 90 ppb, the exposure level is unknown but an instant air measurement taken at the time showed H_2S concentration of 16.1 ppm.

Higher exposure may also occur, when H_2S is accumulating in confined spaces, potentially causing a very dangerous situation. Fortunately these situations seem to be uncommon and were not observed in this study. However several participants observed a rapid discolouration of the sampler when inside buildings (exposure times varied between 1 to 7 hours), but personal exposure levels remained below 50 ppb.

At the Ngapuna site two participants consistently had personal sampler readings above 90 ppb and two other participants at this site had elevated levels during all trials. Additionally the Ngapuna site had the highest environmental reading in this study.
The higher environmental and personal exposure levels could be due to one of several factors or a combination of all: the site is very close to geothermal sources, H_2S emission rates are higher in this geothermal areas and/or the Site A building at Ngapuna is channelling H_2S.

5.2.6 Exposure model

In this study elevated personal exposure was associated with the central corridor in Rotorua and correlated to exposure length and air H_2S concentrations, which varied over time, while other areas in Rotorua may experience intermittently higher levels of exposure.

In order to build a model predicting personal exposure in Rotorua more investigations are required into variations in air H_2S concentration in central Rotorua, in areas of possible intermittent exposure and into the determinants of these variations. Although in the next chapter the influence of weather parameters on air H_2S concentrations will be examined, the findings may only apply to parts of the central corridor, as H_2S concentrations were only monitored at the Te Ngae Road site. For example, it is quite feasible that air H_2S concentrations in the south of the central corridor vary from the ones in the remainder of the corridor and that the weather conditions causing higher H_2S concentrations in the central corridor are not the same as those which potentially cause higher exposure in the east.

Due to the above-mentioned reasons, it is beyond the scope of this study to build a model able to predict personal exposure in Rotorua without further air monitoring of H_2S concentrations over a wider area and time span.

Time spent indoors and outdoors may further affect personal exposure. Originally it was planned to include this factor in the analysis but it was abandoned for the following reason. As little exposure occurred in west and east Rotorua, the effect of time spent indoors and outdoors would, if present, only be observable in central Rotorua. However participants who spend most of their working day outside were all located in the lower exposure areas of Kuirau Park and north of Amohau Street. Therefore it is likely that any differences in personal exposure levels due to time spent indoors and outdoors would have been distorted.

5.3 Influence of meteorological factors on H_2S air concentrations

The discussion on the identification of the main determinants of exposure will focus on meteorological factors, as insufficient data were available to assess the effect of indoor and outdoor living, and the analysis of other environmental factors (*e.g.* the fluctuations in emission rate, and number and location of surface emission points) was beyond the scope of this thesis.

When considering the findings of this chapter, some caution is advised because the number of observations (106) used in the statistical analysis is relatively small for meteorological data.

Furthermore, 36% of observations were above the upper detectable limit and given a value of 150 ppb in accordance with the personal samplers. Even though this value was appropriate for the personal samplers, 150 ppb is likely to be too low for the outside-air samples given that earlier recordings at NIWA have regularly shown H_2S concentrations above 150 ppb (Petersen *et al.*, 1998) as did the data collected in the December 2007 trial. Thus it is possible that the association between weather factors and H_2S levels is underestimated, as H_2S concentrations above the upper detectable limit were perhaps ascribed a value lower than the actual one.

A further point of consideration is that the meteorological data were collected at Rotorua airport which is located 8 km away from the monitoring site in central Rotorua (see Figure 2-1). Being a built-up area, wind patterns and air temperature in the inner city could vary from the recorded data at the airport. Furthermore, the geothermal areas, located close to the inner city, and warmer lake surface temperatures, may affect the atmospheric conditions above the city due to the steam and heat release (Fisher, 2007; Iremonger and Graham, 2007).

5.3.1 Wind direction

NE winds were the major determinant of higher H_2S concentrations at the monitoring site, although not its only source, suggesting that additional H_2S is brought in from a source located to the north-east of the monitoring site. Since the area in this direction is scarcely built-up, the geothermal region of upper Sulphur Bay - Government Gardens is a likely source. Supporting this idea are H_2S and meteorological data from Ti Street (Iremonger, 2008), which lies in close proximity to the NIWA air monitoring site at Te Ngae Road (Figure 5-1 and Figure 2-1). The data spanning the period 1998 to 2005, is displayed in a pollution rose (Figure 5-2). Most interesting to note is the lack of low H_2S recordings when the wind blew from the north-easterly sector.[27] Additionally, complaints about gas being emitted from stormwater drains, which discharge into the

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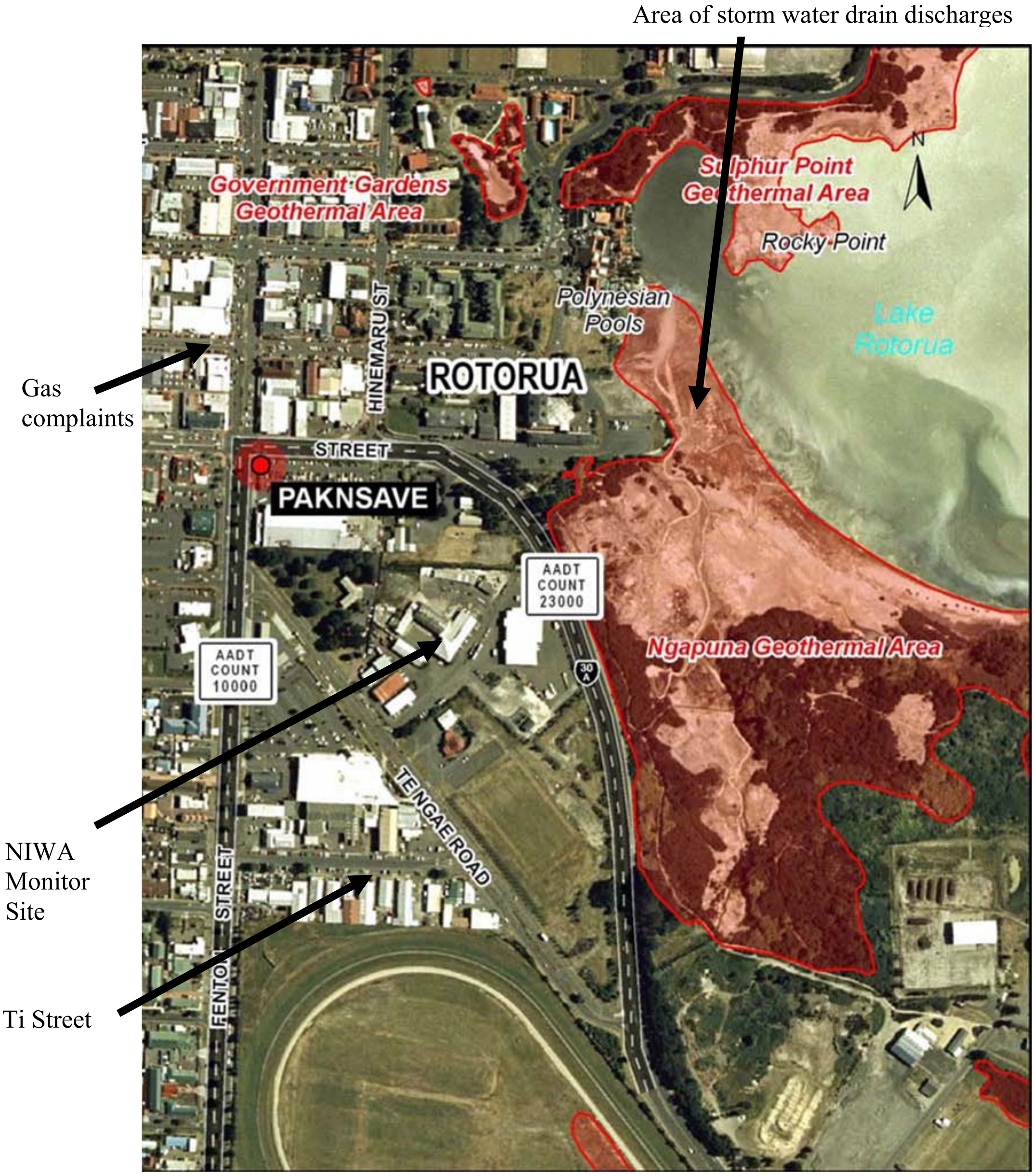
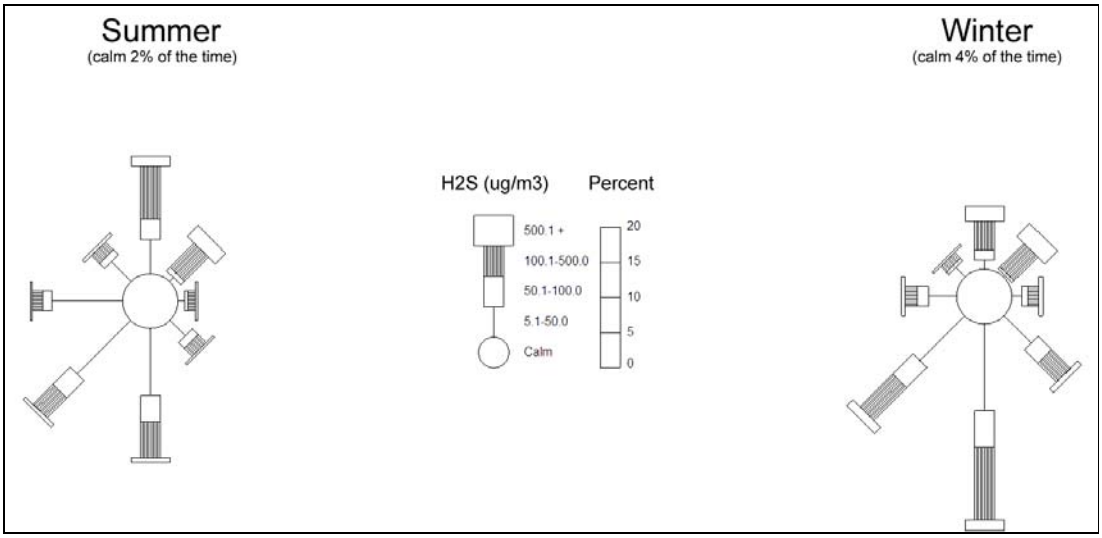
[27] Note: northerly winds were not included in the NE category of this study, but easterly were included.

upper Sulphur Bay area (Figure 5-1), have been linked to NE winds (Brownbridge, 2009b). Horwell *et al.* (1998, 2005) noted that samplers from the west of the city were slightly darker during a week which experienced strong north-easterly winds, but atypical weather conditions did occur at the same time, such as 100% humidity, unusual high temperatures, strong rainfall and a sharp drop in air pressure.



(Source: EBOP - NERM Report 2007)

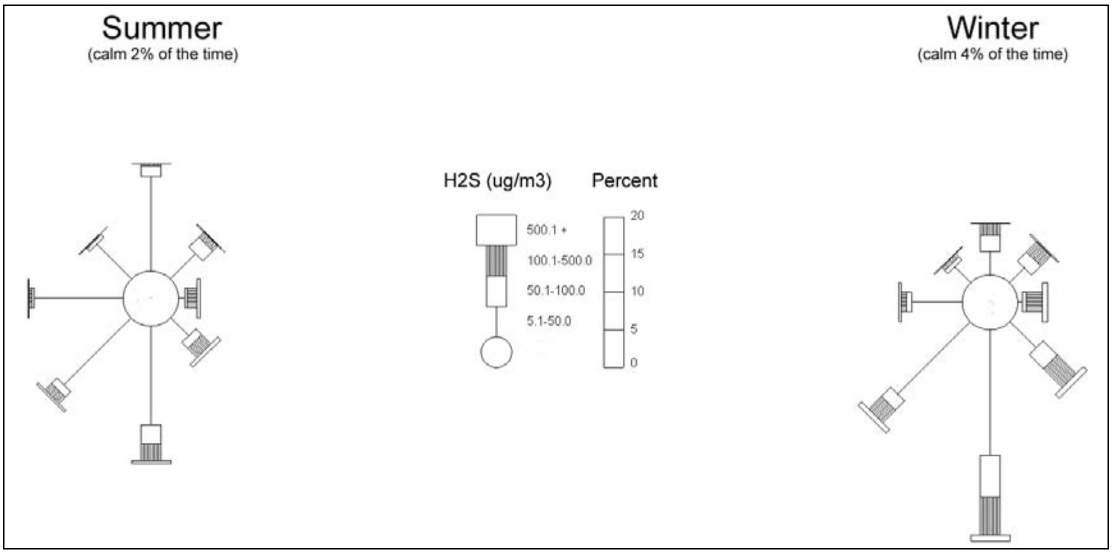
Figure 5-1: Aerial photograph of the NIWA monitoring site.



(Source: EBOP – NERM Report 2007)

Figure 5-2: Pollution rose for Ti Street, Rotorua.

When evaluating the effect of NE winds on H_2S concentrations it is important to remember that air monitoring was only carried out at one location in Rotorua. Other locations in Rotorua may show a different association between H_2S levels and wind direction depending on the location and distance from the source and the emission rate at the source. For example the pollution rose of Arawa Street (Figure 5-3), which lies to the north of Te Ngae Street and Ti Street, shows hardly any low H_2S recordings for easterly winds compared to north-easterlies at Ti Street. Considering that Arawa Street lies to the north of Ti Street, the difference would suggest a mutual source of additional H_2S, but without further investigation there is also the possibility of two separate sources.



(Source: EBOP - NERM Report 2007)

Figure 5-3: Pollution rose for Arawa Street, Rotorua.

Additionally, Horwell *et al.* (1998, 2005) attributed an increase in H_2S concentrations in the north-east of Rotorua to south to south-westerly winds.

5.3.2 Wind and gust speed

The effect of wind and gust speed on H_2S concentrations diminished and lost its statistical significance when entered into the multiple regression models. This was surprising, since wind and gust speed have been implicated to lessen geothermal gas concentrations in ambient air by dispersion, thus linking calmer periods to higher gas concentrations (Carapezza *et al.*, 2003; Petersen *et al.*, 1998; Rogie *et al.*, 2001; Viveiros *et al.*, 2008; Viveiros *et al.*, 2009). When considering the effect of wind and gust speed in Rotorua, it must be remembered that the air monitoring site was only 200m to the west of the Sulphur Point - Ngapuna geothermal area (Figure 5-1) and that winds from the north-eastern sector were associated with higher H_2S concentrations.

With the geothermal area being in such close proximity to the east of the monitoring site, it is likely that winds of low to moderate speeds from this direction actually increase the H_2S concentrations by bringing H_2S-rich air towards the site. For higher speed levels the dispersion effect may override the 'transport effect' and H_2S concentrations would decrease. The December 2007 graph showing wind and gust speed (Figure 4-25), would suggest such an effect for higher speed levels, especially for gust speed. Unfortunately, the graph was only based on 6 data points and during the other observation periods, wind and gust speed remained at lower levels.

Therefore wind and gust speed may have a variable effect on H_2S concentrations at the monitoring site. Winds from the west would reduce H_2S concentrations by pushing the H_2S rich air away from the site, while winds from the east could transport H_2S-rich air towards the site and increase H_2S concentrations. For easterly winds of higher speed the H_2S concentrations are possibly reduced by the dispersion effect. Thus analysing wind and gust speed should best be done with respect to wind direction; unfortunately insufficient data were available in this study to make any incontrovertible conclusions.

5.3.3 Air temperature

Air temperature, as an indirect measure of irradiation, has been described as inversely influencing ground gas emissions of H_2S and CO_2 (Viveiros *et al.*, 2008). D'Alessandro *et al.* (2009) and Vasilakos *et al.* (2005) attributed this inverse effect to photochemical redox reactions, which consume emitted H_2S and are favoured during summer and in daytime. Viveiros *et al.* (2008) hypothesise further, that during stable weather conditions, insolation and consequently air temperature are indicative of atmospheric tides affecting H_2S levels and contributing to nightly peaks, while in Rotorua nightly peaks were attributed to calmer wind conditions (Iremonger, 2004).

It is quite possible that all of these factors contribute to some degree to the variation in H_2S concentrations between day and night time and between winter and summer, which have been observed in Rotorua (Figure 2-2). However care needs to be taken when using temperature as a proxy for irradiation, because in New Zealand spring temperatures may still be relatively low while irradiation is already high due to the Antarctic ozone hole. Unfortunately irradiation data were not available specifically for Rotorua.

Although temperature did not show any statistically significant association with H_2S concentrations in the univariate analysis, the temperature graph of the June 2008 trial would suggest an inverse association. When H_2S levels were regressed on air temperature for the June 2008 data only, the adjusted R^2 rose to 38% ($p \leq 0.001$), suggesting a substantial effect on H_2S concentrations, but the analysis was only based on 51 observations.

It is interesting to note that during June 2008, NE winds were not present and that in the October 2008 graph an inverse association between air temperature and H_2S concentrations is visible at the beginning of the graph, but stops abruptly once the NE winds arrive. Hence a potential association between temperature and H_2S levels could have been missed in the statistical analysis, because it was obscured by the increase of H_2S concentrations due to the NE winds or by the narrow range of the collected data.

5.3.4 Relative humidity

Relative humidity showed a positive association with H_2S concentrations in the multiple regression models, but its R^2 dropped from 26.7% in the univariate analysis to less than 10% in the multiple regression models, indicating possible collinearity with another independent variable.

Increases in air temperature reduce relative humidity. Assuming that there is an inverse association between air temperature and H_2S concentrations, it is possible that the positive association between relative humidity and H_2S concentrations was created by them having an inverse association with air temperature. Thus the parallel rise and fall in H_2S concentrations and relative humidity was not due to an association with each other, but due to changes in air temperature. Why the relationship between air temperature and relative humidity did not show in the collinearity tests might be explained by the high moisture content of NE winds, since these winds travel vast distances over the ocean. The additional moisture content would increase relative humidity, even when air temperature is high, creating enough outliers in the statistical analysis so as not to show collinearity between relative humidity and air temperature. Incidentally, when analysing the June data only, the Pearson correlation coefficient for relative humidity and temperature approached -1 with a value of -0.89.

5.3.5 Air pressure

Air pressure was also positively correlated to H_2S concentrations, which was surprising as previous studies had found an inverse correlation for soil gas emissions elsewhere (Carapezza *et al.*, 2003; Rogie *et al.*, 2001; Viveiros *et al.*, 2008; Viveiros *et al.*, 2009). A possible explanation could be that the pressure readings in this study were only at the higher end of the pressure scale, while the other studies frequently observed pressure levels below 1000 hPA.

5.3.6 Rainfall

Rain did not show any association with H_2S concentrations in the univariate analysis. Rain has been implicated in having an effect on CO_2 ground gas emissions by affecting soil saturation. The complex mechanisms determining whether the effect is positive or negative are described by Viveiros *et al.* (2008). It is possible that similar processes apply to H_2S emission in Rotorua, but were not captured by this dataset because a discernible rainfall period did not occur during the study.

In conclusion, it is likely that a multitude of meteorological and other environmental factors influence H_2S concentration and distribution in Rotorua and that their impact depends on the interactions with each other. Even though this analysis took a number of factors into account, not all meteorological factors were investigated, *e.g.* approaching fronts, and mixing height which is attributed to be a major factor of the increase in H_2S concentrations at night especially during winter (Fisher, 2007; Petersen *et al.*, 1996; Petersen *et al.*, 1998). Furthermore the study had focussed on the Government Gardens – Sulphur Bay geothermal areas due to their proximity to the monitoring site. However other geothermal areas in Rotorua, especially Whakarewarewa and Arikikapakapa where higher H_2S concentrations have been recorded in ambient air (Brownbridge, 2009b; Fisher *et al.*, 1996), may also affect surrounding areas in similar ways.

5.4 Health survey

Compared to the previous health studies on H_2S exposure in Rotorua, which were based on hospital data, this health survey used a questionnaire and hence inference to health status, exposure level and other attributing factors was possible at a personal level.
However, the findings from the health survey and the mapping should be treated as indications only, which require further investigations, due to the following points:

- The number of observations was restricted as denoted by the frequent lack of statistical significance and the width of the CIs.
- Response rates were not available and a low response can therefore not be excluded. A low response rate may have resulted in non-response bias[28] potentially invalidating the results. In order to assess the risk of this bias affecting the results of the health survey, the asthma prevalence rate in this survey was compared with the prevalence rate of asthma symptoms in New Zealand from a study (D'Souza et al., 1999)

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[28] Non-response bias may occur when symptoms prevalence is different between respondents and non-respondents. This is of particular relevance if response rates differ between high and low exposed areas.

conducted around the same time as the current study. The Asthma prevalence was 19.8% (self-reported) in the current study compared to 15.9% (physician diagnosed) in the study by D'Souza et al. (1999). The prevalence of physician diagnosed asthma is always somewhat lower than self-reported asthma, and the asthma prevalence observed in the current study is therefore in the expected range. Thus, response-bias is therefore expected to not play a major role.

- Participants self-reported illness which could lead to bias due to differences in the perception of participants to what constitutes a particular illness or failure to report an illness.
- Most questionnaires were completed with the help of an interviewer, which could introduce bias when the interviewer uses leading questions or comments, or when participants try to provide an expected answer. As interviewers received training and most questions pertained to the presence or absence of a particular disease, it is unlikely that these factors have influenced the results of the survey considerably.
- The analyses of the health survey did not control for social differences in the three exposure groups, because deprivation data was not publicly available at the time of the analyses. This may have resulted in bias, but associations between social economic status and conditions assessed in the current study are generally not strongly associated, suggesting that social economic status is unlikely to be a strong confounder.
- When applying multiple statistical comparisons, e.g. different diseases or different severities of asthma, the probability to find a statistical significant result by chance increases. Some of the statistically significant findings may therefore have been due to chance.

Of all diseases investigated, asthma and cataract showed an association with exposure to H_2S.

For cataract, this association was only observed in the crude OR value and differences in the age distribution between the exposure groups were shown to have been the cause of the higher OR values.

For asthma an association was implicated with the high exposure group by the elevated OR values, but often lacked statistical significance. However, CI values were repeatedly close to 1. Refining the exposure models and using asthma severity categories increased the number of statistical significant OR values, supporting the assumption of an association between asthma and H_2S exposure. On the other hand, the results from the high exposure zone were based on a small area and a relatively low number of cases and hence might be coincidental. Little can be said about the effect size of the association between asthma and H_2S exposure in the high exposure group as the CIs remained wide.

Mapping revealed that the area of high exposure analysed in the health survey was restricted and corresponded to the southern part of the central corridor in Rotorua, which had been identified as an area of elevated personal exposure. As this was the only high exposure area investigated, besides a small group at Whakarewarewa where asthma cases were not observed, it is uncertain whether the results apply to the remainder of the corridor.

Additional consideration needs to be given to the results from the southern part of the central corridor as exposure would have occurred prior to the health survey in 1999. Historical personal exposure in this area may have been higher, especially when considering the long residence time of many participants, because a large number of domestic geothermal bores were closed in this area between 1987 and 2001 as part of the bore closure programme (Gordon *et al.*, 2005; Scott and Cody, 2000). On this basis, using H_2S concentrations measured during the air monitoring study (Horwell, 1998) or the personal exposure levels from this study as exposure limits for an association with asthma, may be invalid.

Air monitoring (Horwell, 1998) had found elevated H_2S concentration in eastern Rotorua, and consequently these areas were classified as medium exposure areas in the health survey, but personal exposure levels were not found to be elevated. As an association between medium exposure and asthma was not detected in the health survey, it is possible that these areas experience intermittent elevated H_2S concentrations and that the frequency and/or the concentrations are not high enough to cause any adverse health effects.

Even though there was some indication for a trend linking asthma with the length of residence, the evidence is weak. It is unclear, whether the lack of statistical significance is due to the decreased number of observations, the high percentage of observations with a residence time above 10 years (75%), or whether the trend between asthma and residence time is inconsistent. Furthermore, in all models, mean residence time was 4 years less in the low exposure group than in the other 2 groups, which could have affected the results of the analysis. However, the difference was only statistically significant between the low and the medium group.

A limitation of the health survey was that asthma was the only disease investigated from the respiratory system as a possible adverse health effect. For instance, chronic bronchitis had shown an association with living in the geothermal area of Furnas in the Azores, Portugal (Amaral and Rodrigues, 2007). This limitation will be addressed in the CHEERS study when participants will undergo lung function tests.

Finally, two more risk factors may contribute to the increased asthma rate in Rotorua, but would not explain the raised OR values in the southern part of the central corridor. Higher concentration of air pollutants from transport and domestic wood fires were found in Rotorua (Iremonger and Graham, 2007) and large pine plantations in the region disperse considerable amounts of pollen.

It is expected that the CHEERS study will elucidate many of the above mentioned uncertainties, as it is based on a much larger study population of 1800 residents, includes additional health investigations and exposure assessments, and will investigate the possible effect of pine pollen.

Chapter 6: Conclusion

Although relatively simple, the Chemcassette® tape was suitable to be used as a personal sampler for the exposure assessment with an apt recording range of 0–90 ppb. It proved to be a usable and cost effective method of exposure assessment and caused little inconvenience to the participants.

In the personal exposure assessment, 75% of the personal samplers had H_2S concentrations $\leq$ 5ppb. It is expected that this percentage is higher in the general population of Rotorua, as the RDC group was not randomly selected. Most of the remaining samplers were in the 6 to 90 ppb range. Only a few samplers had readings above 90 ppb and all were associated with proximity to a geothermal feature or/ and a building with H_2S intrusion.

Western and eastern Rotorua had consistently low personal exposure levels ($\leq$5 ppb) through all trials, although higher air H_2S concentrations had previously been recorded in eastern Rotorua. It is possible that higher H_2S air concentrations are only experienced intermittently in this area when weather conditions are favourable, and that such an event was not captured in this study.

Higher personal exposure levels (>5ppb) were only observed along the central corridor in Rotorua as data from previous geological and air monitoring surveys had suggested, but they were considerably lower than the levels of environmental control samples and previous air measurements. To which degree the lower personal H_2S concentrations were due to the mobility of participants and/ or the sheltering effect of buildings is uncertain.

The northern-most part of the central corridor west of Fenton Street showed lower personal exposure levels than the remainder of the corridor, but it is uncertain whether this is due to the shorter exposure times and/ or the movement patterns of participants from this area. For the southern part of the central corridor, the health survey and subsequent mapping indicated an association between higher H_2S exposure levels and asthma. This finding has to be treated with some caution as the numbers of observations were low and the size of the area restricted. Furthermore, it is possible that other air pollutants contributed to an increase in asthma rates in Rotorua. Even if the association should be confirmed by further studies, the measured exposure levels in this area (<90ppb) may not be indicative for setting exposure limits, as historical exposure levels have possibly been higher.

Due to a lack of personal exposure data, it is uncertain whether the areas of Whakarewarewa, Arikapakapa and between Ranolf Street and Old Taupo Road experience higher personal H_2S concentrations.

Because the central corridor lies at the edge of the Sulphur Bay-Ngapuna geothermal area, H_2S exposure was elevated during all trials. However fluctuations in personal exposure levels and air monitoring data were observed between the trials. Analyses of the meteorological data showed an association between higher air H_2S concentrations and NNE and NE winds, suggesting that additional H_2S is carried in to the central corridor by wind.

The influence of other meteorological factors on H_2S concentrations is uncertain, as the analyses were based on a small number of observations and for some factors (rain, irradiation) data were not available. However it is likely that a multitude of meteorological factors affect H_2S concentrations and distribution in Rotorua. Furthermore, the influence of meteorological factors may vary between areas in Rotorua, depending on the direction and distance to the emission source.

The Sulphur Bay-Ngapuna geothermal area was clearly identified as a source of higher H_2S concentrations in the central corridor by the association with the NE winds. Higher air H_2S concentrations in this area compared to the central corridor are probably due to higher emission rates and H_2S concentrations. However, the area of emission may also be larger as this geothermal region is mostly undeveloped.

Low personal exposure levels from the Kuirau Park area would suggest that this area is not a main contributor of H_2S emissions, which is in alignment with previous geological surveys.

Due to the absence of data it is uncertain whether Arikapakapa and Whakarewarewa contribute to an increase in H_2S concentrations outside the immediate proximity of the geothermal emission points in these areas.

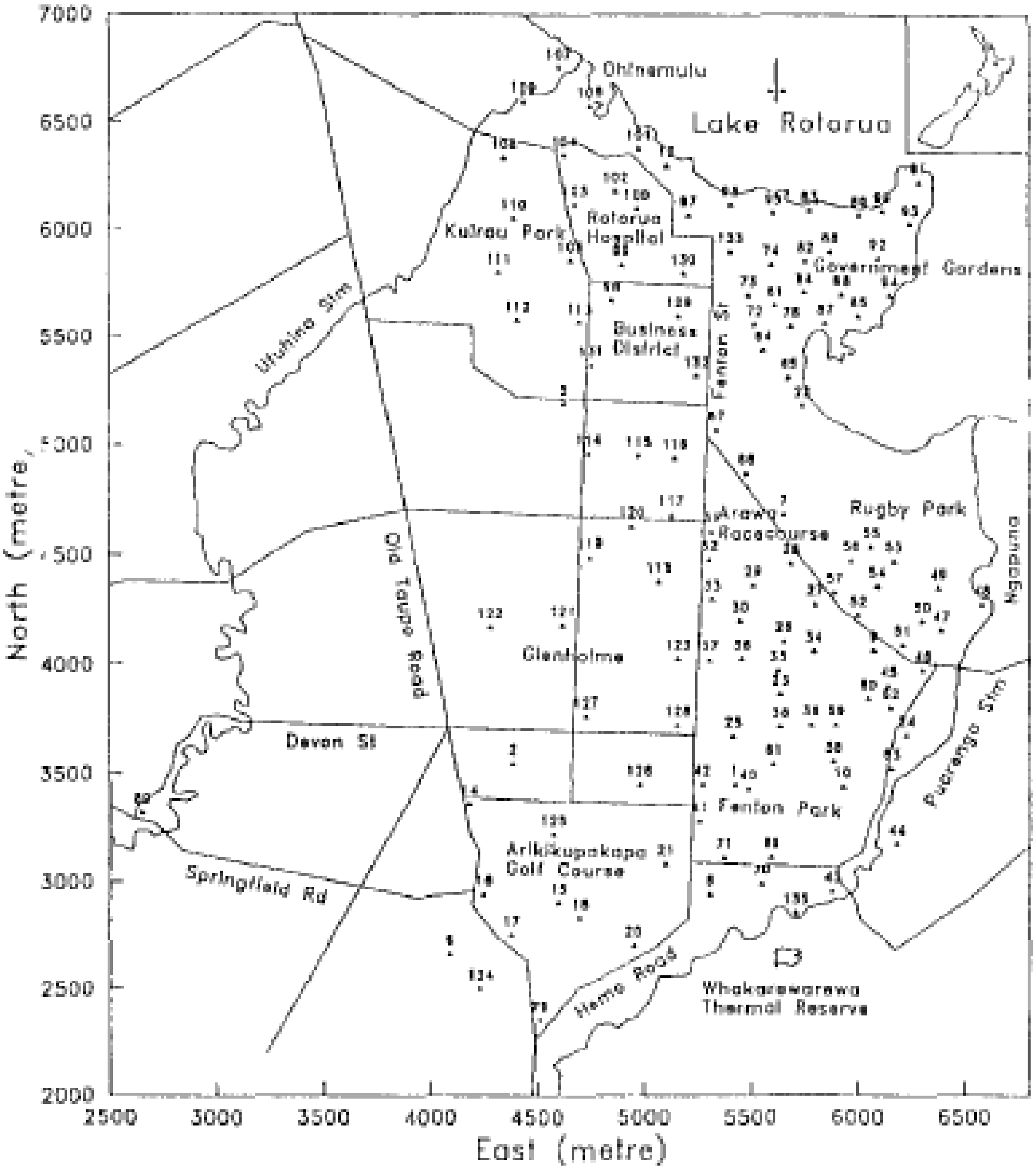
In conclusion, personal exposure to H_2S in Rotorua has been shown to be a complex issue which deserves further investigations in order to build a suitable exposure model, and to deepen the understanding on how to live safely in a geothermal area.

6.1 Recommendations

- Further investigation into the sources of H_2S emission in Rotorua, their emission rates and controlling factors.
- Further investigations into the influence of meteorological factors, including irradiation, on air H_2S concentration. As EBOP has undertaken consistent H_2S monitoring in Rotorua since 1998, it might be possible to analyse some of their data retrospectively.
- Further investigation into the spatial distribution of air H_2S concentrations and factors of influence, especially in eastern Rotorua and the southern part of the central corridor.
- Further investigation on the effect of housing on personal exposure. Consideration should also be given to the possible effects of house insulation, heat pumps and ventilation systems.
- Further investigations on possible health effects from low level exposure to H_2S are already under way with the CHEERS study.
- Personal exposure levels were low in this study, but air monitoring data had shown localised areas of high H_2S concentrations (Brownbridge, 2009b; Durand, 2006) and it should not be forgotten that instances of acute H_2S poisoning have occurred. Although these occasions are rare, their possible fatal consequences warrant investigations into the circumstances leading to exposure to dangerous H_2S concentrations.

Appendices

Appendix l: Map showing soil gas sampling sites



(Source: Finlayson (1992))

Figure A-1: Street map of Rotorua showing the location of sample sites and site numbers of the soil gas survey.

Appendix 2: Location and well discharge steam composition from the geothermal fluid and gas survey

Table A-1: Location of sampled and proxy wells and their properties.

Well Number	Easting	Northing	Location	Cased, m	Drilled, m	Max T, °C	Enthalpy, kJ/kg	T (Enth), °C	T(Sil), °C	T(Sil), °C
									sampled	**proxy**
West Rotorua										
653	2794180	6333600	330 Old Taupo Rd	100	131	140	560	133	143	
825 (proxy for 653)	*2794297*	*6333681*	*64 Devon St*	*117.4*	*120.4*					*152*
738	2794720	6334070	46 Holland St	96.8	134	121			141	
816 (proxy for 738)	*2795063*	*6334088*	*19 Holland St*	*78*	*116.2*	*155*	*593*	*141*		*147*
741	2794880	6334920	Acacia Lodge Motel, 40 Victoria St	104.4	129.93	123			134	
627 (proxy for 741)	*2794954*	*6334861*	*7 Union St*	*94.5*	*124.9*					*135*
865	2795100	6334650	22 Malfroy Rd	98.5	105	130			141	
1016	2795350	6334060	288 Fenton St (adjacent to the Racecourse)	91	120	135			155	
638 (proxy for 1016)	*2795634*	*6334068*	*Rotorua Race Course, Fenton St*	*101.5*	*133*	*166*	*700*	*165*		*163*
Government Gardens										
885	2795560	6335790	Princes Gate Hotel	68	112.23	161	680	160	156	
680 (proxy for 885)	*2795645*	*6336028*	*QE Hospital*	*92*	*135.9*		*670*	*159*		*145*
887	2795720	6335330	Government Gardens	96.21	107.66	149			154	
Kuirau Park										
601A	2794570	6335500	131 Hinemoa St	137.7	173.7	153			142	
913	2794510	6335890	Aquatic Centre	121	146.5	152.5	865	203	166	
681 (proxy for 913)	*2794348*	*6335915*	*Kuirau Park*	*120*	*200*					*147*
619 (proxy for 913)	*2794267*	*6336405*	*96 Lake Rd (1 Tawera Rd)*	*56.5*	*195.1*					*114*
Ngapuna										
M25	2796178	6334563	Treatment Station	245	245	211			216	
889 (proxy for M25)	*2796178*	*6334580*	*Treatment Station*	*234.5*	*248*	*216*	*912*	*213*		*216*

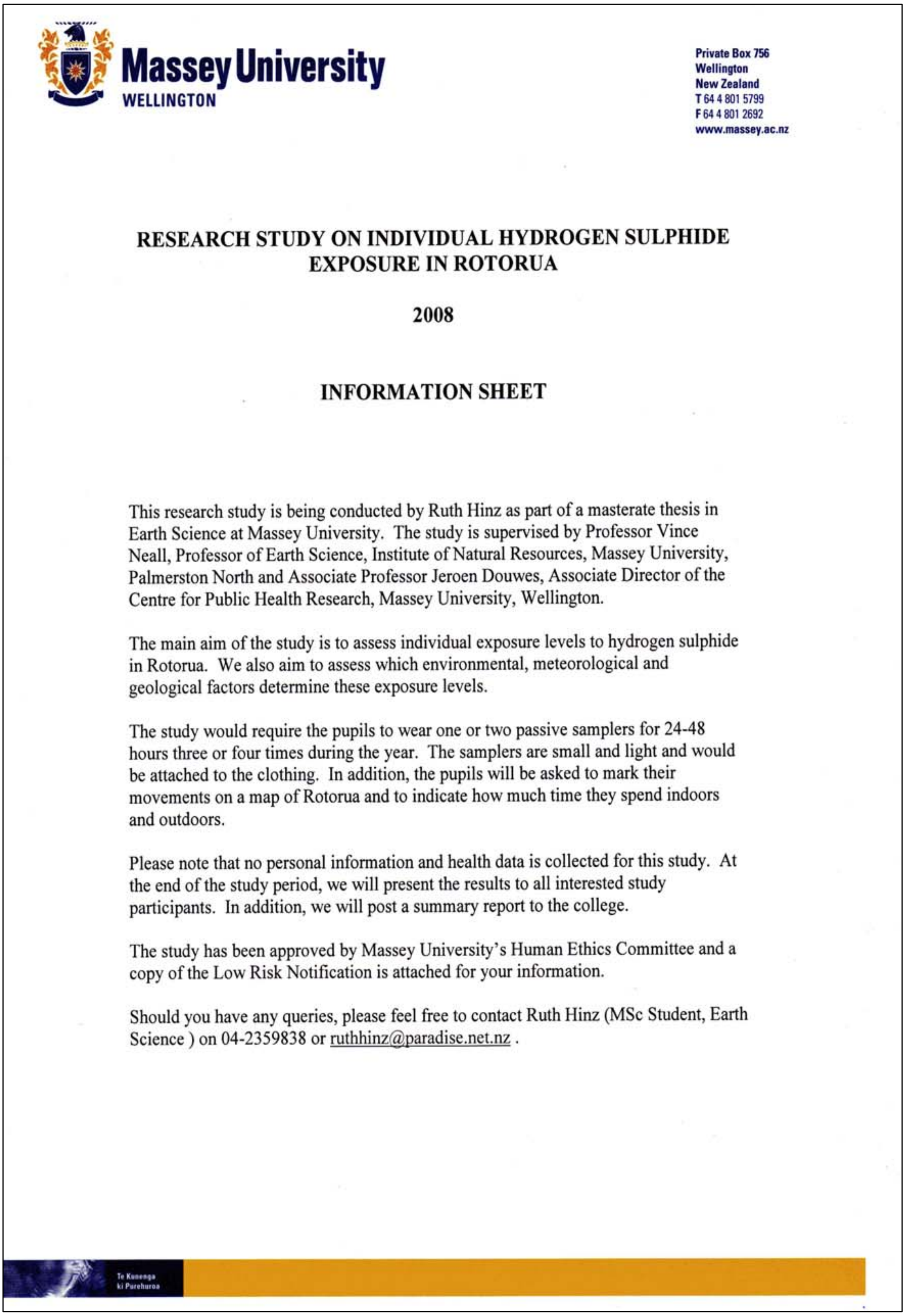
(Source: EBOP (Mroczek *et al.*, 2004))

Table A-2: Well discharge steam compositions for sampled and proxy wells, concentration per mole dry gas. Xg is the gas fraction in steam.

Well No	Sample No	Date	WHP, bg	Enthalpy, kJ/kg	SP, bg	Xg mmol /mol	mmol/ mol								
							CO2	H_2S	H2	He	N2	Ar	NH3	CH4	O2
2300518	RR601A	20/03/03			0.55	11.7	880	80	4.6	0.0086	27	0.50	0.29	8.7	<0.0009
2300015‡	RR738	08/01/03			0.60	79.4	856	116	9.8	0.0076	15.2	0.24		2.8	<0.0001
2300013‡	RR865	07/01/03			0.93	20.3	807	181	8.4	0.0030	2.56	0.05	0.23	1.04	<0.0005
5822/1/S	RR885	13/06/84	2.75	627	2.1	8.7	881	104	10.5		2.4		0.59	1.6	
5822/2/S	RR885	13/06/84	2.25	627	0.75	5.6	866	121	7.9		3.4		0.81	1.1	
2300481	RR885	18/03/03			2.55	9.2	853	126	13.9	0.0076	4.2	0.03	0.47	2.4	<0.0011
	RR887	*†				280	785	58	76.4	0.0033	75	0.71	0.02	4.7	
6004/S	RR887	22/02/85	2.8		2.8	20.4	851	147	1.3		0.32		0.40	0.05	
6724/11/S	RR887	25/09/89	3.65		3.7	13.1	838	158	2.3	0.0026	1.5	0.02		0.21	0.005
6786/18/S	RR887	21/05/90	1.9		1.9	236	778	204	3.0	0.0020	15			0.22	0.199
6786/18/SA	RR887	21/05/90	0.4		0.4	27.0	797	171	3.3	0.0022	29			0.23	
2300012‡	RR887	08/01/03			4.0	14.9	829	166	2.7	<0.0007	1.01	0.02	0.30	0.22	<0.0007
	RR889	*				2.2	630	268	11.9	0.0062	88	1.1	0.85	0.78	
5442/2	RR889	02/06/83	10.7	913	10.7	15.7	744	240	8.5		7.4			0.59	
6724/13/S	RR889	27/09/89	11		6.25	4.3	461	161	9.0		232	2.63		0.44	0.0**
2300517	M25	20/03/03			11.5	5.9	692	285	12.6	0.0051	8.7	0.10	0.70	0.87	<0.0017
6305/S	RR913	27/05/86	6		2.6										
2300014‡	RR913	08/01/03			4.9	9.0	918	22	1.7	0.0122	33	0.34	0.47	24	<0.0011
	RR638	*				0.9	607	201	2.9	0.0065	184	2.7	0.42	1.1	
6724/12/S	RR638	26/09/89	3.2		3.2	9.5	587	377	9.9	0.0106	24	0.29		1.5	
6786/312/s	RR638	23/05/90	3.5		3.4	33.7	793	169	11.9	0.0083	24	0.29		1.8	
2300482	1016	18/03/03			1.85	21.2	809	175	10.4	0.0047	3.7	0.05	0.19	1.8	<0.0005

(Source: EBOP (Mroczek et al., 2004))

Appendix 3: Participants' information sheet and map of Rotorua



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RESEARCH STUDY ON INDIVIDUAL HYDROGEN SULPHIDE EXPOSURE IN ROTORUA

2008

INFORMATION SHEET

This research study is being conducted by Ruth Hinz as part of a masterate thesis in Earth Science at Massey University. The study is supervised by Professor Vince Neall, Professor of Earth Science, Institute of Natural Resources, Massey University, Palmerston North and Associate Professor Jeroen Douwes, Associate Director of the Centre for Public Health Research, Massey University, Wellington.

The main aim of the study is to assess individual exposure levels to hydrogen sulphide in Rotorua. We also aim to assess which environmental, meteorological and geological factors determine these exposure levels.

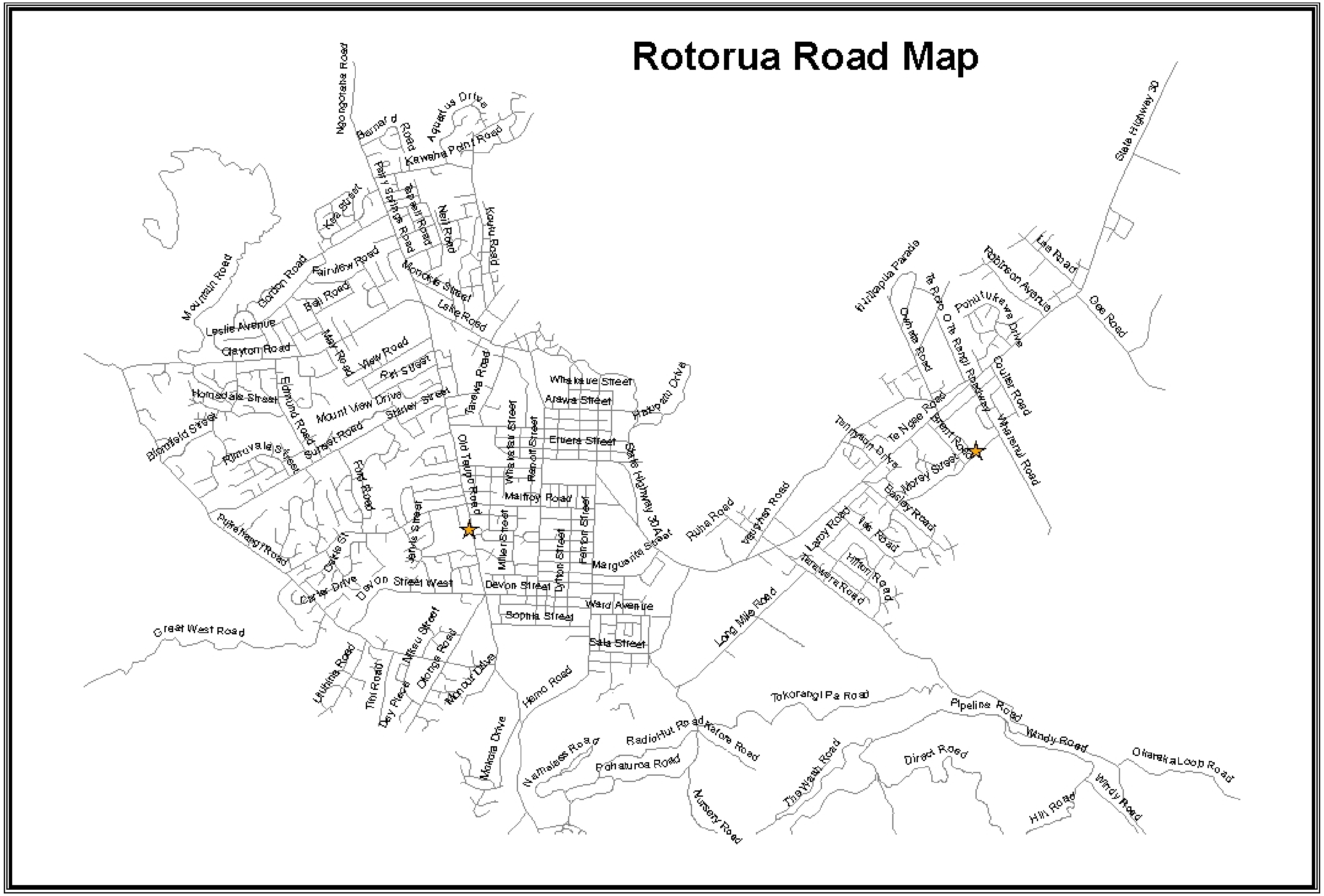
The study would require the pupils to wear one or two passive samplers for 24-48 hours three or four times during the year. The samplers are small and light and would be attached to the clothing. In addition, the pupils will be asked to mark their movements on a map of Rotorua and to indicate how much time they spend indoors and outdoors.

Please note that no personal information and health data is collected for this study. At the end of the study period, we will present the results to all interested study participants. In addition, we will post a summary report to the college.

The study has been approved by Massey University's Human Ethics Committee and a copy of the Low Risk Notification is attached for your information.

Should you have any queries, please feel free to contact Ruth Hinz (MSc Student, Earth Science) on 04-2359838 or ruthhinz@paradise.net.nz .

Te Kunenga
ki Purehuroa



(Source: Rotorua District Council)

Information on how to use this map and table

- Please indicate any location where you spent an hour or more with a cross and a number on the Rotorua Road Map. The number should correspond with the number in the table below.

- If you return to the same location several times, mark the location with an additional number.

- Estimate the total time spent at the location where you were an hour or more to the nearest 15 minute interval *e.g.*, 1 hour, 1hour 15 min, 1 hour 30 min, 1 hour 45 min, 2 hours, etc., and enter in the table below.

- Estimate the time you spent indoors and outdoors at this location (to the nearest 15 minute interval) and enter in the table below.

- If you are close to areas of geothermal activity such as in Kuirau Park or the Government Gardens, even if it is for less than an hour, please note the location and the approximate time you were there under "Remarks"

- Please note under "Remarks" if your sampler has become wet or was exposed to strong chemical fumes or smoke *e.g.* BBQ. Please also note the duration, as this may affect the sampler.

- Please note under "Remarks" if you notice any rapid changes in the discolouration of the sampler. If possible note the discolouration and the time span *e.g.* "light beige to light brown in 15 minutes" and mark the location on the map.
  We expect the sampler to discolour gradually from white to brown/dark brown in 24 hours. The discolouration could be faster in the first 6-12 hours, but any rapid colour change in 30 minutes or less is worth noting.

Location	Time total	Indoors	Outdoors
1			
2			
3			
4			
5			
6			
7			
8			
9			
10			
11			
12			
13			
14			
15			
16			

Remarks

……………………………………………………

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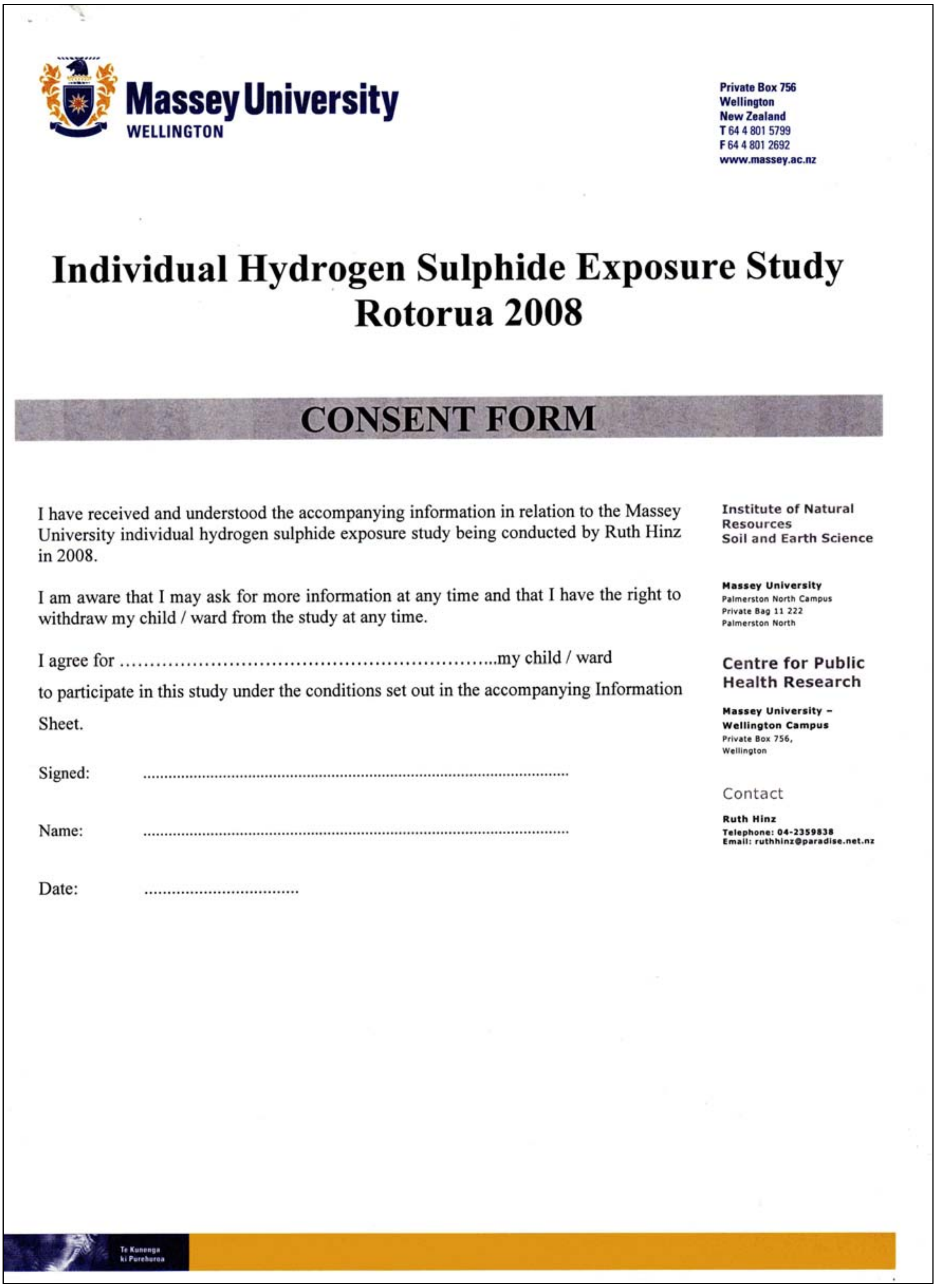
Appendix 4: Parental consent form



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Individual Hydrogen Sulphide Exposure Study
Rotorua 2008

CONSENT FORM

I have received and understood the accompanying information in relation to the Massey University individual hydrogen sulphide exposure study being conducted by Ruth Hinz in 2008.

I am aware that I may ask for more information at any time and that I have the right to withdraw my child / ward from the study at any time.

I agree for ……………………………………………………..my child / ward

to participate in this study under the conditions set out in the accompanying Information Sheet.

Signed: ....

Name: ....

Date: ....

Institute of Natural
Resources
Soil and Earth Science

Massey University
Palmerston North Campus
Private Bag 11 222
Palmerston North

Centre for Public
Health Research

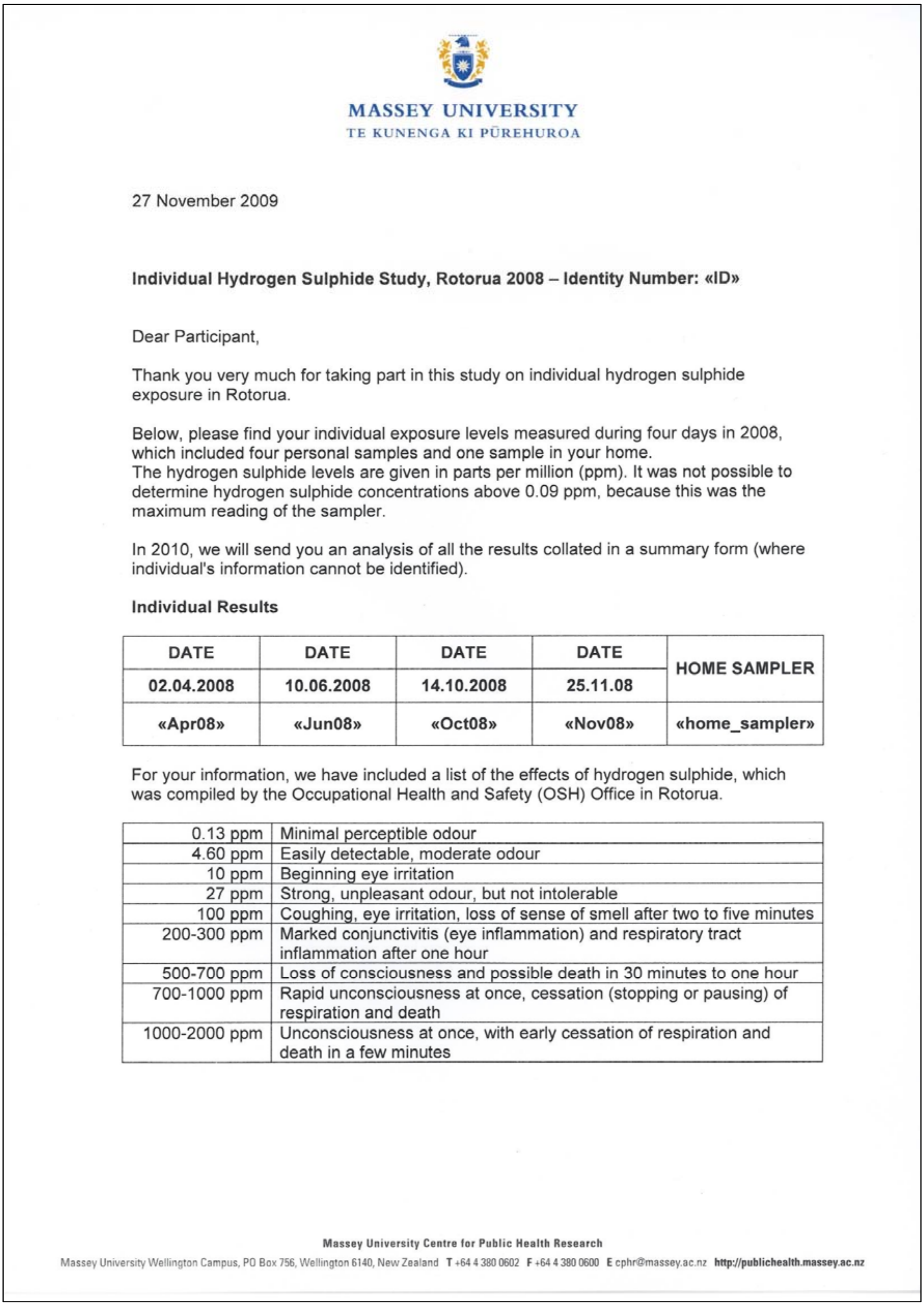
Massey University –
Wellington Campus
Private Box 756,
Wellington

Contact

Ruth Hinz
Telephone: 04-2359838
Email: ruthhinz@paradise.net.nz

Te Kunenga
ki Purehuroa

Appendix 5: Letter to participants reporting individual H_2S levels



MASSEY UNIVERSITY
TE KUNENGA KI PŪREHUROA

27 November 2009

Individual Hydrogen Sulphide Study, Rotorua 2008 – Identity Number: «ID»

Dear Participant,

Thank you very much for taking part in this study on individual hydrogen sulphide exposure in Rotorua.

Below, please find your individual exposure levels measured during four days in 2008, which included four personal samples and one sample in your home.
The hydrogen sulphide levels are given in parts per million (ppm). It was not possible to determine hydrogen sulphide concentrations above 0.09 ppm, because this was the maximum reading of the sampler.

In 2010, we will send you an analysis of all the results collated in a summary form (where individual's information cannot be identified).

Individual Results

DATE	DATE	DATE	DATE	HOME SAMPLER
02.04.2008	**10.06.2008**	**14.10.2008**	**25.11.08**	
«Apr08»	**«Jun08»**	**«Oct08»**	**«Nov08»**	**«home_sampler»**

For your information, we have included a list of the effects of hydrogen sulphide, which was compiled by the Occupational Health and Safety (OSH) Office in Rotorua.

0.13 ppm	Minimal perceptible odour
4.60 ppm	Easily detectable, moderate odour
10 ppm	Beginning eye irritation
27 ppm	Strong, unpleasant odour, but not intolerable
100 ppm	Coughing, eye irritation, loss of sense of smell after two to five minutes
200-300 ppm	Marked conjunctivitis (eye inflammation) and respiratory tract inflammation after one hour
500-700 ppm	Loss of consciousness and possible death in 30 minutes to one hour
700-1000 ppm	Rapid unconsciousness at once, cessation (stopping or pausing) of respiration and death
1000-2000 ppm	Unconsciousness at once, with early cessation of respiration and death in a few minutes

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Massey University Wellington Campus, PO Box 756, Wellington 6140, New Zealand **T** +64 4 380 0602 **F** +64 4 380 0600 **E** cphr@massey.ac.nz **http://publichealth.massey.ac.nz**

If you have any questions regarding your results, please do not hesitate to contact us.

If you are concerned at any time about exposure to higher hydrogen sulphide levels, please contact Peter Brownbridge, General Inspector (Geothermal), at the Rotorua District Council for further advice and help on 07-3484199.

Once again thank you very much for your support of this research.

Yours sincerely

Ruth Hinz

Ruth Hinz
(MSc Student)

Appendix 6: Information sheet – home sampler

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Institute of Natural Resources

Centre for Public Health Research

11 September 2008

Dear Participant

For this trial, you have received an additional sampler to your personal device.

Please use your personal sampler together with the map as previously.

The additional sampler is for measuring Hydrogen Sulphide levels in your home. We plan to use the additional data from this source for comparing indoor and outdoor exposure levels.

When at home, please take the sampler out of the bag and place it with the numbered side up in a convenient place inside the living room in your house. Leave it there until the following day. On Wednesday, please put the sampler back into the plastic bag, seal the bag and return the sampler together with the personal sampler and the map.

If you decide not to participate in this part of the trial, please use your personal sampler as previously, but kindly dispose of the home sampler into the rubbish.

Thank you very much indeed for your continued participation in this research project.

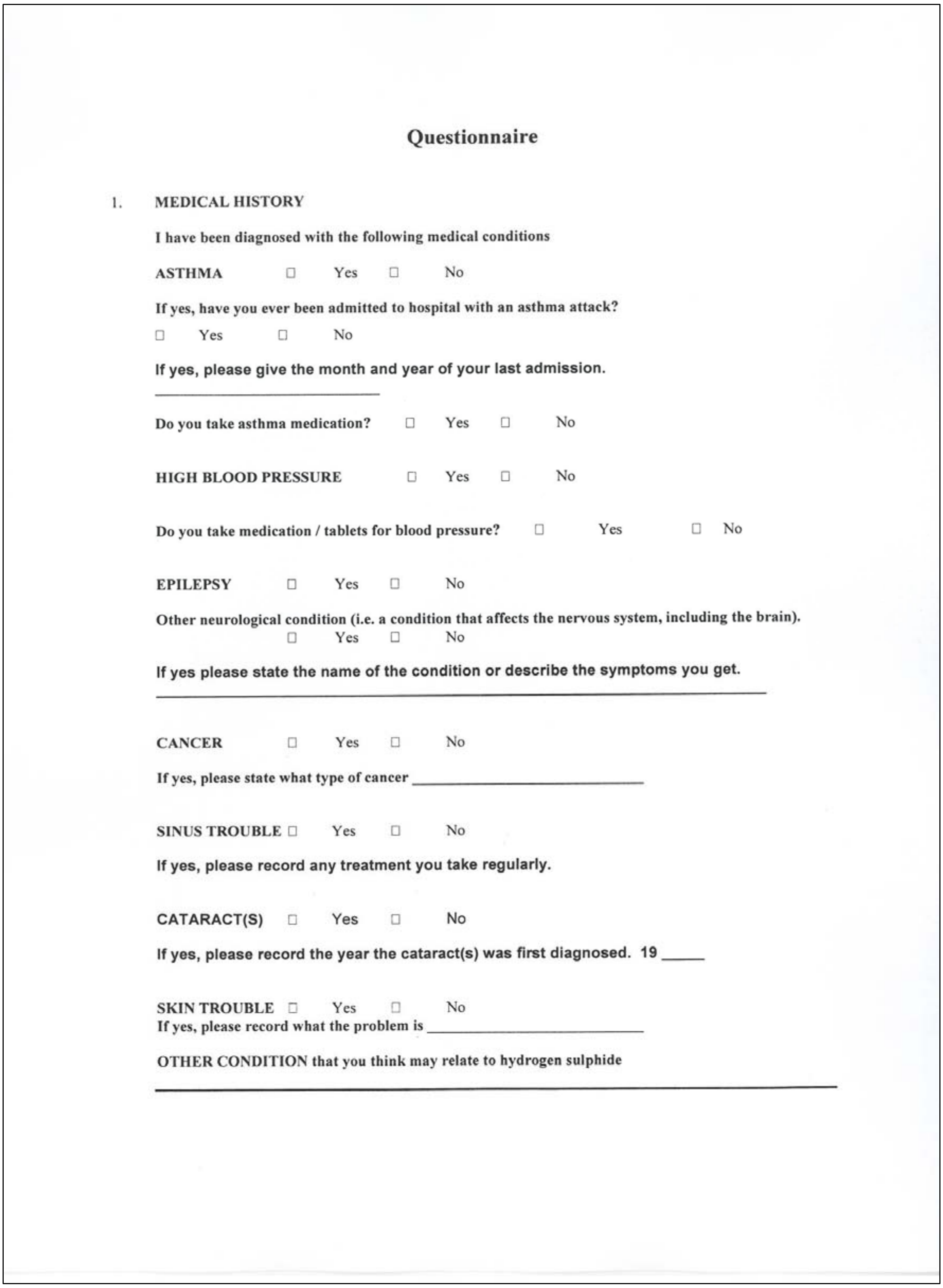
Yours sincerely

Ruth Hinz

Ruth Hinz
MSc Student
Earth Science

Te Kunenga
ki Pūrehuroa

Appendix 7: Health Survey- Questionnaire



Questionnaire

1. **MEDICAL HISTORY**

I have been diagnosed with the following medical conditions

ASTHMA ☐ Yes ☐ No

If yes, have you ever been admitted to hospital with an asthma attack?

☐ Yes ☐ No

If yes, please give the month and year of your last admission.

____

Do you take asthma medication? ☐ Yes ☐ No

HIGH BLOOD PRESSURE ☐ Yes ☐ No

Do you take medication / tablets for blood pressure? ☐ Yes ☐ No

EPILEPSY ☐ Yes ☐ No

Other neurological condition (i.e. a condition that affects the nervous system, including the brain).
☐ Yes ☐ No

If yes please state the name of the condition or describe the symptoms you get.

____

CANCER ☐ Yes ☐ No

If yes, please state what type of cancer ____________________

SINUS TROUBLE ☐ Yes ☐ No

If yes, please record any treatment you take regularly.

CATARACT(S) ☐ Yes ☐ No

If yes, please record the year the cataract(s) was first diagnosed. 19 _____

SKIN TROUBLE ☐ Yes ☐ No
If yes, please record what the problem is ____________________

OTHER CONDITION that you think may relate to hydrogen sulphide

____

2. **In what other way(s) do you feel your health may be affected by hydrogen sulphide?**

Good Effects ________________________________

Bad Effects ________________________________

Which of the medical conditions you suffer from do you think are made worse by hydrogen sulphide (H_2S)?

____

3. **When were you born?** Day ____ Month ____ Year ____

4. **Are you** ☐ Male ☐ Female

5. **Tick as many boxes as you need to show which ethnic group(s) you belong to:**

☐ NZ Maori ☐ NZ European or Pakeha ☐ Pacific Islander

☐ Other (Please Specify) ____________________

6. **How long have you lived at your current address?**

__________ Months or __________ Years

7. **If you have lived at your present address for less than two years what was your previous address?**

________________________ Street

________________________ Town/City

8. **Have you ever moved house / changed address because of problems with hydrogen sulphide?**
☐ Yes ☐ No

If yes, what was the address of the house you moved out of?

________________________ Street

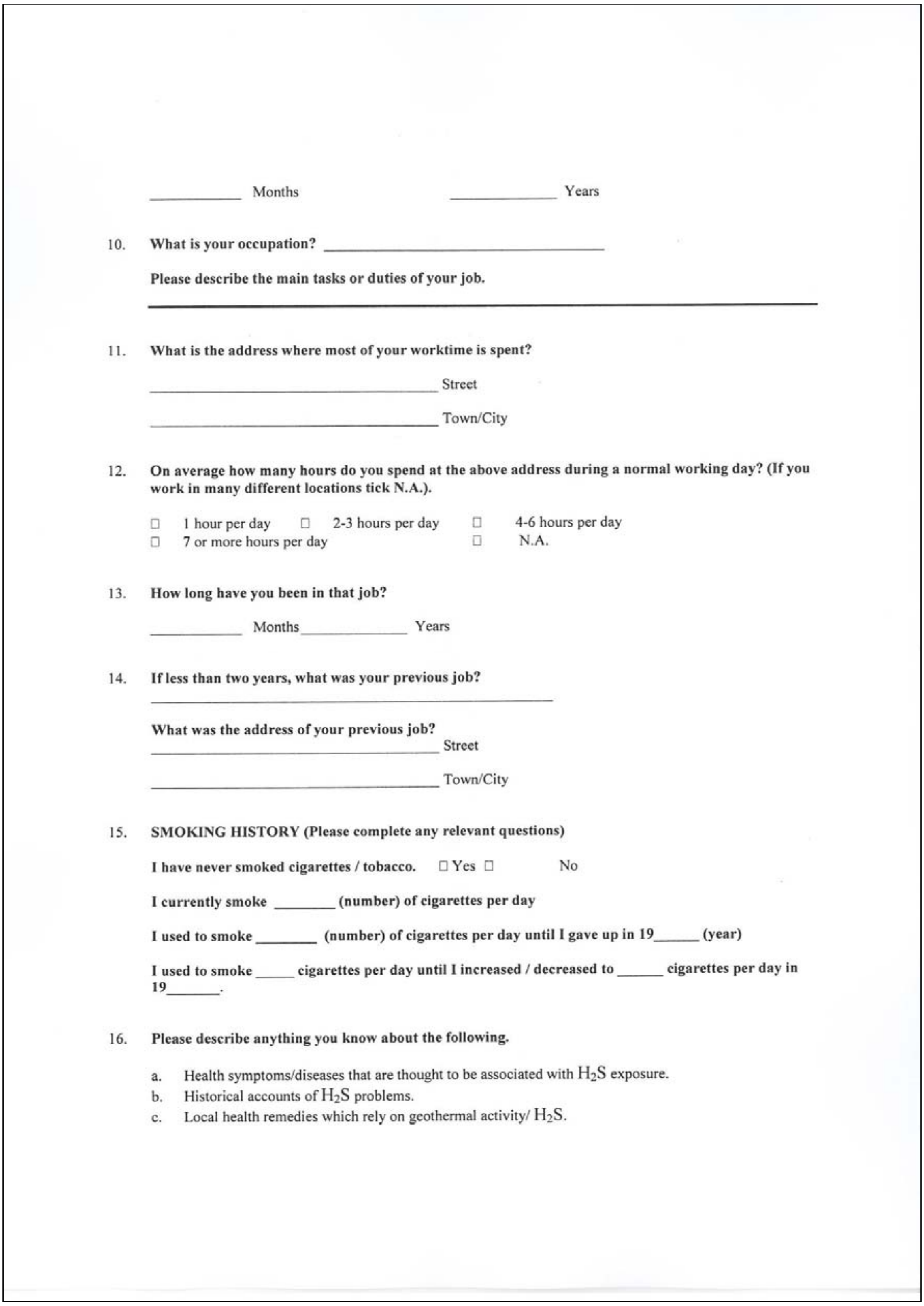
________________________ Town/City

If yes, what problems did you have from hydrogen sulphide that made you move?

____

____

9. **How long (adding all the different times) have you lived in Rotorua?**



___________ Months ____________ Years

10. **What is your occupation?** ________________________________

Please describe the main tasks or duties of your job.

____

11. **What is the address where most of your worktime is spent?**

_________________________________ Street

_________________________________ Town/City

12. **On average how many hours do you spend at the above address during a normal working day? (If you work in many different locations tick N.A.).**

☐ 1 hour per day ☐ 2-3 hours per day ☐ 4-6 hours per day
☐ 7 or more hours per day ☐ N.A.

13. **How long have you been in that job?**

___________ Months ____________ Years

14. **If less than two years, what was your previous job?**

____

What was the address of your previous job?

_________________________________ Street

_________________________________ Town/City

15. **SMOKING HISTORY (Please complete any relevant questions)**

I have never smoked cigarettes / tobacco. ☐ Yes ☐ No

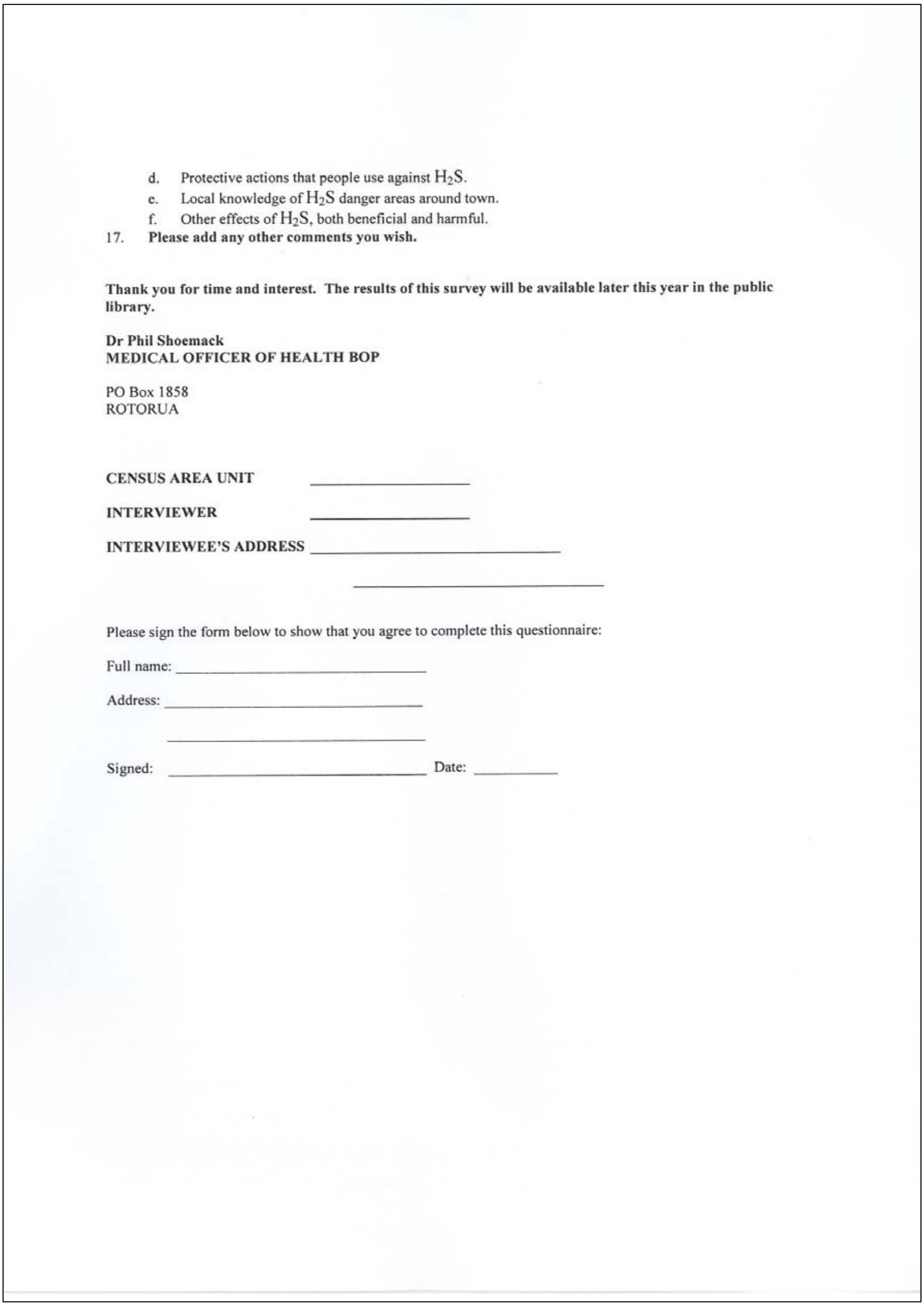
I currently smoke ________ (number) of cigarettes per day

I used to smoke ________ (number) of cigarettes per day until I gave up in 19______ (year)

I used to smoke _____ cigarettes per day until I increased / decreased to ______ cigarettes per day in 19_______.

16. **Please describe anything you know about the following.**

a. Health symptoms/diseases that are thought to be associated with H_2S exposure.
b. Historical accounts of H_2S problems.
c. Local health remedies which rely on geothermal activity/ H_2S.



   d. Protective actions that people use against H_2S.
   e. Local knowledge of H_2S danger areas around town.
   f. Other effects of H_2S, both beneficial and harmful.

17. **Please add any other comments you wish.**

Thank you for time and interest. The results of this survey will be available later this year in the public library.

Dr Phil Shoemack
MEDICAL OFFICER OF HEALTH BOP

PO Box 1858
ROTORUA

CENSUS AREA UNIT ____________________

INTERVIEWER ____________________

INTERVIEWEE'S ADDRESS ________________________________

____

Please sign the form below to show that you agree to complete this questionnaire:

Full name: ________________________________

Address: ________________________________

____

Signed: ________________________________ Date: __________

Appendix 8: Health survey – Instruction sheet for interviewers

PURPOSE OF RESEARCH
Remember this research is trying to identify if there is any indication of health effects from living and working in a geothermal area. We do not anticipate getting a precise measure of the scale of any health effects, just whether such effects exist. To do this it is important that the survey is conducted randomly. That is the reason for some of the details of the study design; i.e. to ensure that interviewees are selected randomly.

QUESTIONS
Ring Phil Shoemack on 3493520 (working hours) or 025 985534 (any time) with any concern or query.
SAFETY
Use your discretion if faced with any situation where you do not feel comfortable or safe. You should work in pairs always ensuring you are in sight of each other. Do not challenge big dogs…. just pick another address. Apologise for disturbing an angry person and leave politely. Do not accept an invitation to go inside a house. Anyone wanting further information about the research (e.g. for verification) can be referred to Phil Shoemack.

TIME OF INTERVIEWS
Spread your work over the hours in a day and over the days in a week. This will help to find a selection of people from different backgrounds who are likely to be at home at different times of the day.

"THE WALK"
For each Census Area Unit (CAU) start your walk at the intersection indicated on the map. Begin walking in the direction of the arrow and on the indicated side of the street. Do not cross a road unless you come to a dead end. If you come to a CAU boundary stay on the side of the road within the CAU you are working in. Where this is not possible return to the original start point, cross the road and walk in the same direction as the arrow. Similarly if your walk brings you back to your start point cross the road and walk in the same direction as the arrow.

ADDRESS SELECTION
Select every third residential address (i.e. miss out two). If there is no answer at an address skip two residential addresses and go on to the third. Do not select business addresses. One exception is that a Motel can be treated as a residential address for the people who run it. Treat a block of flats or apartments as one residential address and select the flat or apartment nearest to the footpath/road.

SELECTION OF INTERVIEWEE
Explain that you want the questionnaire to be completed by the person in the household over the age of 16 who has the next birthday. If that person is not available ask if you can leave the questionnaire for him/her to complete. If the person says Yes, arrange a time for you to phone to answer any queries about the questionnaire and also make a time to return to collect the completed questionnaire. Record the relevant address and the time you have arranged to call back on the master sheet. If the person you are speaking to does not want to be involved thank him/her for their time and leave. Skip two residential addresses and try the third.

RECORD EXACT ADDRESSES
Please record the exact address at the end of each completed questionnaire. i.e. a street number and name, not just a neighbourhood or street name.

OTHER
Ensure you have recorded your interviewer number and the Census Area Unit number at the end of the completed questionnaire.

Thanks,
PHIL SHOEMACK

Appendix 9: Statistics of scanner grayscale histograms

Table A-3: Statistics of grayscale histograms reported by the scanner for each sampler

mean	median	sd	CV (%)		mean	median	sd	CV (%)
255	255	0.48	0.19		180.22	183	22.03	12.22
255	255	0.20	0.08		179.43	181	18.99	10.58
255	255	0.20	0.08		178.53	180	23.11	12.94
255	255	0.08	0.03		177.43	179	21.89	12.34
255	255	0.06	0.02		177.08	178	26.07	14.72
255	255	0.02	0.01		175.83	177	27.49	15.63
255	255	0	0		174.62	175	19.15	10.97
255	255	0	0		173.24	174	18.24	10.53
255	255	0	0		173.02	175	25.43	14.70
254.99	255	0.79	0.31		172.67	173	18.13	10.50
254.99	255	0.41	0.16		172.26	174	21.38	12.41
254.99	255	0.22	0.09		170.99	172	21.27	12.44
233.05	233	9.10	3.90		170.78	172	29.12	17.05
232.54	232	9.15	3.93		167.49	168	26.37	15.74
231.65	231	8.75	3.78		166.00	167	27.02	16.28
231.19	231	6.49	2.81		165.00	166	25.08	15.20
231.12	231	8.17	3.53		159.78	160	29.58	18.51
231.08	232	8.61	3.73		158.09	158	24.25	15.34
219.90	218	8.89	4.04		134.09	134	18.10	13.50
219.26	220	8.65	3.95		131.09	131	19.54	14.91
217.85	218	9.52	4.37		130.24	130	19.14	14.70
217.71	218	10.25	4.71		126.69	126	19.49	15.38
217.49	218	9.24	4.25		126.65	126	19.97	15.77
217.02	217	9.43	4.35		124.62	124	18.46	14.81
203.49	204	13.1	6.44		123.60	123	18.28	14.79
203.25	204	12.84	6.32		122.18	123	22.26	18.22
200.34	201	13.43	6.70		121.09	121	19.21	15.86
197.41	199	14.22	7.20		120.33	120	18.69	15.53
194.50	196	15.57	8.01		120.28	121	20.84	17.33
194.37	195	15.15	7.79		119.23	119	18.08	15.16
186.49	187	17.24	9.24		119.22	119	18.92	15.87
185.66	186	16.74	9.02		118.69	118	19.41	16.35
182.45	184	27.28	14.95		117.41	118	23.21	19.77
182.14	183	17.59	9.66		117.23	118	24.11	20.57
181.32	182	18.41	10.15		110.55	111	22.43	20.29
181.12	183	28.77	15.88		109.78	111	23.69	21.58
180.92	183	25.87	14.30					

The table displays the mean, median and standard deviation as reported by the scanner for a variety of grayscale values. Additionally the coefficient of variation (%)[29] was calculated for each sampler.

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[29] CV: Coefficient of variation = sd / mean x 100% gives the relative variation of distribution.

Appendix 10: Data used for the calibration analysis

Table A-4: Table displaying the grayscale value recorded and predicted H_2S concentration and the group median for each calibration model

Date	ID	grayscale value	H_2S monitor (ppb)	H_2S_linear	H_2S_quad	H_2S_sp200	H_2S_sp190	H_2S_sp180	>90ppb	group median
24.11.08	M_0900_1	255	0	2.60	0.65	0.70	0.84	1.00	0	255
24.11.08	M_0900_2	255	0	2.60	0.65	0.70	0.84	1.00	0	
24.11.08	M_0900_3	255	0	2.60	0.65	0.70	0.84	1.00	0	
24.11.08	M_0900_4	255	0	2.60	0.65	0.70	0.84	1.00	0	
24.11.08	M_0900_5	255	0	2.60	0.65	0.70	0.84	1.00	0	
24.11.08	M_0900_6	255	0	2.60	0.65	0.70	0.84	1.00	0	
24.11.08	M_1100_1	255	0	2.60	0.65	0.70	0.84	1.00	0	
24.11.08	M_1100_2	255	0	2.60	0.65	0.70	0.84	1.00	0	255
24.11.08	M_1100_3	255	0	2.60	0.65	0.70	0.84	1.00	0	
24.11.08	M_1100_4	255	0	2.60	0.65	0.70	0.84	1.00	0	
24.11.08	M_1100_5	255	0	2.60	0.65	0.70	0.84	1.00	0	
24.11.08	M_1100_6	255	0	2.60	0.65	0.70	0.84	1.00	0	
25.11.08	T_0900_3	231	2.55	4.49	2.53	2.52	2.56	2.66	0	
25.11.08	T_0900_5	231	2.55	4.49	2.53	2.52	2.56	2.66	0	
25.11.08	T_0900_6	231	2.55	4.49	2.53	2.52	2.56	2.66	0	
25.11.08	T_0900_2	232	2.55	4.39	2.40	2.39	2.44	2.56	0	
25.11.08	T_0900_4	232	2.55	4.39	2.40	2.39	2.44	2.56	0	
25.11.08	T_0900_1	233	2.55	4.29	2.28	2.26	2.33	2.45	0	232
25.11.08	T_1100_4	217	4.67	6.18	4.94	5.34	4.90	4.72	0	
25.11.08	T_1100_1	218	4.67	6.05	4.72	5.06	4.67	4.53	0	218
25.11.08	T_1100_2	218	4.67	6.05	4.72	5.06	4.67	4.53	0	
25.11.08	T_1100_5	218	4.67	6.05	4.72	5.06	4.67	4.53	0	
25.11.08	T_1100_6	218	4.67	6.05	4.72	5.06	4.67	4.53	0	

Date	ID	grayscale value	H_2S monitor (ppb)	H_2S_linear	H_2S_quad	H_2S_sp200	H_2S_sp190	H_2S_sp180	>90ppb	group median
25.11.08	T_1100_3	220	4.67	5.78	4.31	4.54	4.26	4.17	0	
25.11.08	T_1300_5	195	8.87	10.21	11.81	14.35	13.58	11.58	0	
25.11.08	T_1300_6	196	8.87	9.98	11.41	14.13	12.96	11.12	0	
25.11.08	T_1300_4	199	8.87	9.32	10.25	13.49	11.28	9.83	0	
25.11.08	T_1300_1	201	8.87	8.91	9.52	12.59	10.28	9.06	0	
25.11.08	T_1300_2	204	8.87	8.32	8.49	10.72	8.95	8.02	0	
25.11.08	T_1300_3	204	8.87	8.32	8.49	10.72	8.95	8.02	0	200
25.11.08	T_1500_4	173	15.03	16.86	22.58	20.22	21.60	23.22	2	
25.11.08	T_1500_5	174	15.03	16.48	22.03	19.91	21.31	22.95	2	
25.11.08	T_1500_1	182	15.03	13.73	17.80	17.58	19.10	19.69	2	
25.11.08	T_1500_3	183	15.03	13.42	17.29	17.31	18.84	18.90	2	
25.11.08	T_1500_2	186	15.03	12.54	15.82	16.52	18.09	16.72	2	
25.11.08	T_1500_6	187	15.03	12.25	15.34	16.26	17.84	16.05	2	181
26.11.08	W_1100_4	111	42.26	69.29	42.33	53.14	50.43	48.69	16	
26.11.08	W_1100_6	111	42.26	69.29	42.33	53.14	50.43	48.69	16	
26.11.08	W_1100_1	118	42.26	59.07	43.08	47.65	45.83	44.79	16	
26.11.08	W_1100_2	118	42.26	59.07	43.08	47.65	45.83	44.79	16	
26.11.08	W_1100_5	121	42.26	55.17	43.11	45.47	43.99	43.21	16	
26.11.08	W_1100_3	123	42.26	52.71	43.03	44.08	42.80	42.19	16	117
26.11.08	W_0730_5	118	43.76	59.07	43.08	47.65	45.83	44.79	18	
26.11.08	W_0730_4	119	43.76	57.74	43.11	46.91	45.21	44.26	18	
26.11.08	W_0730_6	124	43.76	51.52	42.96	43.39	42.22	41.69	18	
26.11.08	W_0730_1	126	43.76	49.23	42.77	42.06	41.08	40.71	18	
26.11.08	W_0730_2	126	43.76	49.23	42.77	42.06	41.08	40.71	18	
26.11.08	W_0730_3	130	43.76	44.94	42.14	39.52	38.89	38.81	18	124
26.11.08	W_0900_6	119	44.77	57.74	43.11	46.91	45.21	44.26	19	
26.11.08	W_0900_5	120	44.77	56.44	43.12	46.18	44.59	43.73	19	
26.11.08	W_0900_4	121	44.77	55.17	43.11	45.47	43.99	43.21	19	

Date	**ID**	**grayscale value**	**H_2S monitor (ppb)**	**H_2S_linear**	**H_2S_quad**	**H_2S_sp200**	**H_2S_sp190**	**H_2S_sp180**	**>90ppb**	**group median**
26.11.08	W_0900_2	123	44.77	52.71	43.03	44.08	42.80	42.19	19	
26.11.08	W_0900_1	131	44.77	43.92	41.94	38.91	38.37	38.35	19	
26.11.08	W_0900_3	134	44.77	41.02	41.22	37.13	36.82	37.00	19	125
09.06.08	223	158	24.15	23.74	30.92	25.55	26.52	27.78	5	
09.06.08	240	160	24.15	22.68	29.83	24.76	25.81	27.12	5	
09.06.08	230	166	24.15	19.78	26.49	22.55	23.77	25.25	5	
09.06.08	233	167	24.15	19.33	25.93	22.21	23.45	24.95	5	
09.06.08	234	168	24.15	18.90	25.37	21.86	23.13	24.65	5	
09.06.08	227	172	24.15	17.25	23.14	20.54	21.90	23.50	5	
09.06.08	239	172	24.15	17.25	23.14	20.54	21.90	23.50	5	
09.06.08	228	174	24.15	16.48	22.03	19.91	21.31	22.95	5	
09.06.08	221	175	24.15	16.11	21.49	19.60	21.02	22.68	5	
09.06.08	224	175	24.15	16.11	21.49	19.60	21.02	22.68	5	
09.06.08	238	177	24.15	15.39	20.41	19.00	20.45	22.14	5	
09.06.08	237	178	24.15	15.05	19.87	18.71	20.18	21.88	5	
09.06.08	229	179	24.15	14.71	19.35	18.42	19.90	21.62	5	
09.06.08	225	180	24.15	14.37	18.82	18.13	19.63	21.36	5	
09.06.08	226	181	24.15	14.05	18.31	17.85	19.37	20.51	5	
09.06.08	222	183	24.15	13.42	17.29	17.31	18.84	18.90	5	
09.06.08	231	183	24.15	13.42	17.29	17.31	18.84	18.90	5	
09.06.08	235	183	24.15	13.42	17.29	17.31	18.84	18.90	5	
09.06.08	232	184	24.15	13.12	16.79	17.04	18.59	18.14	5	175

Appendix 11: Regression analyses for reclassified groups using the map locations.

Table A-5: Univariate regression analysis of personal samplers using reclassified groups.

H_2S 1-hour average	Ratio(10^B)	95% Confidence Interval	Partial R^2 (%)
April 2008	1.27	0.85-1.90	0.37
June 2008	2.00 ***	1.34-3.00	3.06***
October 2008	1.46	0.91-2.21	0.89
Number of observations: 369		**Adjusted R^2 (%) Model: 2.46****	
RLH	1.27	0.97-1.68	0.79
RDC	7.12***	5.54-9.16	39.09***
Number of observations: 369		**Adjusted R^2 (%) Model: 41.16*****	

*p=<0.05, **p=<0.01, ***p=<0.001

Reference groups: November 2008 trial and RGH respectively

Table A-6: Regression analysis of personal samplers stratified by trial using reclassified groups.

Trial	Group	Ratio(10^B)	95% Confidence Interval	Partial R^2 (%)
April 2008	**RLH**	1.68*	1.01-2.80	4.14*
	RDC	6.04***	3.73-9.72	36.15***
Number of observations: 99			**Adjusted R^2 (%) Model: 35.55*****	
June 2008	**RLH**	0.94	0.58-1.51	0.08
	RDC	6.61***	4.32-10.11	44.48***
Number of observations: 100			**Adjusted R^2 (%) Model: 48.44*****	
October 2008	**RLH**	1.33	0.81-2.18	1.47
	RDC	19.05***	12.00-30.23	65.45***
Number of observations: 88			**Adjusted R^2 (%) Model: 67.02*****	
November 2008	**RLH**	1.26	0.67-2.36	0.65
	RDC	3.59***	2.05-6.29	20.60***
Number of observations: 82			**Adjusted R^2 (%) Model: 20.09*****	

*p=<0.05, **p=<0.01, ***p=<0.001

Reference group: RGH

Table A-7: Regression analysis of personal samplers stratified by group using reclassified groups.

Group	Trial	Ratio(10^B)	95% Confidence Interval	Partial R^2 (%)
RGH	**April 2008**	1.06	0.78-1.44	0.11
	June 2008	1.77^{***}	1.31-2.39	8.50^{***}
	October 2008	0.9	0.66-1.22	0.30
Number of observations: 154			**Adjusted R^2 (%) Model: 12.98**	
RLH	**April 2008**	1.42	0.97-2.09	3.75
	June 2008	1.32	0.89-1.95	2.17
	October 2008	0.95	0.64-1.41	0.08
Number of observations: 91			**Adjusted R^2 (%) Model: 3.90**	
RDC	**April 2008**	1.78	0.89-3.76	1.96
	June 2008	3.25^{**}	1.58-6.69	8.01^{**}
	October 2008	4.78^{***}	2.23-10.24	12.09^{***}
Number of observations: 124			**Adjusted R^2 (%) Model: 11.84**	

*p=<0.05, **p=<0.01, ***p=<0.001 Reference group: November 2008 trial

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Appendix 12: Population statistics and crude OR values for the refined exposure models of the health survey

Table A-8: Population statistics for the refined exposure models of the health survey.

Exposure Category	low	medium	high	low	medium	high	low	medium	high
Exposure Model	**1. current residential exposure**			**2. previous residential exposure**^{1}			**3. observation excluded if residential exposure category changed**		
Age (n) **Mean (SD)**	(140) 43.9 (15.6)	(133) 46.2 (16.3)	(70) 52.4 (21.2)	(162) 44.2(15.6)	(111) 46.5(17.2)	(57) 54.8 (20.0)	(131) 43.8 (15.3)	(108) 47.1 (17.0)	(49) 56.5 (19.6)
Sex (n) **Female %**	(151) 67.6	(138) 76.1	(71) 66.2	(173) 68.2	(115) 75.7	(59) 67.8	(142) 67.6	(112) 75.0	(50) 68.0
Ethnicity (n) **Maori/Pacific %**	(148) 54.1	(133) 32.3	(67) 23.9	(170) 44.1	113 31.9	(56) 16.5	(141) 47.5	(110) 31.8	(47) 21.3
Smoking (n) **Ex-smoker %** **Smoker %**	(152) 29.6 26.7	(139) 26.6 23.7	(71) 26.0 24.1	(174) 29.3 27.0	(116) 25.9 20.1	(59) 42.4 16.9	(123) 29.3 26.0	(117) 26.5 24.8	(65) 36.9 20
Residence time (n) **Mean (SD)**	(142) 19.9 (14.5)	(127) 24.1 (14.5)	(66) 23.4 (14.1)	(163) 20.0 (14.9)	(109) 24.8 (14.3)	(56) 24.1 (12.8)	(135) 20.0 (14.7)	(106) 25.0 (14.4)	(47) 24.7 (13.2)
Exposure Model	**1. current combined exposure**			**2. previous combined exposure**			**3. observations excluded if combined exposure category changed**		
Age (n) **Mean (SD)**	(114) 44.5 (16.0)	(112) 46.2 (16.8)	(64) 53.3 (21.1)	(131) 44.1 (16.0)	(97) 46.8 (17.5)	(53) 56.28 (19.4)	(92) 45.7 (15.64)	(84) 48.8 (17.7)	(44) 58.5 (18.7)
Sex (n) **Female %**	(123) 71.5	(116) 76.7	(65) 67.7	(140) 70.0	(100) 76.0	(55) 69.1	(100) 72.0	(87) 74.7	(45) 68.9
Ethnicity (n) **Maori/ Pacific %**	(121) 46.0	(114) 32.5	(61) 23.0	(137) 44.5	(98) 32.7	(52) 17.3	(98) 43.9	(85) 27.1	(42) 14.3
Smoking (n) **Ex-smoker %** **Smoker %**	(123) 29.3 26.0	(117) 26.5 24.8	(65) 36.9 20.0	(140) 27.9 26.5	(101) 24.8 21.8	(55) 43.6 20.0	(100) 28.0 23.0	(88) 23.9 21.6	(45) 40.0 17.8
Residence time (n) **Mean (SD)**	(117) 20.1 (14.5)	(110) 24.5 (14.6)	(60) 22.5 (13.6)	(132) 19.6 (14.5)	(97) 25.2 (14.5)	(52) 24.1 (12.8)	(94) 20.1 (14.2)	(84) 25.9 (14.9)	(43) 24.3 (13.2)

Table A-9: Crude OR for asthma and cataract using the refined exposure models.

Exposure Category	**medium** OR (95% CI)	**high** OR (95% CI)	**medium** OR (95% CI)	**high** OR (95% CI)	**medium** OR (95% CI)	**high** OR (95% CI)
Exposure Model	**1. current residential exposure**		**2. previous residential exposure[1]**		**3. observation excluded if residential exposure category changed**	
Asthma (1.n=362 , 2.n=349, 3.n=306)	1.2 (0.63-2.19)	1.9 (0.95-3.82)	0.7 (0.35-1.33)	2.0 (1.03-3.98)*	0.7 (0.38-1.69)	2.2 (0.98-4.76)
Hospitalisation all asthmatics (1.n=361, 2.n=348, 3.n=306)	0.9 (0.31-2.87)	2.3 (0.76-6.73)	0.6 (0.18-1.90)	1.5 (0.49-4.61)	0.8 (0.23-3.04)	2.0 (0.54-7.35)
Hospitalisation for asthma [1] (1.n=317, 2.n=304, 3.n=274)	1.0 (0.31-2.94)	2.4 (0.81-7.28)	0.6 (0.17-1.86)	1.7 (0.56-5.39)	0.8 (0.23-3.00)	2.2 (0.59-8.28)
On medication all asthmatics (1.n=362, 2.n=349, 3.n=306)	1.1 (0.57-2.16)	1.8 (0.84-3.70)	0.7 (0.33-1.43)	2.4 (1.20-4.88)*	0.7 (0.32-1.64)	2.6 (1.16-5.85)*
On medication for asthma [2] (1.n=352, 2.n=339, 3.n=300)	1.1 (0.57-2.19)	1.8 (0.87-3.83)	0.7 (0.33-1.42)	2.4 (1.17-4.81)*	0.7 (0.32-1.65)	2.5 (1.13-5.72)*
Cataract (1.n=355, 2.n=343, 3.n=301)	3.2 (1.0-10.33)*	5.0 (1.45-17.18)**	3.5 (1.19-10.46)*	4.8 (1.45-15.70)**	3.8 (1.16-12.14)*	6.0 (1.68-21.67)**
Exposure Model	**1. current combined exposure**		**2. previous combined exposure**		**3. observations excluded if combined exposure category changed**	
Asthma (1.n=305, 2.n=296, 3.n=233)	1.1 (0.54-2.09)	1.7 (0.80-3.53)	0.6 (0.28-2.23)	1.8 (0.87-3.70)	0.7 (0.26-1.70)	2.2 (0.88-5.30)
Hospitalisation all asthmatics (1.n=305, 2.n=296, 3.n=233)	0.6 (0.17-2.06)	1.4 (0.42-4.54)	0.3 (0.06-1.39)	0.8 (0.22-3.22)	0.3 (0.03-2.52)	1.7 (0.37-8.00)
Hospitalisation for asthma [1] (1.n=265, 2.n=256, 3.n=209)	0.6 (0.17-2.14)	1.5 (0.45-4.97)	0.3 (0.06-1.35)	1.0 (0.25-3.78)	0.3 (0.03-2.48)	1.9 (0.41-9.03)
On medication all asthmatics (1.n=305, 2.n=296, 3.n=233)	1.0 (0.47-2.06)	1.6 (0.70-3.45)	0.6 (0.24-1.27)	2.1 (1.00-4.51)*	0.5 (0.18-1.65)	2.9 (1.13-7.47)*
On medication for asthma [2] (1.n=295, 2.n=287, 3.n=227)	1.0 (0.48-2.09)	1.6 (0.72-3.57)	0.6 (0.24-1.26)	2.1 (0.98-4.45)	0.5 (0.18-1.66)	2.8 (1.10-7.23)*
Cataract (1.n=301, 2.n=292, 3.n=229)	3.4 (0.89-12.8)	5.9 (1.51-23.2)**	3.4 (1.01-11.2)*	5..3 (1.48-18.9)**	3.7 (0.98-14.30)	6.5 (1.58-26.4)**

[1] excluding asthmatics who never been hospitalised for asthma

[2] excluding asthmatics who are not on asthma medication

* p =< 0.05, ** p =< 0.01

Appendix 13: Adjusted OR values for ‘asthma’ and ‘asthma on medication’ using a residence time longer than 3, 5, 7, 10 years

Table A-10: Adjusted OR values for ‘Asthma’ using the residential and combined exposure models and a residence time longer than 3, 5, 7, 10 years.

Exposure Category	**medium** OR (95% CI)	**high** OR (95% CI)	**medium** OR (95% CI)	**high** OR (95% CI)	**medium** OR (95% CI)	**high** OR (95% CI)
Exposure Model	**1. current residential exposure**		**2. previous residential exposure**		**3. observation excluded if residential exposure category changed**	
Residence time over 3 years (1.n=291, 2.n=285, 3.n=250)	1.0 (0.47-1.97)	2.0 (0.90-4.45)	0.5 (0.25-1.17)	2.1 (0.96-4.66)	0.6 (0.25-1.42)	1.9 (0.73-4.77)
Residence time over 5 years (1.n=262, 2.n=256, 3.n=226)	0.8 (0.36-1.74)	2.1 (0.90-4.95)	0.5 (0.20-1.10)	2.1 (0.90-5.06)	0.5 (0.18-1.24)	2.1 (0.77-5.54)
Residence time over 7 years (1.n=244, 2.n=239, 3.n=210)	0.8 (0.37-1.93)	2.1 (0.90-5.15)	0.5 (0.20-1.15)	2.1 (0.87-5.05)	0.5 (0.19-1.39)	2.1 (0.77-5.85)
Residence time over 10 years (1.n=224, 2.n=219, 3.n=193)	0.9 (0.41-2.18)	2.1 (0.87-5.30)	0.5 (0.19-1.14)	2.1 (0.87-5.21)	0.6 (0.21-1.58)	2.4 (0.84-6.69)
Exposure Model	**1. current combined exposure**		**2. previous combined exposure**		**3. observations excluded if combined exposure category changed**	
Residence time over 3 years (1.n=249, 2.n=245, 3.n=193)	0.9 (0.43-2.03)	1.9 (0.79-4.42)	0.5 (0.21-1.17)	1.8 (0.79-4.42)	0.4 (0.13-1.36)	1.4 (0.46-4.25)
Residence time over 5 years (1.n=224, 2.n=221, 3.n=178)	0.8 (0.35-1.95)	2.1 (0.81-5.17)	0.5 (0.20-1.25)	2.2 (0.85-5.48)	0.3 (0.09-1.12)	1.3 (0.41-4.37)
Residence time over 7 years (1.n=209, 2.n=206, 3.n=165)	0.9 (0.38-2.26)	2.2 (0.83-5.63)	0.5 (0.20-1.34)	2.2 (0.83-5.61)	0.4 (0.10-1.40)	1.5 (0.43-5.16)
Residence time over 10 years (1.n=192, 2.n=188, 3.n=151)	1.0 (0.41-2.55)	2.2 (0.81-5.94)	0.5 (0.19-1.38)	2.3 (0.87-6.08)	0.4 (0.11-1.72)	1.9 (0.52-6.62)

*p =< 0.05, ** p =< 0.01

Table A-11: Adjusted OR for 'asthmatics on medication' using the residential and combined exposure models and a residence time longer than 3, 5, 7, 10 years.

Exposure Category	medium OR (95% CI)	high OR (95% CI)	medium OR (95% CI)	high OR (95% CI)	medium OR (95% CI)	high OR (95% CI)
Exposure Model	**1. current residential exposure**		**2. previous residential exposure[1]**		**3. observation excluded if residential exposure category changed**	
Residence time over 3 years (1.n=291, 2.n=285, 3.n=250)	0.9 (0.41-1.90)	1.7 (0.72-3.96)	0.6 (0.24-1.31)	2.6 (1.12-5.85)*	0.5 (0.20-1.34)	2.2 (0.84-5.72)
Residence time over 5 years (1.n=262, 2.n=256, 3.n=)	0.7 (0.30-1.65)	2.0 (0.82-4.91)	0.5 (0.18-1.17)	2.5 (1.02-6.24)*	0.4 (0.13-1.16)	2.5 (0.91-6.99)
Residence time over 7 years (1.n=244, 2.n=239, 3.n=)	0.8 (0.32-1.88)	2.1 (0.83-5.26)	0.5 (0.19-1.28)	2.6 (1.01-6.45)*	0.4 (0.14-1.35)	2.7 (0.93-7.70)
Residence time over 10 years (1.n=224, 2.n=219, 3.n=)	0.9 (0.35-2.15)	2.1 (0.79-5.42)	0.5 (0.17-1.27)	2.6 (1.02-6.75)*	0.5 (0.16-1.59)	3.1 (1.04-9.08)*
Exposure Model	**1. current combined exposure**		**2. previous combined exposure**		**3. observations excluded if combined exposure category changed**	
Residence time over 3 years (1.n=249, 2.n=245, 3.n=193)	0.8 (0.37-1.95)	1.5 (0.61-3.90)	0.5 (0.19-1.29)	2.3 (0.92-5.71)	0.3 (0.07-1.23)	1.7 (0.54-5.56)
Residence time over 5 years (1.n=224, 2.n=221, 3.n=178)	0.7 (0.28-1.86)	1.9 (0.73-5.19)	0.5 (0.17-1.31)	2.6 (0.96-6.93)	0.3 (0.04-0.97)*	1.7 (0.48-5.84)
Residence time over 7 years (1.n=209, 2.n=206, 3.n=165)	0.8 (0.31-2.24)	2.1 (0.76-5.91)	0.5 (0.18-1.48)	2.7 (0.97-7.39)	0.2 (0.04-1.33)	2.0 (0.53-7.77)
Residence time over 10 years (1.n=192, 2.n=188, 3.n=151)	0.9 (0.34-2.60)	2.1 (0.73-6.26)	0.5 (0.16-1.52)	2.9 (1.02-8.16)*	0.3 (0.05-1.77)	2.7 (0.66-11.18)

*p =< 0.05, ** p =< 0.01

References

Amaral, A.F.S. and Rodrigues, A.S., 2007. Chronic exposure to volcanic environments and chronic bronchitis incidence in the Azores, Portugal. *Environmental Research, 103(3): 419-423.*

Bates, M., N., Garrett, N., Graham, B. and Read, D., 1997. Air pollution and mortality in the Rotorua geothermal area. *Australian and New Zealand Journal of Public Health, 21(6): 581-586.*

Bates, M.N. and Crane, J., 2008. Investigating possible health effects of hydrogen sulfide in Rotorua, New Zealand. http://ehs.sph.berkeley.edu/cheers/.

Bates, M.N., Garrett, N., Graham, B. and Read, D., 1998. Cancer incidence, morbidity and geothermal air pollution in Rotorua, New Zealand. *International Journal of Epidemiology, 27(1): 10-14.*

Bates, M.N., Garrett, N. and Shoemack, P., 2002. Investigation of health effects of hydrogen sulfide from a geothermal source. *Archives of Environmental Health, 57(5): 405-411.*

Baxter, P.J., Baubron, J.-C. and Coutinho, R., 1999. Health hazards and disaster potential of ground gas emissions at Furnas volcano, São Miguel, Azores. *Journal of Volcanology and Geothermal Research, 92(1-2): 95-106.*

Brownbridge, P., 2009a. Council Files. General Inspector - Geothermal and General Bylaws, Rotorua District Council.

Brownbridge, P., 2009b. Personal Communication. General Inspector - Geothermal and General Bylaws, Rotorua District Council.

Campagna, D. et al., 2004. Ambient hydrogen sulfide, total reduced sulfur, and hospital visits for respiratory diseases in northeast Nebraska, 1998-2000. *Journal of Exposure Analysis and Environmental Epidemiology, 14(2): 180-187.*

Carapezza, M.L., Badalamenti, B., Cavarra, L. and Scalzo, A., 2003. Gas hazard assessment in a densely inhabited area of Colli Albani Volcano (Cava dei Selci, Roma). *Journal of Volcanology and Geothermal Research, 123(1-2): 81-94.*

Cody, A.D. and Scott, B.J., 2005. Surface Feature Activity, Environmental Bay of Plenty.

D'Alessandro, W.B., L; Kyriakopoulos, K; Michas, G; Papadakis, G, 2009. Hydrogen sulphide as a natural air contaminant in volcanic/geothermal areas: the case of Sousaki, Corinthia (Greece). *Environmental Geology 57(8): 1723-1728.*

D' Souza, W. et al., 1999. The prevalence of asthma symptoms, bronchial hyperresponsiveness and atopy in New Zealand adults. *New Zealand Medical Journal, 112(1089): 198-202.*

Davy, B., 1992. Seismic reflection profiling on southern Lake Rotorua - evidence for gas-charged lake floor sediments. *Geothermics, 21(1-2): 97-108.*

Department of Labour, 1999. The ABCs of Hydrogen Sulphide in Geothermal Bores. http://www.osh.govt.nz/order/catalogue/pdf/hydrogensulphide.pdf.

Durand, M., 2006. Indoor air pollution caused by geothermal gases. *Building and Environment, 41(11): 1607-1610.*

Durand, M. and Scott, B.J., 2005. Geothermal ground gas emissions and indoor air pollution in Rotorua, New Zealand. *Science of the Total Environment, 345(1-3): 69-80.*

Durand, M. and Wilson, J.G., 2006. Spatial analysis of respiratory disease on an urbanized geothermal field. *Environmental Research, 101(2): 238-245.*

Ellery, G.R., 2007. Historical Data Summaries in Live Monitoring, Environment Bay of Plenty

Faller, S. et al., 2010. Inhaled hydrogen sulfide protects against ventilator-induced lung injury. *Anesthesiology, 113(1): 104.*

Finlayson, J.B., 1992. A soil gas survey over Rotorua geothermal field, Rotorua, New Zealand. *Geothermics, 21(1-2): 181-195.*

Fisher, G., D. Thornton, and J. Godfrey, 2007. Rotorua Airshed Modelling Investigation Final Report.

Fisher, G.W., Petersen, J. and Timpany, G., 1996. Survey of Background Hydrogen Sulphide in Rotorua–1996. NIWA Report AK96058, Auckland.

Giggenbach, W.F. and Glover, R.B., 1992. Tectonic regime and major processes governing the chemistry of water and gas discharges from the Rotorua geothermal field, New Zealand. *Geothermics, 21(1-2): 121-140.*

Glover, R.B., 1992. Integrated heat and mass discharges from the Rotorua geothermal system. *Geothermics, 21(1-2): 89-96.*

Gordon, D.A., Scott, B.J. and Mroczek, E.K., 2005. Rotorua Geothermal Field Management Monitoring Update: 2005. Environment Bay of Plenty.

Horwell, C., 1998. Geothermal Hydrogen Sulphide mapping across Rotorua, New Zealand: Implication for the assessment of Public Health, Victoria University, Wellington.

Horwell, C.J., Allen, A.G., Mather, T.A. and Patterson, J.E., 2004. Evaluation of a novel passive sampling technique for monitoring volcanogenic hydrogen sulfide. *Journal of Environmental Monitoring, 6(7): 630-635.*

Horwell, C.J., Patterson, J.E., Gamble, J.A. and Allen, A.G., 2005. Monitoring and mapping of hydrogen sulphide emissions across an active geothermal field: Rotorua, New Zealand. *Journal of Volcanology and Geothermal Research, 139(3-4): 259-269.*

Inserra, S.G. et al., 2004. Neurobehavioral evaluation for a community with chronic exposure to hydrogen sulfide gas. *Environmental Research, 95(1): 53-61.*

Iremonger, S., 2004. NERMN Air Monitoring Review. ISSN 1175-9372.

Iremonger, S., 2008. NERMN Air Monitoring 2007.

Iremonger, S. and Graham, B., 2007. Rotorua Air Emissions Inventory 2005. In: E.B.o. Plenty (Editor). Environmental Publication.

Legator, M.S., Singleton, C.R., Morris, D.L. and Philips, D.L., 2001. Health effects from chronic low-level exposure to hydrogen sulfide. *Archives of Environmental Health, 56(2): 123-131.*

Logue, J.N., Ramaswamy, K. and Hersh, J.H., 2001. Investigation of Illness Associated with Exposure to Hydrogen Sulfide among Pennsylvania School Students. *Journal of Environmental Health, 63(6).*

Mongillo, M.A. and Bromley, C.J., 1992. A helicopter-borne video thermal infrared survey of the Rotorua geothermal field. *Geothermics, 21(1-2): 197-214.*

Mroczek, E.K., Stewart, M.K. and Scott, B.J., 2004. Chemistry of the Rotorua Geothermal Field Part 3: Hydrology, Environmental Bay of Plenty.

Mroczek, E.K., Stewart, M.K. and Scott, B.J., 2005. Chemistry of the Rotorua Geothermal Field. Environmental Publication 2005/12, Environmental Bay of Plenty.

Pearson, L.K., 2007. The Nature, Composition and distribution of sediment in Lake Rotorua, New Zealand, University of Waikato.

Petersen, J., Fisher, G.W. and Timpany, G., 1996. Survey of Background Hydrogen Sulphide in Rotorua -1996. AK96058, NIWA.

Petersen, J., Fisher, G.W. and Timpany, G., 1998. Survey of Background Hydrogen Sulphide in Rotorua - 1996/97. AK98013, NIWA.

Richardson, D.B., 1995. Respiratory effects of chronic hydrogen-sulfide exposure. *American Journal of Industrial Medicine, 28(1): 99-108.*

Ritter, J.M., 2010. Human pharmacology of hydrogen sulfide, putative gaseous mediator. *British journal of clinical pharmacology, 69(6): 573-575.*

Rogie, J.D., Kerrick, D.M., Sorey, M.L., Chiodini, G. and Galloway, D.L., 2001. Dynamics of carbon dioxide emission at Mammoth Mountain, California. *Earth and Planetary Science Letters, 188(3-4): 535-541.*

Roth, S.H. and Goodwin, V.M., 2003. Health Effects of Hydrogen Sulphide: Knowledge Gaps. Alberta Environment,http://environment.gov.ab.ca/info/library/6708.pdf.

Scott, B.J. and Cody, A.D., 2000. Response of the Rotorua geothermal system to exploitation and varying management regimes. *Geothermics, 29(4-5): 573-592.*

Siegel, S.M., Penny, P., Siegel, B.Z. and Penny, D., 1986. Atmospheric hydrogen sulfide levels at the sulphur bay wildlife area, Lake Rotorua, New Zealand. *Water, Air, & Soil Pollution, 28(3): 385-391.*

Symonds, R.B., Gerlach, T.M. and Reed, M.H., 2001. Magmatic gas scrubbing: implications for volcano monitoring. *Journal of Volcanology and Geothermal Research, 108(1-4): 303-341.*

The International Volcanic Health Hazard Network, 2009. Health effects of respiratory exposure to hydrogen sulphide http://www.ivhhn.org.

Timpany, G., 2007. Personal Communication.

Vasilakos, C., Maggos, T., Bartzis, J.G. and Papagiannakopoulos, P., 2005. Determination of Atmospheric Sulfur Compounds Near a Volcanic Area in Greece. *Journal of Atmospheric Chemistry, 52(2): 101-116.*

Viveiros, F., Ferreira, T., Cabral Vieira, J., Silva, C. and Gaspar, J.L., 2008. Environmental influences on soil CO2 degassing at Furnas and Fogo volcanoes (São Miguel Island, Azores archipelago). *Journal of Volcanology and Geothermal Research, 177(4): 883-893.*

Viveiros, F., Ferreira, T., Silva, C. and Gaspar, J.L., 2009. Meteorological factors controlling soil gases and indoor CO2 concentration: A permanent risk in degassing areas. *Science of the Total Environment, 407(4): 1362-1372.*

Wegműller, M. and Peterson, J., 1998. Method to quantify the H_2S - Exposure for the urban area of Rotorua. AK98024, NIWA.

Whiteford, P.C., 1992. Heat flow in the sediments of Lake Rotorua. *Geothermics, 21(1-2): 75-88.*

WHO, 2003. Hydrogen Sulfide: Human Health Aspects. *Concise International Chemical Assessment Document, 53.*

Woodall Jr, G.M., Smith, R.L. and Granville, G.C., 2005. Proceedings of the Hydrogen Sulfide Health Research and Risk Assessment Symposium October 31-November 2, 2000. *Inhalation Toxicology, 17(11): 593-639.*

Wood, C.P., 1992. Geology of the Rotorua geothermal system. *Geothermics, 21(1-2): 25-41.*