State of the Environment report: Air quality trends 2005 – 2023

June 2024

Otago Regional Council

Otago Regional Council
Private Bag 1954, Dunedin 9054
70 Stafford Street, Dunedin 9016
Phone 03 474 0827
Fax 03 479 0015
Freephone 0800 474 082
www.orc.govt.nz

Front cover image by Simon Darby.

Report writer: Sarah Harrison, Scientist – Air Quality, Otago Regional Council

Reviewed by: Tamsin Mitchell, Senior Environmental Scientist – Air Quality, Greater Wellington Te Pane Matua Taiao

Ben Mackey, Science Team Leader – Land, Otago Regional Council

Published 27 June 2024

The author would like to thank the ORC Environmental Monitoring team for the air quality data collection, verification and network oversight, and Tamsin Mitchell for her technical input into the data analysis.

Executive summary

Otago Regional Council (ORC) operates a State of the Environment (SOE) air quality monitoring network. The aims of the programme include reporting data in accordance with the National Environmental Standards for Air Quality (NESAQ) and the Resource Management Act (RMA), and to develop understanding of the influences of emissions and meteorology on pollutant concentrations. Over the past 20 years this monitoring has focused on PM_{10}, small particles with a diameter of less than 10 micrometres.

This report evaluates the air quality monitoring results for the period of 2005 – 2023, with particular emphasis on the long-term trends to provide up to date analyses for the review of the Regional Plan: Air.

Particulate matter is highly seasonal in Otago in most areas. High PM_{10} concentrations are observed in many towns during winter months, which is caused by home heating emissions combined with calm weather and temperature inversions. Airsheds such as Alexandra, Arrowtown and Mosgiel regularly exceed the National Environmental Standard for Air Quality (NESAQ) for PM_{10}. This extreme seasonality means that non-winter concentrations are low, and all sites are currently meeting the annual Ambient Air Quality Guideline (AAQG).

Long-term trend analysis indicates that PM_{10} concentrations have improved in Arrowtown, Central Dunedin, Clyde, Cromwell, Milton, and to a lesser degree, Mosgiel. In Alexandra, PM_{10} analysis indicates concentrations show an increasing trend, however further data is required to confirm this.

The results of this report will be used to inform future work on air quality strategy and policy in Otago.

Contents

List of figures

List of tables

Glossary

AAQG	Ambient Air Quality Guidelines (2002)
Airshed	Area designated by a regional council for air quality management
BAM	Beta Attenuation Monitor
Exceedance	Where a contaminant exceeds its threshold concentration
MfE	Ministry for the Environment
NESAQ	National Environmental Standard for Air Quality (2004)
PM	Particulate Matter
$PM_{2.5}$	Particulate matter less than 2.5 µm in diameter
PM_{10}	Particulate matter less than 10 µm in diameter
µm	Micrometre, one millionth of a metre
$\mu g/m^3$	Microgram per cubic metre, unit of concentration
WHO	World Health Organization

1. Introduction

Clean ambient air is a fundamental resource for human health and the natural environment. Ambient air quality is affected by the amounts and types of pollutants that are emitted into air, and the meteorological conditions that impact their dispersion. Otago has a varied and complex topography, producing varying climate zones from alpine to coastal environments.

Of the ambient air pollutants commonly monitored in New Zealand, particulate matter (PM) is the biggest concern in Otago, with some airsheds regularly failing to meet national standards. The main emission source of PM in Otago is solid fuel burning for home heating, with lesser additional influence from vehicle emissions, industry, outdoor burning, and natural sources (Wilton, 2019).

This report evaluates the long-term trends of the SOE monitoring results for 2005 – 2023.

1.1. Purpose of this report

This report aims to:

- Report and evaluate the long-term trends for PM_{10}, providing the most recent analysis for the review of Otago's Regional Plan: Air.
- Inform future policy and strategy work for Otago.

1.2. Scope and outline

This report presents and analyses data collected by the monitoring network for the since 2005.

The following sections are included in this report:

- Section 2 describes the current air quality assessment framework.
- Section 3 describes Otago's monitoring network.
- Section 4 provides analyses of the temporal trends in air quality.
- Section 5 discusses the results of the analyses.

2. Air quality assessment framework

2.1. National air quality indicators

The National Ambient Air Quality Guidelines (AAQG) were first established in 1994 by the Ministry for the Environment (MfE), based on international public health information (MfE, 2002). The AAQG was revised in 2002, which recommended limits on concentrations for certain ambient air pollutants.

In 2004 the National Environmental Standards for Air Quality (NESAQ) were adopted (revised in 2011) and established mandatory minimum requirements for five pollutants – PM_{10}, nitrogen dioxide (NO_2), sulphur dioxide (SO_2), carbon monoxide (CO) and ozone (O_3). The objectives of these standards are to provide an acceptable level of protection to human health and the environment. These standards are currently being revised to include $PM_{2.5}$ (particulate matter with a diameter of less than 2.5 micrometres). Table 1 provides the current ambient air quality standards and guidelines for PM_{10}.

Pollutant	Limit type	Threshold concentration (µg/m^3)	Averaging period	Number of allowable exceedances
PM_{10}	Standard	50	24-hour	1 per year
	Guideline	20	Annual	n/a

Table 1 New Zealand standards and guidelines for particulate matter

2.2. Ambient pollutants

2.2.1. Particulate matter

Particulate matter (PM) refers to particles, or aerosols, suspended in the atmosphere. PM can be natural or anthropogenic in origin and can either be directly emitted or formed in the atmosphere as a result of chemical reactions between other pollutants. PM therefore occurs in a range of sizes and chemical compositions. PM can be classified by size – fine and coarse. Fine particulate matter consists of particle sizes up to 2.5 µm in diameter ($PM_{2.5}$). Coarse particulate matter is the group of particles with diameter sizes between 2.5-10 µm. PM_{10} is the fine and the coarse fractions combined.

Fine particulate matter, or $PM_{2.5}$, is mainly a result of incomplete combustion such as vehicle emissions, and the combustion of wood and coal for industry or heating. It is comprised of organic and inorganic compounds, metals and black carbon (soot). These particles can remain suspended in the air for many days and can be transported hundreds of kilometres.

Coarse particulate matter ($PM_{2.5-10}$) is a product of mechanical forces such as wind erosion, crushing and abrasion. Natural sources include pollen, soils and sea salt. Anthropogenic sources include dust suspended from roads and industrial activity. Coarse PM tends to fall out of suspension within minutes or hours and can travel up to 50 kilometres from the source.

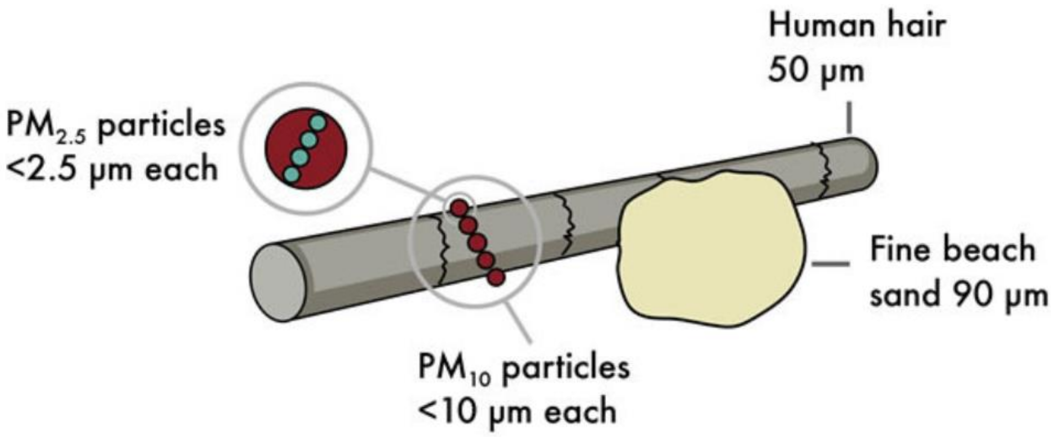


Figure 1 **Comparison of particle sizes. Source: Ministry for the Environment**

While ORC has largely focused on monitoring PM_{10} in the past, it is worth noting that during wood burning seasons, the majority of the PM_{10} particles are made up of the smaller fractions, $PM_{2.5}$ and smaller.

2.2.2. Particulate matter health impacts

Both short and long-term exposure to particulate matter can cause and exacerbate serious health issues, specifically to the respiratory and circulatory systems. The most vulnerable to PM are the young, the elderly and anyone with pre-existing conditions. Fine and ultra-fine (PM_1 and smaller) are the most dangerous as smaller particles can penetrate the respiratory system further and enter the blood stream (WHO, 2013). Currently there is no established safety threshold for particulate matter.

In 2022 the Health and Air Pollution New Zealand study (HAPINZ), which models the impact of air pollution exposure on health and subsequent social costs, was updated for the year 2016. It was found that the overall social cost to New Zealand, including premature deaths, decreased quality of life and lost productivity was $15.6 billion in 2016. The main sources of harmful air pollution were traffic emissions (nitrogen dioxide, NO_2[1]) and home heating emissions ($PM_{2.5}$). The below graph (Figure 2) shows the number of hospitalisations and premature deaths attributed to air pollution in Otago for 2016. In addition to these health impacts, the number of asthma cases attributed to NO_2 was 410 and the number of reduced activity days due to $PM_{2.5}$ was 217, 332.

[1] In Otago nitrogen dioxide was monitored between 1997 and 2004, and again in 2021 and was found to be compliant with the NESAQ. The results of the HAPINZ report and the updated WHO guideline (40 µg/m³ annual limit) indicate the importance of further monitoring NO_2, as health impacts are occurring at lower pollutant concentrations than previously realised.

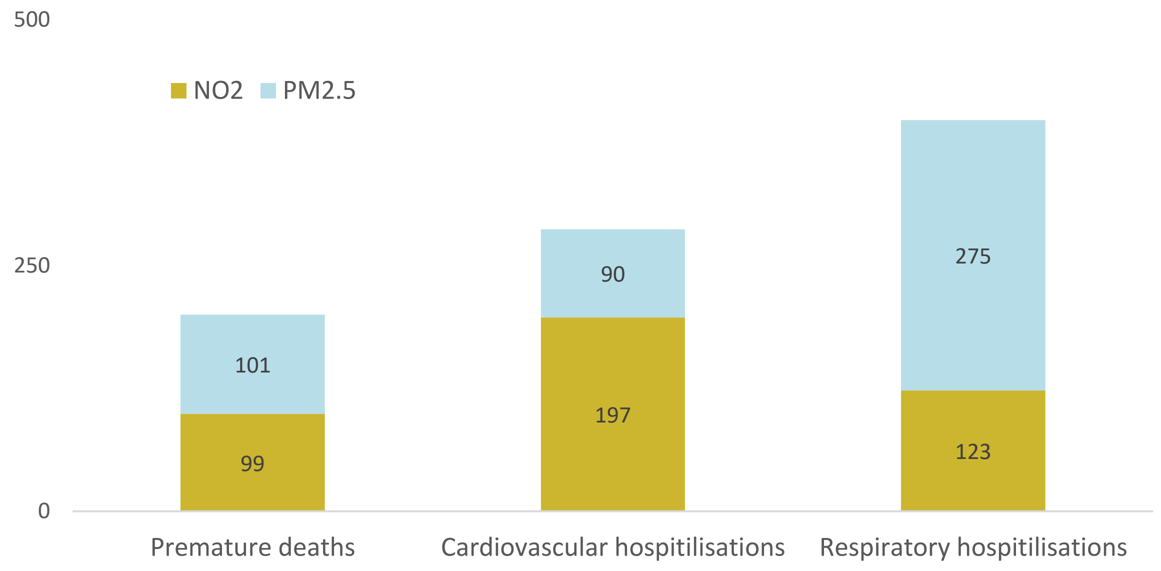


Figure 2 **Health impacts of $PM_{2.5}$ and nitrogen dioxide in Otago for 2016, data source: HAPINZ 3.0, (Kuschel, *et. al.,* 2022).**

2.3. Pressures and influences on air quality

Ambient air quality at any location is the result of a complex relationship between emissions and meteorology. Anthropogenic emission sources include home heating, vehicle exhaust, industrial and commercial discharges and outdoor burning. Local meteorology and long-term climate help determine how pollution accumulates or disperses and can have a greater influence on ambient air quality than emission quantities do. Temperature inversions in the atmosphere are common in many Otago towns during winter, which vastly limits the dispersion of PM and causes degraded air quality.

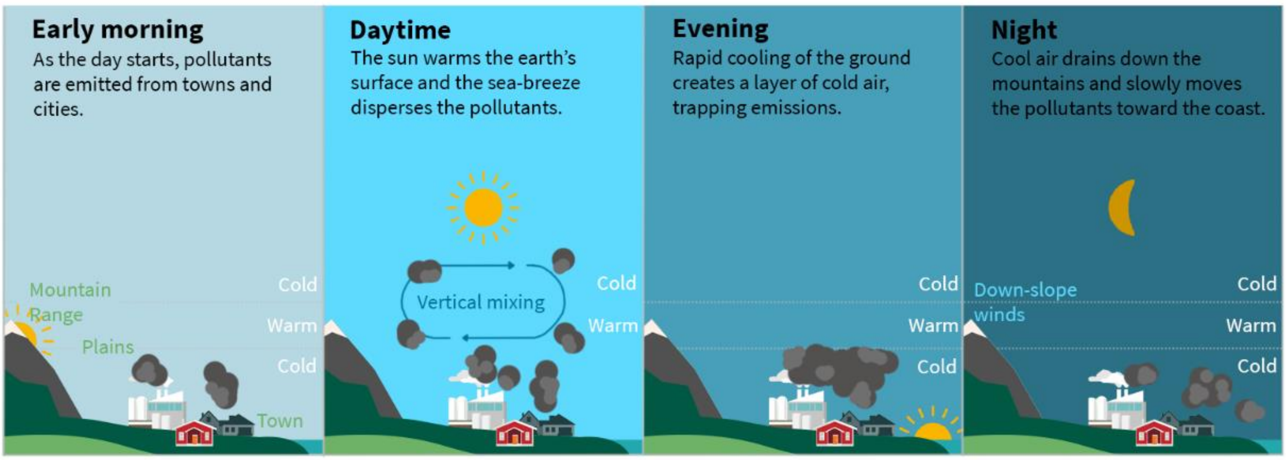


Figure 3 **Temperature inversion. Source: LAWA**

Emissions inventories estimate the total emissions for a town using information such as fuel types, burner types and age, fuel usage, and census data for domestic emissions, and consents and traffic data for industrial and vehicle emissions. The emissions inventories that have been undertaken in Otago show that solid fuel burning for domestic heating is the source of most of the PM, up to 90% in some towns (Wilton, 2019).

The 2018 census data showed that the use of wood burners was reported in 51% of households in Otago, which is much higher than the national average of 31% (Stats NZ, 2020), and a general trend in many Otago towns is that the number of wood burners has increased due to urban development (Harrison, 2021).

The emissions inventories carried out in Otago have provided the following trend estimates of total PM_{10} emissions for Otago towns (Table 2). These reductions were attributed to the reduction in the use of coal for domestic heating and the replacement of older burners to those compliant with the NESAQ. In Mosgiel approximately a third of emissions reductions were due to industry closure or transitioning to cleaner fuels (Wilton, 2016).

Town	2005 total emissions (kg/day)	2016 total emissions (kg/day)	% decrease
Alexandra	367	171	51%
Arrowtown	183	94	48%
Milton	250	119	50%
Mosgiel	533	271	49%

Table 2 Emissions (kg/day) in Otago airsheds

Between 2008 and 2020 ORC undertook an incentive (Clean Heat Clean Air subsidy to replace older solid-fuel burners with cleaner heating options) to help Otago residents replace older burners in Alexandra, Arrowtown, Clyde, Cromwell and Milton. Analysis of these results indicated that there were positive influences on air quality, in terms of number of exceedances and annual and winter averages, but these improvements were strongest during the most active phases of the programme, in the years prior to 2013 (Mills, 2018).

Emissions sources and quantities and meteorology are discussed in further detail in previous SOE reports (Harrison, 2021 and Mills, 2016).

2.4. International air quality indicators

New Zealand standards and guidelines have in the past been consistent with the World Health Organization (WHO) recommendations (WHO, 2006) for PM. However, in 2021 WHO released updated guidelines based on more recent research that confirms pollutants are more harmful at lower concentrations than previously thought. Table 3 lists the WHO guidelines for PM.

Pollutant	Threshold concentration (µg/m3)	Averaging period
$PM_{2.5}$	15	24-hour
	5	annual
PM_{10}	45	24-hour
	15	annual

Table 3 World Health Organization guideline values for PM_{10} and $PM_{2.5}$

2.5. Otago airshed management

2.5.1. Airsheds

Otago Regional Council gazetted 22 airsheds in 2005 in accordance with NESAQ requirements. The airsheds are ranked from Airshed 1 (most degraded air quality) to Airshed 4 (not expected to be degraded). Twenty-two towns and cities have been allocated one of these four airsheds (Figure 4). Rural areas outside of town boundaries are considered to be a fifth airshed, where air quality is expected to be acceptable.

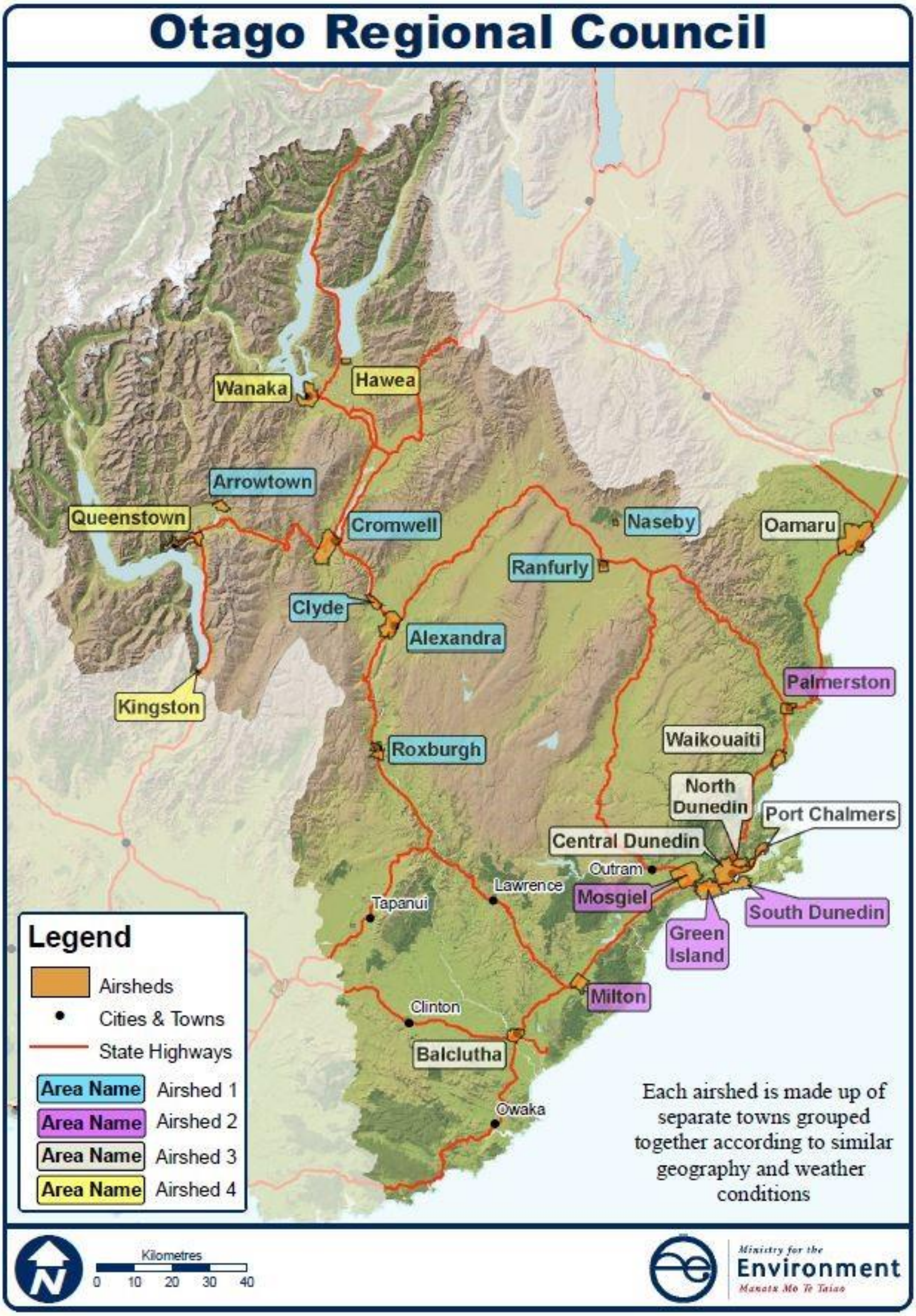


Figure 4 **Otago Regional Council gazetted airsheds**

3. Air quality monitoring network

3.1. Background

ORC operates a long-term air quality monitoring network in the region. Monitoring began in 1997, and since that time ambient pollutants PM_{10}, $PM_{2.5}$, NO_2, SO_2 and CO have been monitored in various locations throughout Otago at various times. Most of the monitoring performed over the last 15 years has been in response to the requirements of the NESAQ, with a focus on particulate matter.

Otago's large area and wide distribution of population centres set amongst varying terrain and climate make it challenging to provide a true and complete representation of ambient air quality. Where possible, monitoring sites are situated in accordance with the NESAQ; in places where the standard is breached by the greatest margin or frequency.

3.2. Monitoring objectives

The objective of Otago's air quality monitoring programme is to provide scientifically robust data for the following purposes:

- To manage the region's air resource
- To measure the effects of ORC's air quality management initiatives
- To fulfil the statutory requirements of the Resource Management Act 1991 (RMA)
- To measure and report on compliance with the NESAQ

A range of monitoring activities and investigations are needed to fulfil these objectives. In addition to continuous site monitoring, other activities include emissions inventories, source apportionment studies, spatial investigations, and screening studies of other pollutants such as nitrogen dioxide, sulphur dioxide and carbon monoxide.

3.3. Monitoring programme

There are two types monitoring site used in the air quality monitoring network:

[1] Regulatory monitoring at long-term sites that run continuously in Alexandra, Arrowtown, Central Dunedin and Mosgiel, referred to as key indicator sites. Results from these sites are used to report compliance with NESAQ.

[2] Survey monitoring was performed at sites that ran during winter months only, Clyde, Cromwell and Milton (there was also a site at Balclutha until 2018, and results for this site are analysed in the previous SOE reports). Results are used to quantify air quality during winter and assist in tracking trends. Table 3 lists the monitoring history for 2005 – 2023.

Airshed	Site	Purpose	Length of record
1	Alexandra	Regulatory	2005 - 2016 2017 - 2023
	Arrowtown		2007 - 2014 2014 - 2023
	Clyde	Winter survey	2008 – 2020*
	Cromwell		2008 – 2021*
2	Milton		2008 – 2021*
	Mosgiel	Regulatory	2008 - 2023
3	Central Dunedin		2006 - 2023

*All winter survey EBAMs were replaced in 2020/2021 with MetOne ES642 sensors to measure $PM_{2.5}$ instead of PM_{10}.

Table 4 Air monitoring sites and their purpose in the network

3.4. Monitoring methods

3.4.1. Particulate matter monitoring and measurement

PM_{10} was monitored using two types of beta attenuation monitor (BAM), manufactured by Teledyne in the USA. BAMs measure the particle mass density by comparing the sample deposited on the filter tape with the blank tape; as the particle mass increases, the beta count decreases. Standard sampling methods are required for reporting for compliance with the NESAQ. The BAM1020 is accepted by the US Environmental Protection Agency (USEPA) as an equivalent reference method for measuring PM_{10}. BAM1020 were used at the Alexandra, Arrowtown, Central Dunedin and Mosgiel sites.

The survey sites were monitored using an Environmental Beta Attenuation Monitor (EBAM). The EBAM is not considered an equivalent reference method, and as such, cannot be compared against the NESAQ, but it is designed to provide accurate PM_{10} averages and can be used for trend analysis. All stations are sited and operated where possible, using ASNZS 3580.1.1:2016 Methods for sampling and analysis of ambient air – Guide to siting monitoring equipment.

3.4.2. Meteorological monitoring and measurement

Air temperature, wind speed and wind direction all influence the accumulation and dispersion of pollutants. These parameters were recorded continuously at the PM_{10} monitoring sites in order to describe localised meteorological effects on PM_{10}.

Figure 5 **ORC air quality monitoring station at Arrowtown, with particulate matter instrument inlets circled in red, and the meterological sensors circled in yellow.**

4. Particulate matter trends

Air quality varies greatly temporally over short and long-term time periods. Day to day variability is often due to weather effects such as temperature and wind speed. Seasonal variability is driven by changes in sources, such as the increase of home heating emissions in winter.

Long term trends in air quality are affected by regulatory requirements, changes to fuel choices and burner technology over time, the addition or removal of point sources of emissions, and natural variability of long-term climate patterns (e.g., El Niño Southern Oscillation).

4.1. Compliance with standards and guidelines

4.1.1. 24-hour PM_{10} standard

The following table shows the number of NESAQ exceedances, defined as the number of days the daily average PM_{10} exceeded 50 µg/m³.

Year	Alexandra - 65 Ventry Street	Alexandra - 5 Ventry St	Arrowtown - School	Arrowtown - Alexander Street	Central Dunedin	Mosgiel
2005	42					11
2006	45		17		6	8
2007	33		39		1	4
2008	74		38		9	9
2009	40		31		6	7
2010	51		39		11	8
2011	40		27		14	8
2012	40		24		1	N/A*
2013	46		15		1	5
2014	51			48	0	5
2015	22			30	0	7
2016	38			32	0	9
2017		3		45	0	9
2018		2		29	1	4
2019		6		19	0	4
2020		6		25	0	5
2021		3		23	1	4
2022		4		12	0	1
2023		3		10	0	4

*Data was not recorded during winter months

Table 5 Number of NESAQ exceedances for key indicator sites

The Alexandra at 65 Ventry Street site has the highest number of exceedances, with 74 during 2008. The fewest exceedances occurred in 2015, with 22. Since the site was relocated in 2017, the number of exceedances has been much lower, with between 2 and 6 exceedances occurring each year. The differences between sites are due to spatial differences in concentrations (Longley, 2023) and increased wind dispersion at the current site (ORC, 2021). The difference in concentrations between the two sites is approximately 23% (Longley, 2023).

For Arrowtown, the highest number of exceedances occurred in 2014, the first year the site was relocated to its current location, with 48 exceedances. Since then, the number of exceedances has trended downwards.

The number of NESAQ exceedances occurring in Central Dunedin has decreased over time. Since 2012, the site has recorded at most, one exceedance every few years, which complies with the NESAQ.

The Mosgiel site's number of exceedances has stayed within the same range of between four and 11 since 2005, excepting 2022 where there was only one. The highest frequency of exceedances (11) occurred in 2005.

An overall trend for all sites is that the years 2018-2023 have fewer exceedances than previous years.

4.1.2. Annual PM_{10} guideline

The graph below shows the annual averages of the regulatory sites relative to the AAQG and WHO 2021 guidelines of 20 and 15 µg/m³, respectively.

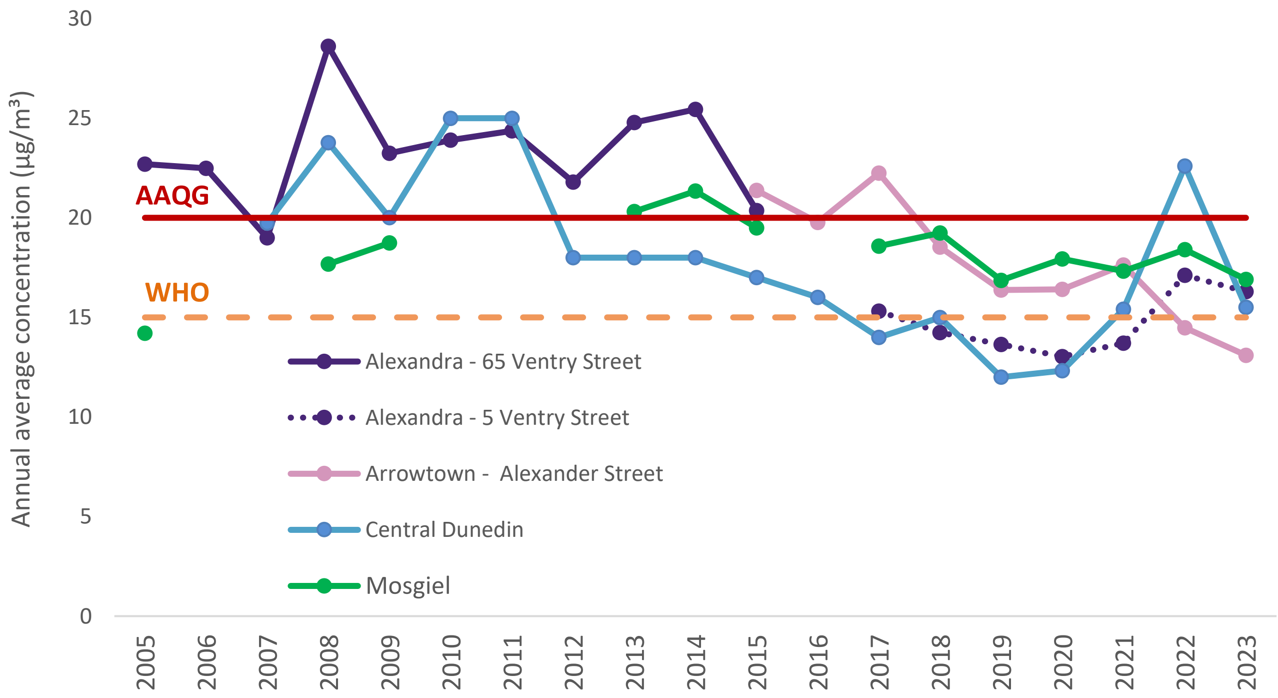


Figure 6 **Annual average PM_{10} concentrations (µg/m³) for key indicator sites**

The annual data for the 65 Ventry Street site in Alexandra frequently exceeded the guidelines with peak concentration recorded in 2008. Since the site was moved to 5 Ventry Street, the data met both guidelines for the years 2018 to 2021 but exceeded the WHO guideline for 2022 and 2023.

Arrowtown annual averages have trended downwards and since 2018 has complied with the AAQG and met the WHO guideline in 2022 and 2023.

Since 2012 Central Dunedin has met the AAQG, and between 2017 and 2020, also met the WHO 2021 guideline. The annual average for 2022 increased to exceed both guidelines, and it is thought that the data was impacted by significant construction occurring at the site.

The Mosgiel site has been compliant with the AAQG from 2015 onwards, however has not met the WHO guideline during this time.

4.2. Short-term temporal trends

Short-term spatial trends can show the different emission sources and characteristics in the airsheds. The patterns in PM concentrations can be seen at various timescales, i.e., hourly, daily, weekly and seasonal. Figure 7 shows the four key indicator sites for the years 2017 – 2023. All four sites have different patterns over the different timescales. The Central Dunedin site shows daily and weekday patterns most consistent with traffic and industrial emissions, with an increase in PM_{10} concentrations between 6:00 and 8:00 in the morning and slow decline in the evening; consistent through the week but much lower on weekends. This site doesn't have a seasonal pattern, unlike the other three sites.

Alexandra and Arrowtown have strong seasonal patterns, with the highest concentrations occurring over winter months, and very strong home heating signatures (morning and evening peaks) in the daily plot. Mosgiel has a combination of the two of these patterns, it exhibits slightly weaker seasonal and daily patterns because it has a combination of PM_{10} sources, including home heating emissions, traffic and industrial (Figure 7).

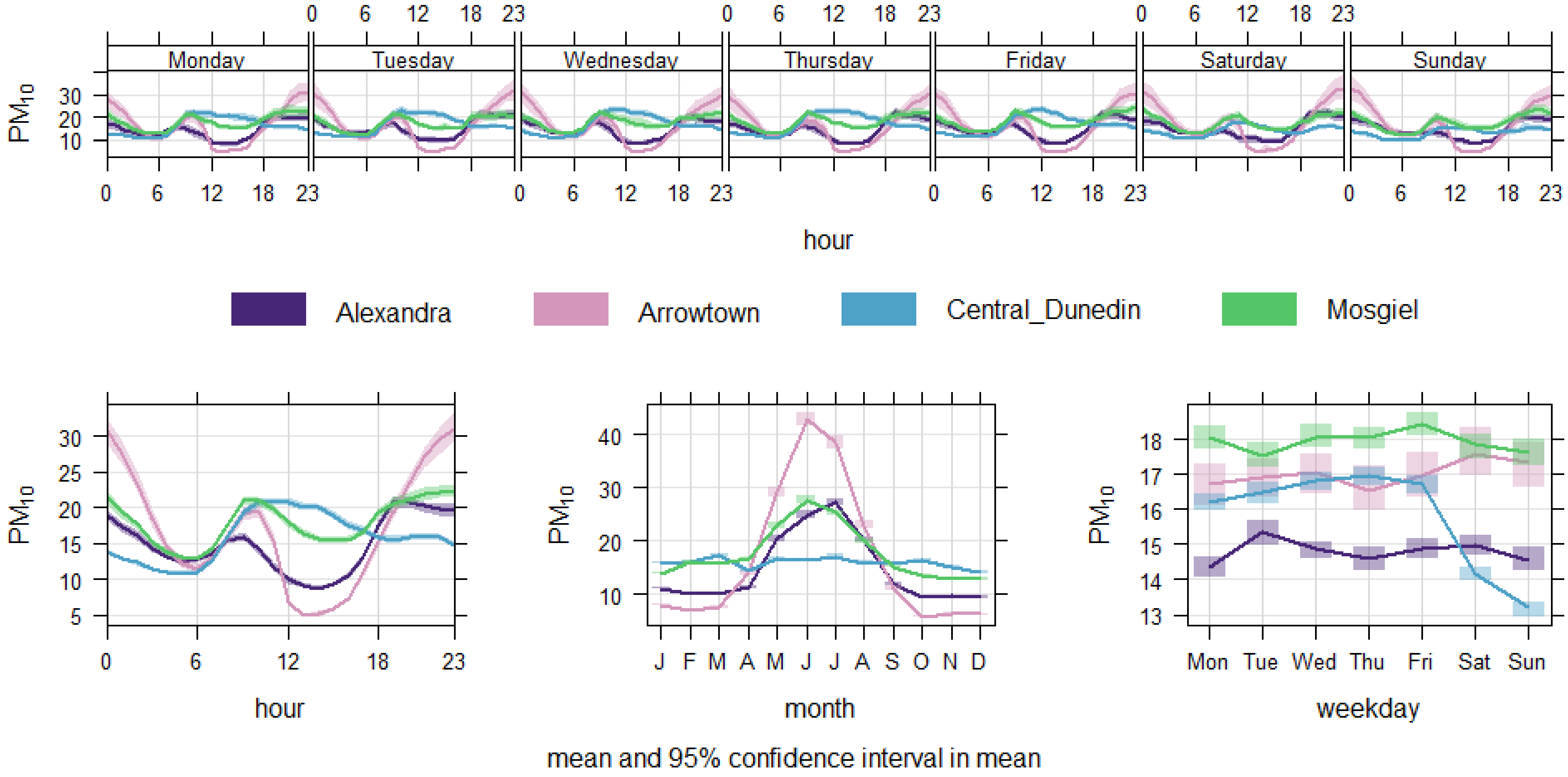


Figure 7 **Daily, monthly and week day patterns for the key indicator site**

4.3. Long-term temporal trends

4.3.1. Trend visualisation

Long-term data can be visualised in a trend level graph, which plots the concentrations by time of day, month and year. In these trend level graphs the PM_{10} concentrations are represented by colours ranging from blue (low concentrations) to red (high concentrations). Figures 8 to 11 show the trend level plots for Alexandra, Arrowtown, Central Dunedin and Mosgiel.

For Alexandra, the highest concentrations occur during morning and night in winter however there is a background concentration of between 10 and 20 µg/m³ during morning and evening hours and non-winter months (Figure 8).

At Arrowtown the winter months are clearly highlighted with high concentrations for the morning and evening hours. These peak concentrations are lower in 2021 and 2022 (Figure 9).

For Central Dunedin there are no clear seasonal patterns, however on a daily basis, the highest concentrations occur from 8am onwards. This graph also shows that concentrations were frequently above 50 µg/m³ prior to and including 2011 (Figure 10). The 2022 year also stands out as having higher concentrations than preceding years and this is discussed in section 4.3.2.

The trend level plot for Mosgiel shows the complexity of this airshed (Figure 11). Across the years for every month there is a slight increase in concentrations at around 8 am in the morning, which indicates a traffic influence. This plot also shows the seasonal home heating concentrations occurring in winter at morning and evenings.

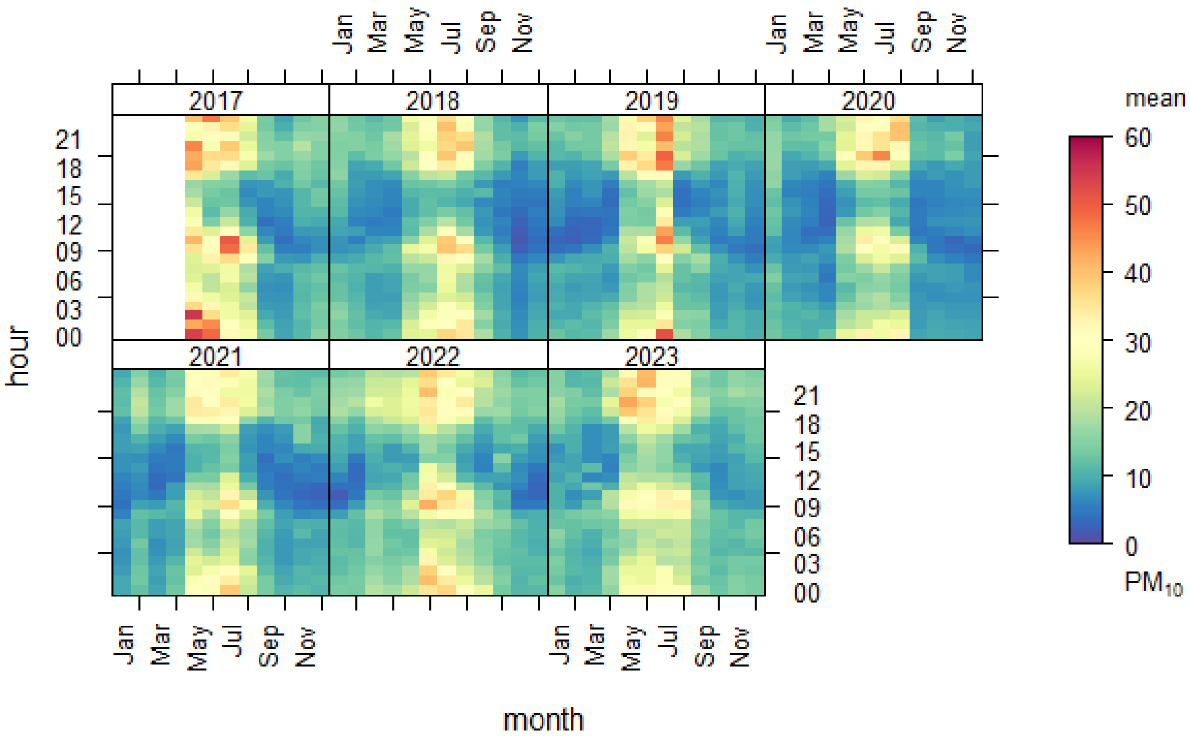


Figure 8 **Trend level plot for Alexandra PM_{10}**

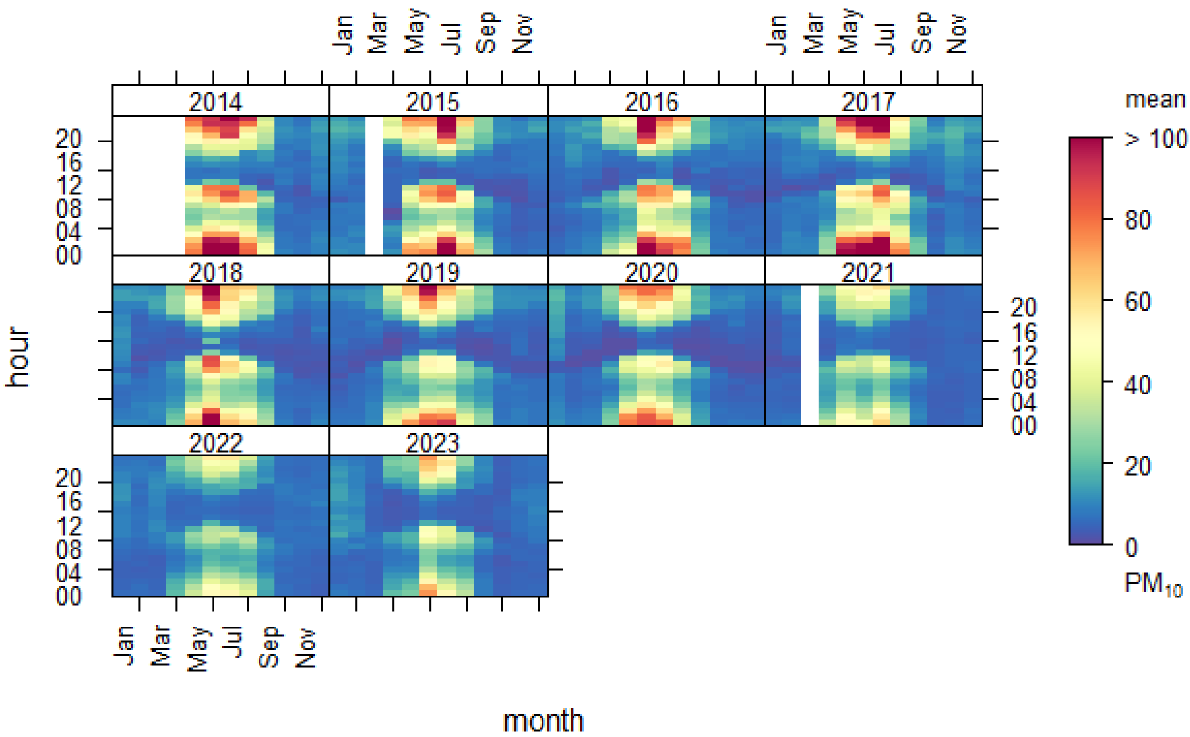


Figure 9 **Trend level plot for Arrowtown PM_{10}**

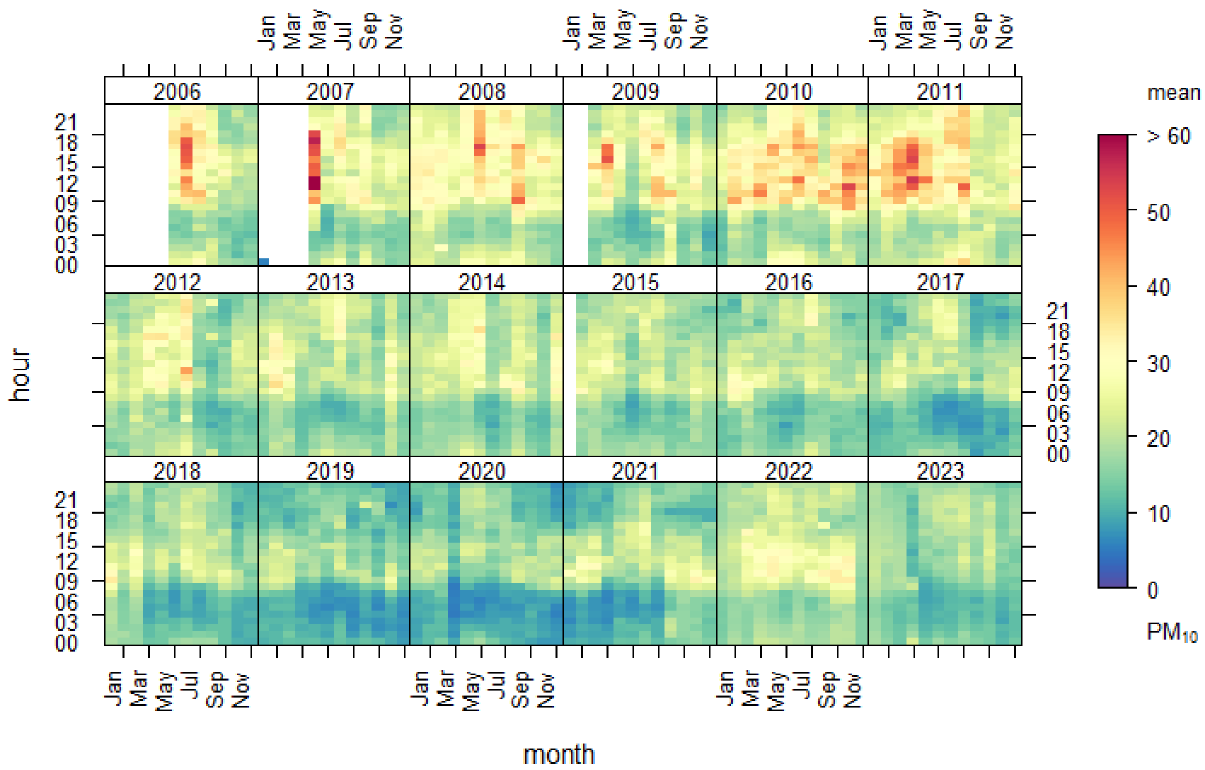


Figure 10 **Trend level plot for Central Dunedin PM_{10}**

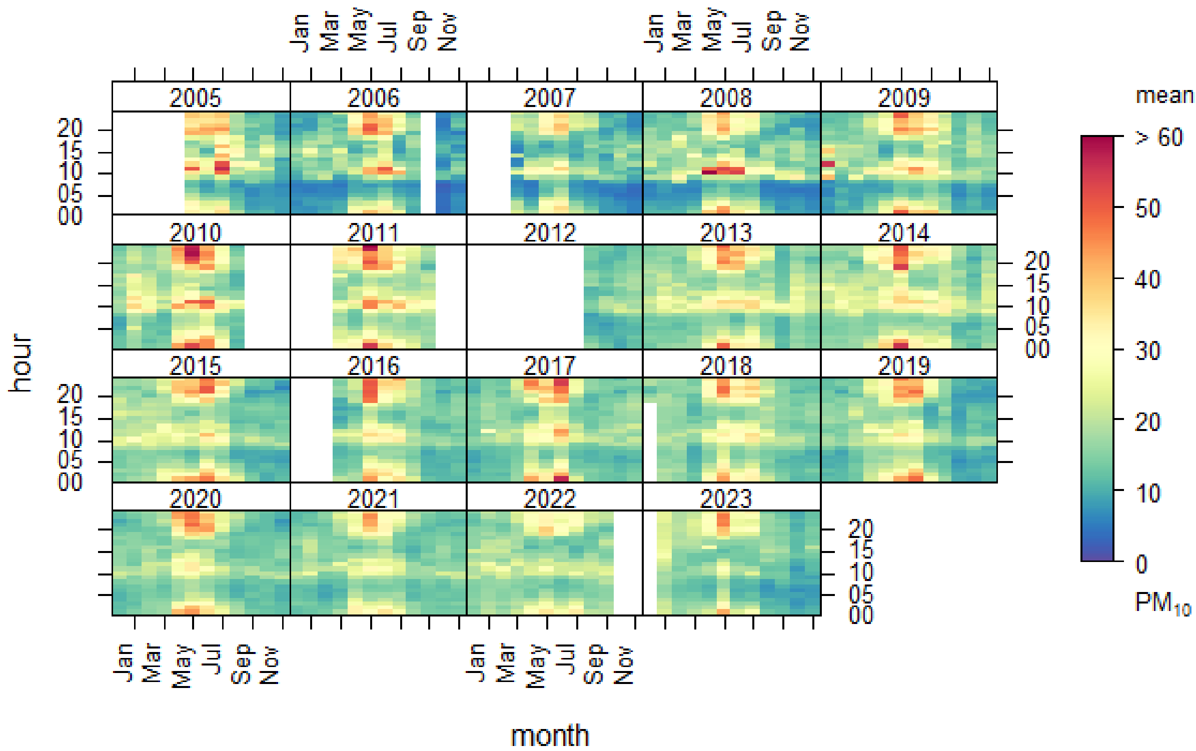


Figure 11 **Trend level plot for Mosgiel PM_{10}**

Figures 11 to 13 show the trend levels for Clyde, Cromwell and Milton. Like Arrowtown, the Clyde trend level plot shows high winter concentrations, as well as the slow progression from higher to lower concentrations through the years (Figure 12).

The Cromwell trend level plot is also very similar however it does have higher concentrations than Clyde, especially during the evening hours. The years 2018-2020 are significantly lower in terms of evening concentrations than the preceding years (Figure 13).

The trend level for Milton is also similar to the other winter-only sites. In contrast to Clyde and Cromwell, the PM_{10} concentrations remain very high in the early hours of the morning, particularly for the years prior to 2018 (Figure 14).

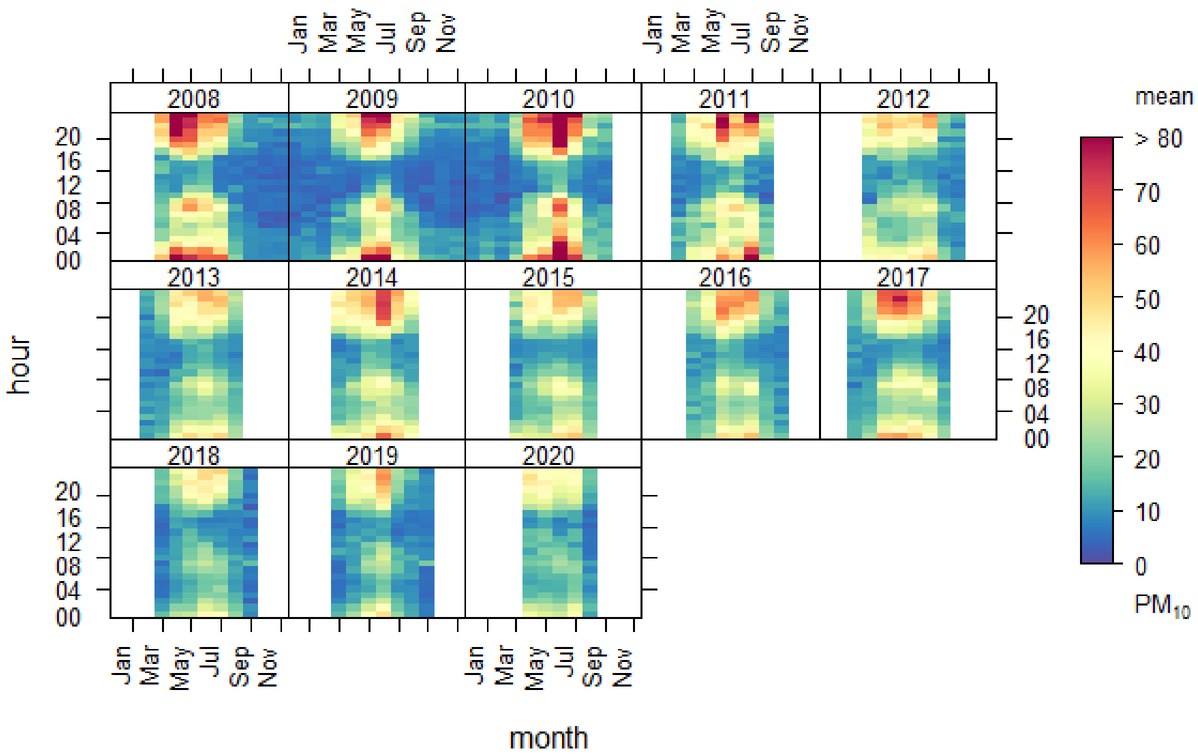


Figure 12 **Trend level plot for Clyde PM_{10}**

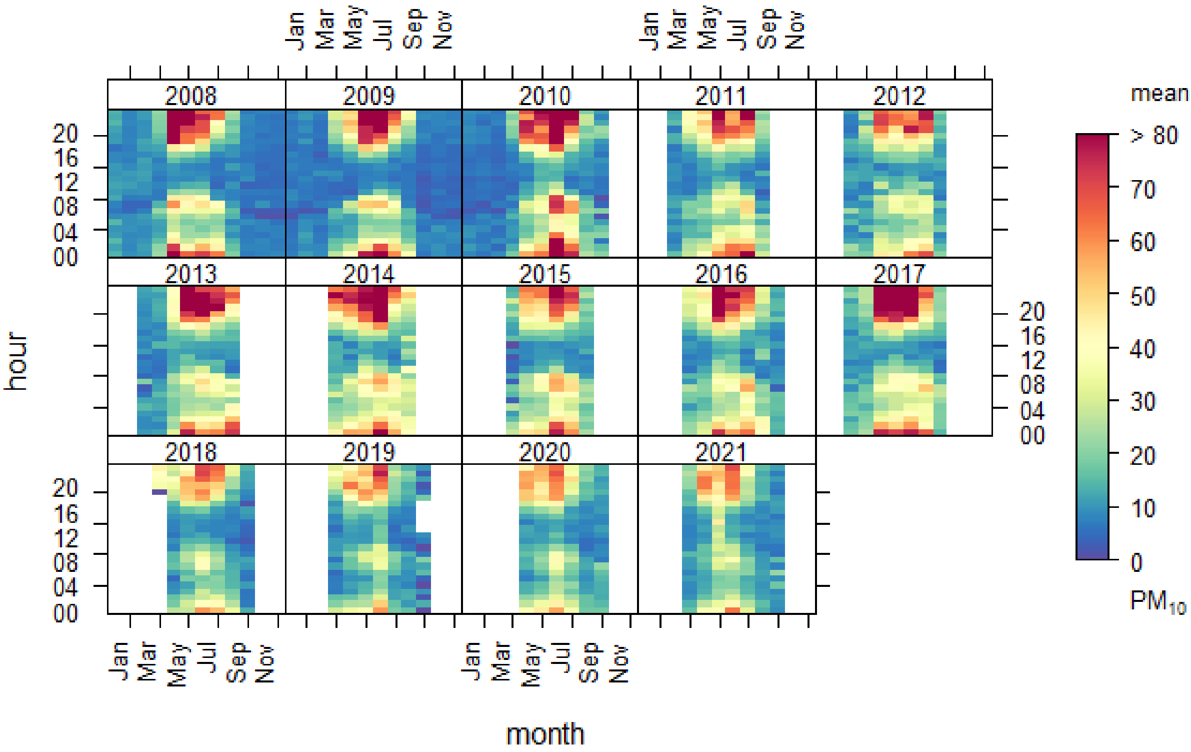


Figure 13 **Trend level plot for Cromwell PM_{10}**

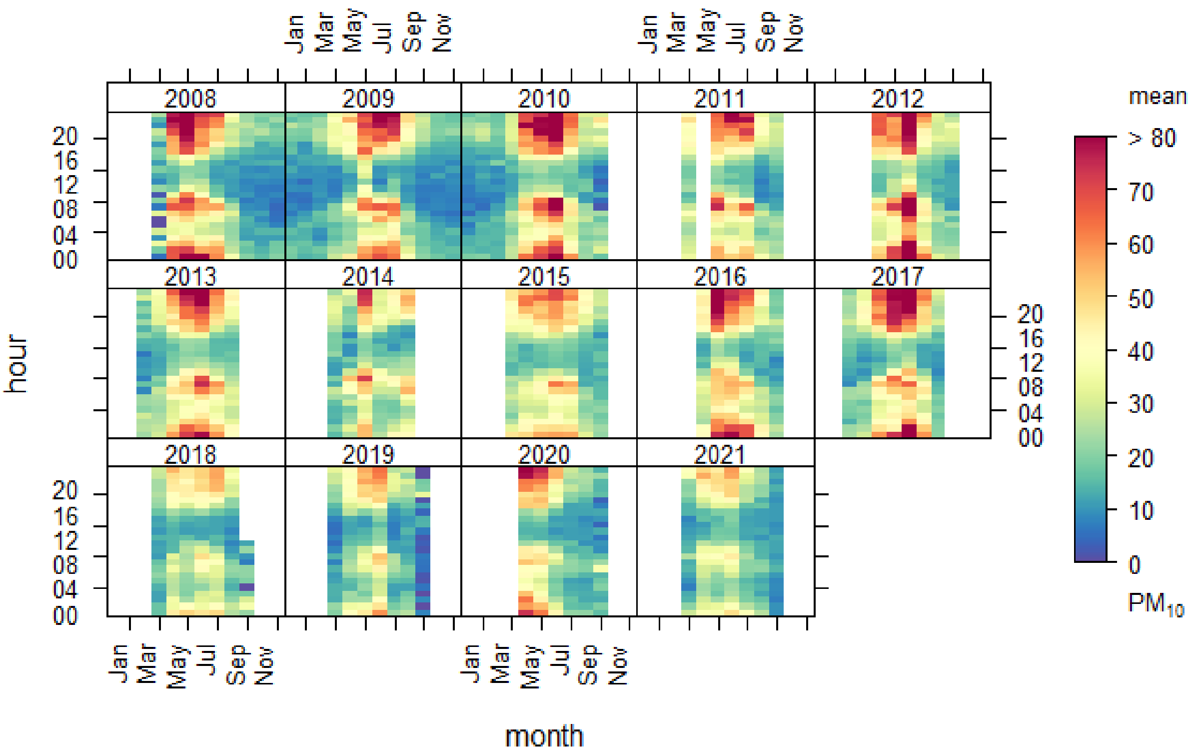


Figure 14 **Trend level plot for Milton PM_{10}**

4.3.2. Dunedin data

As discussed in the previous sections the construction of a building (including the demolition of the previous building) was occurring adjacent the Dunedin site from September 2021 to November 2022 and this resulted in higher-than-normal PM_{10} concentrations, likely due to suspension of dust and emissions from construction vehicles. The below graph shows the difference between the data prior to (2017-2021) and during the construction/demolition process. The daily and week-day patterns have the same shape, but with a difference of approximately 5 µg/m³ (Figure 15).

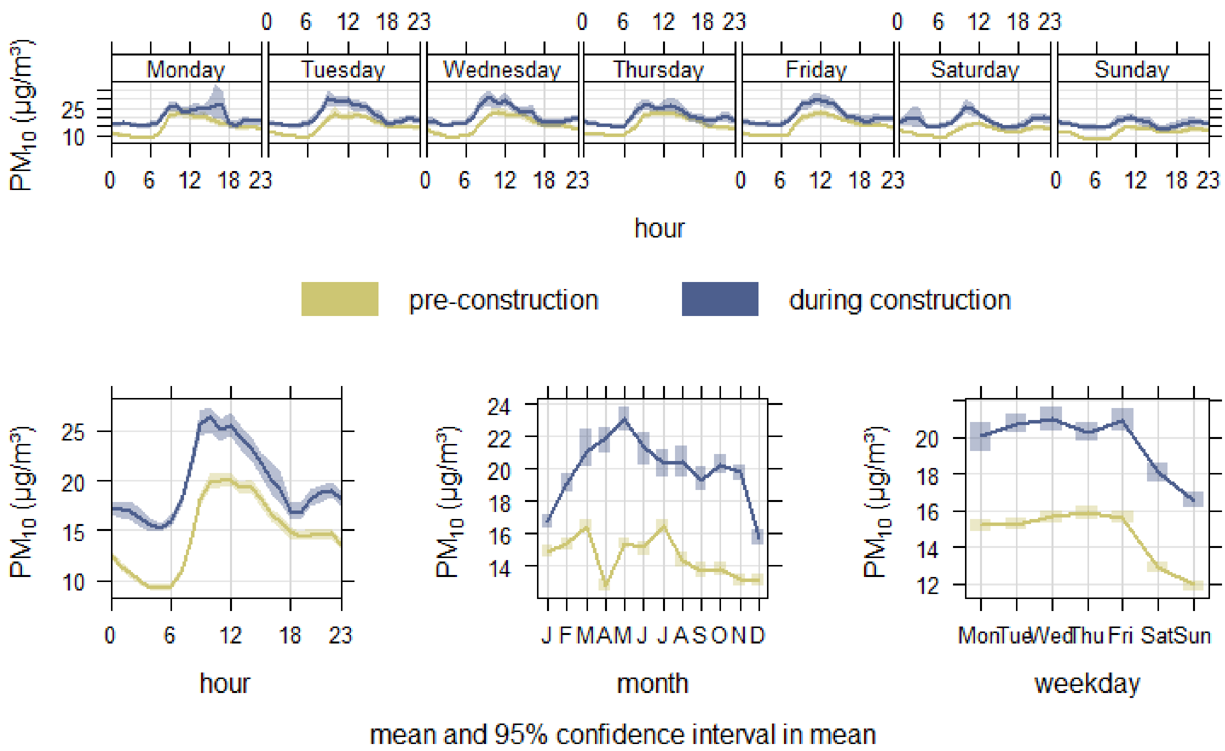


Figure 15 **Time variation of the Dunedin site showing impact of local construction on PM_{10} concentrations.**

4.3.3. Trend analyses

Statistical testing can be used to determine overall increasing or decreasing trends of long-term air quality data. It provides a p-value, that represents the probability that random chance could explain a change in ambient air quality. A p-value of 0.1 suggests that we are 90% confident that the changes observed in PM_{10} are not due to chance. For this report trend analyses were performed at all sites for all available data. However, some sites have been re-located to an area with different typical concentrations within this timeframe, such as at Alexandra and Arrowtown. Trend analysis can only be performed on some of the years due to these differences.

Trends were evaluated using two types of techniques – the Theil-Sen and the smooth-trend. The Theil-Sen is a non-parametric regression analysis customised for air quality data (Carslaw and Ropkins 2012). Theil-Sen analyses work best when applied to monotonic trends i.e., data that is either only increasing or only decreasing, and is best performed on continuous data with data gaps of less than five months duration, and complete start and end years (NAQWG, 2024).

The smooth-trend analysis fits a smooth line to the dataset using monthly mean concentrations. The line is fit to show important features and variation within the data without including excessive noise from the dataset (Carslaw *et al.,* 2014). Both analyses can be applied to deseasonalised data, which means to remove the seasonal variation, so underlying trends can be assessed. The Alexandra, Arrowtown and Mosgiel sites were deseasonalised for the following analyses.

4.3.4. Trend results

Theil-Sen analyses were done for the key indicator sites Alexandra, Arrowtown, Central Dunedin and Mosgiel. Table 6 shows the results of these analyses.

Site		Trend period	Average % change per year [confidence intervals]	Significance
Alexandra 5 Ventry Street	Year-round	2018-2023	3.2, [1.2, 5.6]	$p < 0.001$
	Winter	2017-2023	-0.4 [-4.7, 4.3]	no trend
Arrowtown	Year round	2015-2023	-6.2 [-6.4, -5.9]	$p < 0.001$
	Winter	2015-2023	-6.1 [-6.5, -5.7]	$p < 0.001$
Central Dunedin	Year round	2008-2023	-3.1 [-3.6, -2.6]	$p < 0.001$
Mosgiel	Year round	2013-2023	-1.8 [-2.2, -1.5]	$p < 0.001$
	Winter	2013-2023	-2.4 [-3.4, -0.7]	$p < 0.01$

Table 6 Theil-Sen analysis results of PM_{10} monthly means at the key indicator sites

The Alexandra data shows a degrading trend for year-round data, with an increase of 3.2% per year. There is no trend when the winter data is analysed by itself (Table 6). Unlike the other three regulatory sites, the smooth trend analysis shows no change in the 95th percentiles between 2017 and 2023. It shows a slight increase of the mean (Figure 16). It is important to note that while the minimum recommendation for Theil-Sen analysis is at least six complete years and this data meets that requirement; more data from future years will produce a more accurate trend. The Alexandra data is further analysed in the next section.

There has been a decrease of PM_{10} concentrations of 6.2% per year in Arrowtown, which equates to a cumulative 56% decrease over the nine years of analysis (Table 6). This trend is similar to the previous analysis on the Arrowtown School site data for 2006-2013, where a 4% annual decrease was reported for winter months (Mills, 2016). This confirms that Arrowtown PM_{10} concentrations have been decreasing consistently over time, as this trend is shown in both site locations. The smooth trend analysis shows that the 95th and 50th percentiles of the de-seasonalised monthly concentrations have been decreasing over the years (Figure 16).

Central Dunedin shows a significant decrease in PM_{10} of 3.1% per year totalling 49% improvement over 16 years (Table 6). A large part of improvement seen in Dunedin was due to the resource consent renewals during the early 2010's, which switched many industrial discharges to using better emission controls and/or cleaner fuels, and resulted in lowered emissions for PM_{10} (Mills, 2016). This decrease can be seen in the 95th percentiles for the smooth-trend for years 2010-2013 (Figure 16).

The Mosgiel Theil-Sen analysis indicates an improving trend of 1.8% per year, which is the lowest rate of improvement of all the Otago sites, excluding Alexandra. The 95th percentile shows this steady decrease in Figure 16. Mosgiel winter trend analysis indicates a 2.4% improvement per year.

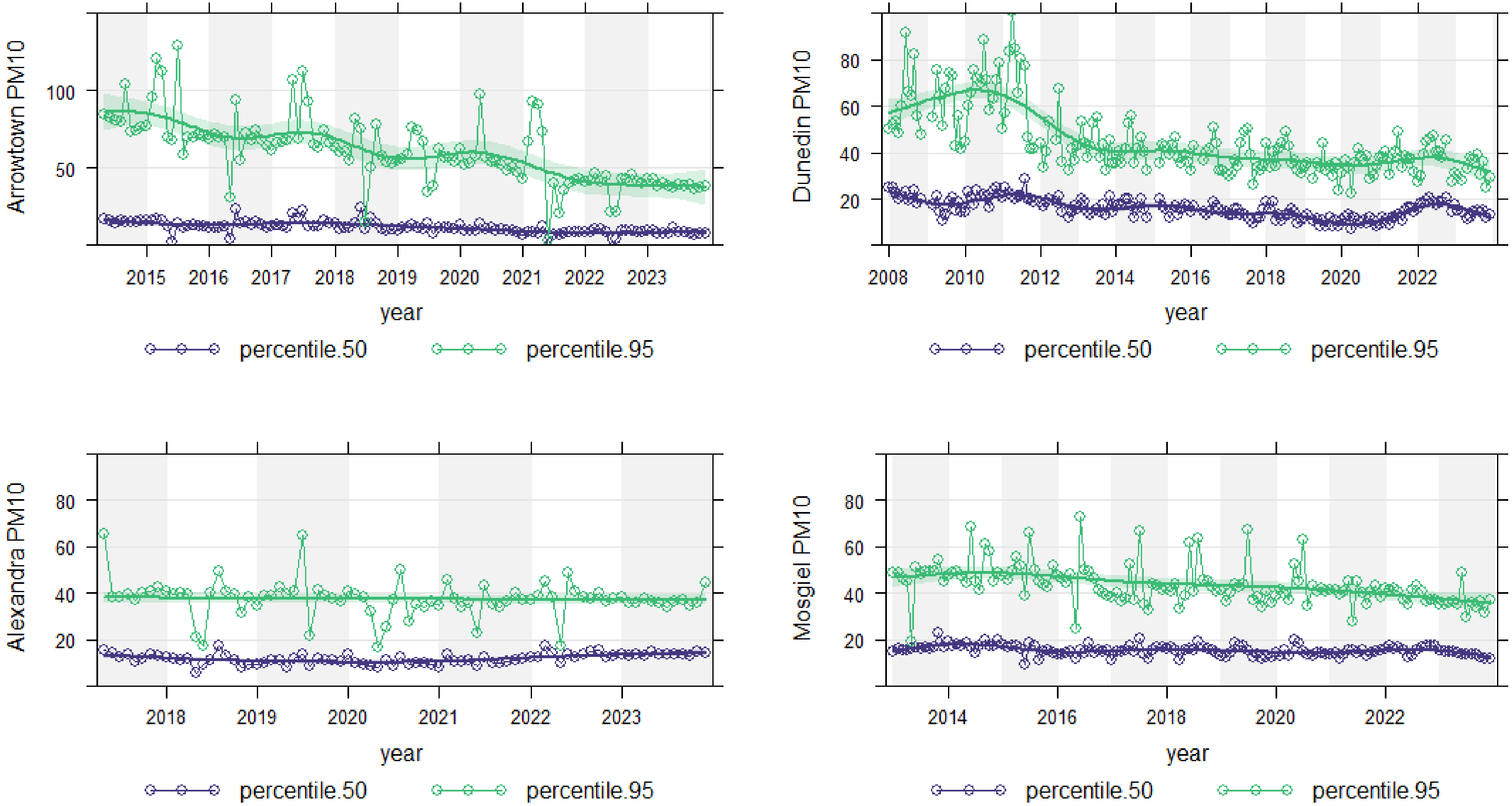


Figure 16 **Smooth-trend analysis for Arrowtown, Alexandra, Central Dunedin and Mosgiel – 95th percentile and median**

4.3.5. Alexandra trend results

Table 7 provides the results of further analysis on Alexandra data.

Site		Trend period	Average % change per year	Significance
5 Ventry Street	Summer	2017-2023	4.5 [-0.2, 11.4]	$p < 0.1$
	Winter	2017-2023	-0.4 [-4.7, 4.3]	no trend
65 Ventry Street	Year round	2006-2016	-0.5 [-1.1, 0.3]	no trend
	Winter	2005-2016	-1.5 [-2.8, 0.2]	$p < 0.1$

Table 7 Theil-Sen results of Alexandra data

The Alexandra winter data shows no trend, which indicates that home heating emissions have not been the driver for the degrading trend seen on the year-round data. Further analysis of the winter months versus the summer months show that the years 2022 and 2023 in particular have quite high concentrations during summer, and are frequently above 10 µg/m³ on a monthly average. These high summer concentrations seem to be the driver for an increasing trend for years analysed, although this has a significance of $p<0.1$ which is not a strong result.

Analysis on the Alexandra data for 2006 to 2016 shows no trends on either year-round data and only a weak improving trend ($p<0.1$) on the winter data (Table 7). This indicates that in general, the Alexandra airshed has neither improved nor degraded significantly in terms of average PM_{10} concentrations since ORC began monitoring it in 2005.

4.3.6. Trend results for survey sites

The survey sites were monitored during winter months only. Theil-Sen analysis was undertaken to infer trends on the winter season data. Table 8 displays the Theil-Sen results for the survey sites.

Site		Trend period	Average % change per year	Significance
Clyde	Winter only	2008-2020	-3.3 [-4.2, -1.8]	$p < 0.001$
Cromwell	Winter only	2008-2021	-1.8 [-2.9, 0.1]	$p < 0.1$
Milton	Winter only	2008-2021	-2.9 [-3.9, -2.0]	$p < 0.001$

Table 8 Theil-Sen analysis results of PM_{10} monthly means at the survey sites

Clyde and Milton experienced statistically significant decreases in PM_{10} concentrations over the monitoring period. Clyde showed a 3.3% improvement per year, over the 13 years, which adds up to a total of 44.2%. This downward trend can be seen clearly in the smooth-trend 50th and 95th percentile (Figure 17).

Cromwell shows the least improvement, with 28% over the 14 years. It can be seen in the smooth-trend analysis that there has been a downward shift from 2018 onwards in the 95th percentile, prior to this there was no obvious downward trend.

Milton has improved by 41.2% in total over the 14 years, and this downward trend appears to be consistent, as seen in the 50th and 95th percentiles (Figure 17).

During this analysis it was noted that the data for these three sites for the years 2018 onwards was lower than previous years, and this may be impacting these trends.

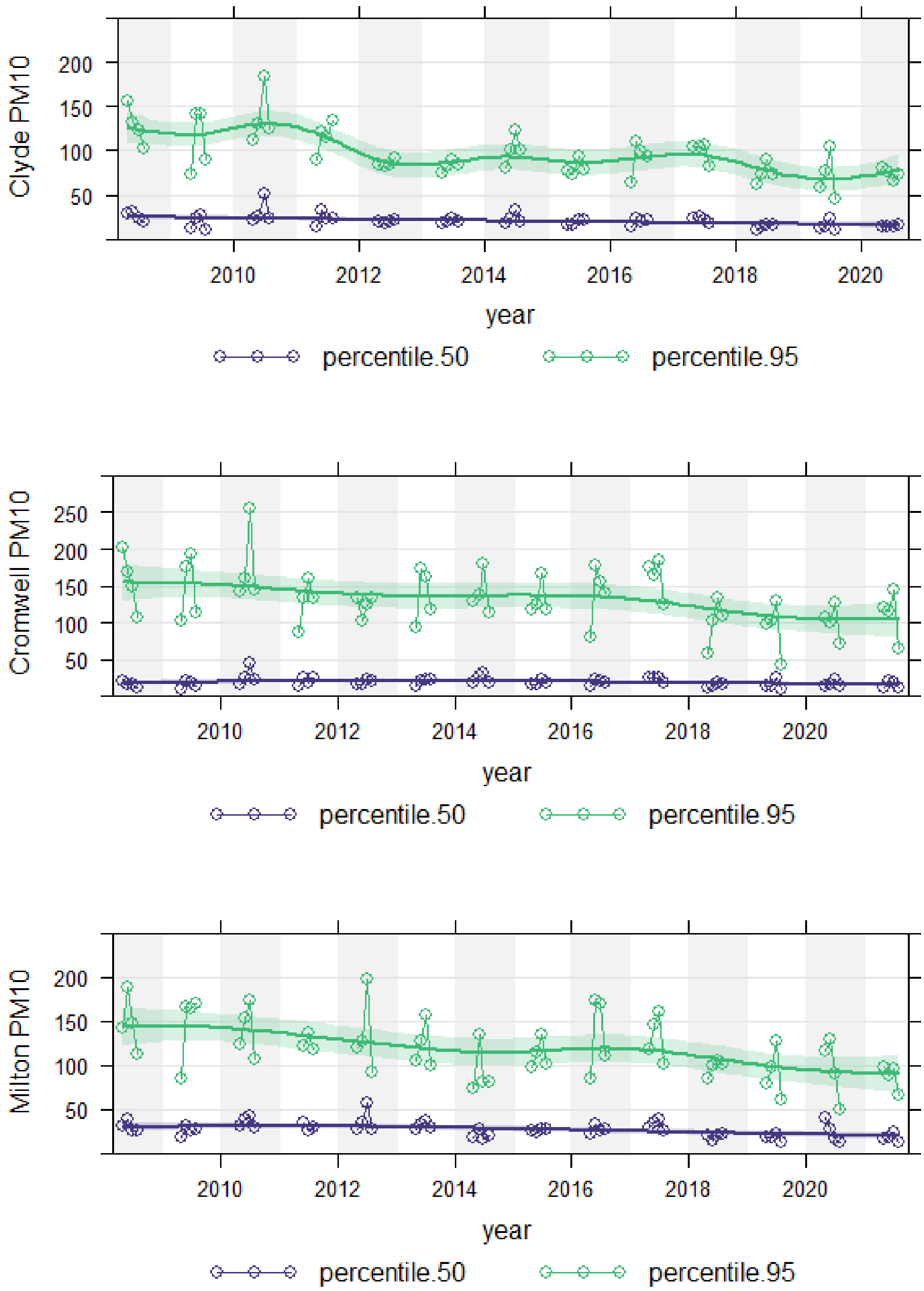


Figure 17 **Smooth-trend analysis for the survey sites – 95th percentile and median**

5. Discussion

Air quality monitoring results indicate a wide range of ambient air quality throughout the region. Many towns are characterised by highly seasonal patterns in PM_{10} due to solid fuel burning in winter. There is evidence that replacing older burners with more efficient ones has had a positive impact on reducing emissions, and consequently the concentrations. However, this has not been enough to meet the NESAQ limit for PM_{10} in many Otago towns and further actions would be required to achieve this.

The long-term air quality trends in Otago indicate that air quality has been improving across all the monitored airsheds except for the Alexandra airshed. The trend analyses show that Arrowtown followed by Clyde have had the highest degree of improvement, with 6.2% and 3.3% change in concentrations per year, respectively. Both of these sites, along with Milton have shown the most consistently decreasing PM concentrations across their respective monitoring periods. The Arrowtown site's number of NESAQ exceedances have also halved over the last ten years. The Cromwell site has improved by 1.8% per year which is the lowest rate of improvement for the Air Zone 1 areas (airsheds which received incentives to replace older solid-fuel burners with cleaner heating options), excluding Alexandra. Neither of the Alexandra sites have shown improvement since monitoring began in 2005, and the current site at 5 Ventry Street is showing degradation, although six years is a short time-period for trend analysis and to properly assess trends more data is required.

The Central Dunedin site's improvements are attributed to resource consent limits becoming stricter around the year 2011 (Mills, 2016). Neither Mosgiel nor Dunedin homes were eligible for financial incentives to improve home heating methods, however it is expected that these emissions will have improved over time as wood burner technology improves. Further investigation into the sources of emissions in Mosgiel and Central Dunedin would be beneficial for the future management of air quality in these airsheds.

Previous reports (Harrison, 2021 and Mills, 2016) have discussed the possibility of urban growth having a negative impact on the air quality trends, where new burners are being added to the fleet at the same rate as old burners are being replaced. In the case of Cromwell, it has experienced the highest percentage of increased number of dwellings than the other monitored airsheds, with 33% between the years 2006 and 2018 (Stats NZ, 2020), so it is possible that the reason for the low rate of improvement of PM concentrations is due to this. For Alexandra the increase of number of dwellings is only 12% which is lower than both Arrowtown and Clyde (24% and 22% respectively, Stats NZ, 2020). Further research into the emission sources for Alexandra is recommended.

The influence of seasonal variability on air quality data can be removed for trend analysis, however there are larger climactic cycles that also occur and can have an impact on air quality, such as the El Niño Southern Oscillation. In New Zealand El Niño commonly causes southerly winds during winter, resulting in colder than usual temperatures, while La Niña causes warmer than average land and sea temperatures. The years 2021 and 2022 were both La Niña years, with 2022 being the strongest La Niña since 1950 (Stats NZ, 2023). These results remain comparable to previous trend analyses, but future analysis with additional years of data is recommended.

6. References

Carslaw, D.C., Ropkins, K. (2012). Openair — *an R package for air quality data analysis*. Environmental Modelling & Software, Volume 27-28, 52-61 pp.

Carslaw, D.C. (2019). *The openair manual — open-source tools for analysing air pollution data*. Manual for version 2.6-6, University of York.

Carslaw, D.C., Beevers, S.D., Tate J.E. (2007). *Modelling and assessing trends in traffic-related emissions using a generalised additive modelling approach*. Atmospheric Environment 41 (26), 5289-5299 pp.

Kuschel et. al., (2022). *Health and air pollution in New Zealand 2016 (HAPINZ 3.0): Volume 1 – Finding and implications*. Report prepared by G Kuschel, J Metcalfe, S Sridhar, P Davy, K Hastings, K Mason, T Denne, J Berentson-Shaw, S Bell, S Hales, J Atkinson and A Woodward for Ministry for the Environment, Ministry of Health, Te Manatū Waka Ministry of Transport and Waka Kotahi NZ Transport Agency, March 2022. https://environment.govt.nz/assets/publications/HAPINZ/HAPINZ-3.0-Findings-and-implications.pdf

Longley, I. (2023). *Mapping of winter air quality in Alexandra*. National Institute of Water and Atmospheric Research Ltd

Ministry for the Environment (2002). *Ambient air quality guidelines – 2002 update*. Air Quality Report No. 32. Wellington: Ministry for the Environment.

National Air Quality Working Group, (2024). *Guidance for calculating LAWA air quality trends.*

Otago Regional Council (2009). *Regional Plan: Air for Otago*. Otago Regional Council, Dunedin.

Mills, D. (2016). *SOE Report: Air Quality 2005 – 2014*. Otago Regional Council, Dunedin.

Mills, D. (2018). *An assessment of the Clean Heat Clean Air Program's effectiveness*. Otago Regional Council Committee report.

Harrison, S. (2021). *State and Trends of Air Quality in the Otago Region 2010 – 2019*. Otago Regional Council, Dunedin.

Standards New Zealand (2016). AS/NZS 3580.1.1. *Methods for sampling and analysis of ambient air - Guide to siting air monitoring equipment.*

Standards New Zealand (2016). *AS/NZS 3580.9.11. Methods for sampling and analysis of ambient air, Method 9.11: Determination of suspended particulate matter – PM_{10} beta attenuation monitors.*

Stats NZ (2020). *Statistical area 1 dataset for 2018 Census – updated March 2020*. Stats NZ Tatauranga Aotearoa.

Stats NZ (2023). *El Nino Southern Oscillation,* updated 27 September 2023. Accessed on 8 February 2024. https://www.stats.govt.nz/indicators/el-nino-southern-oscillation/#about

Wilton, E. (2019). *Wanaka, Cromwell and Clyde Air Emission Inventory – 2019*. Environet Limited.

World Health Organization (2006). *WHO air quality guidelines for particulate matter, ozone, nitrogen dioxide and sulfur dioxide – global update 2005*. Regional office for Europe.

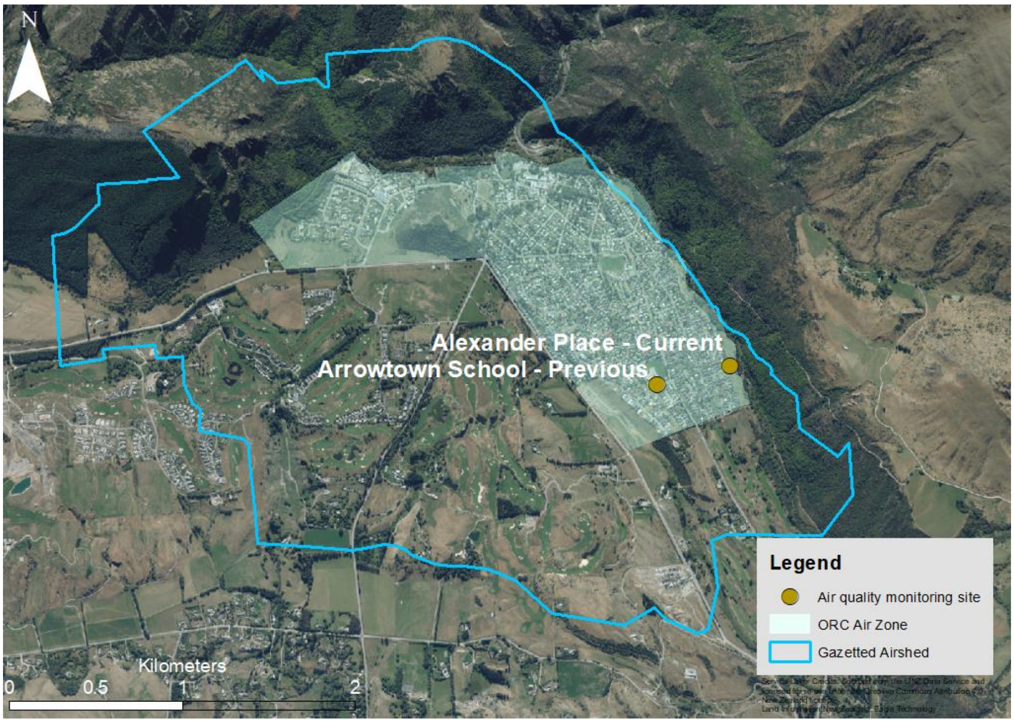
World Health Organization (2013). *Review of evidence of health aspects of air pollution – REVIHAAP Project Technical Report*. Regional office for Europe.

World Health Organization (2021). *WHO global air quality guidelines. Particulate matter ($PM_{2.5}$ and PM_{10}), ozone, nitrogen dioxide, sulfur dioxide and carbon monoxide.* Geneva: World Health Organization; 2021.

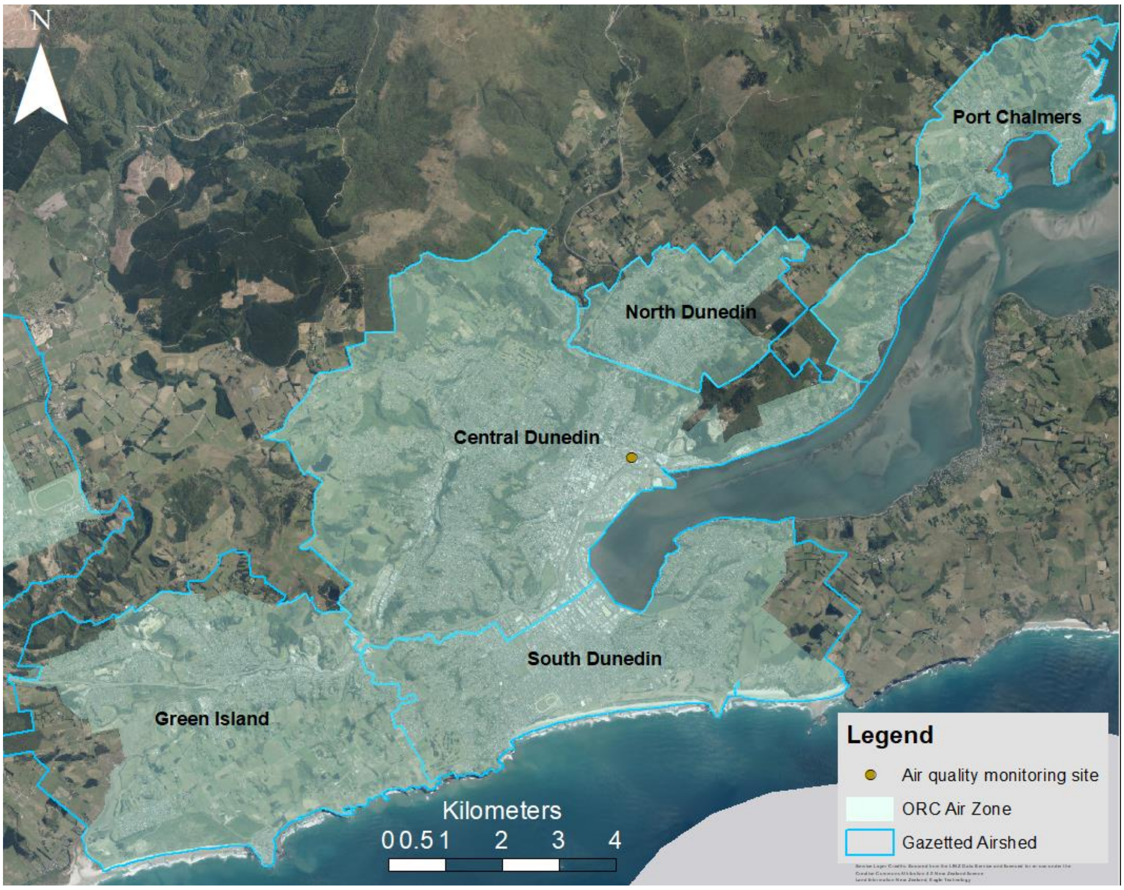
Appendix: Airshed and Air Zone boundary maps

Note: ORC Air Zones were established under the Air Plan to better align land use with air quality management.

Arrowtown

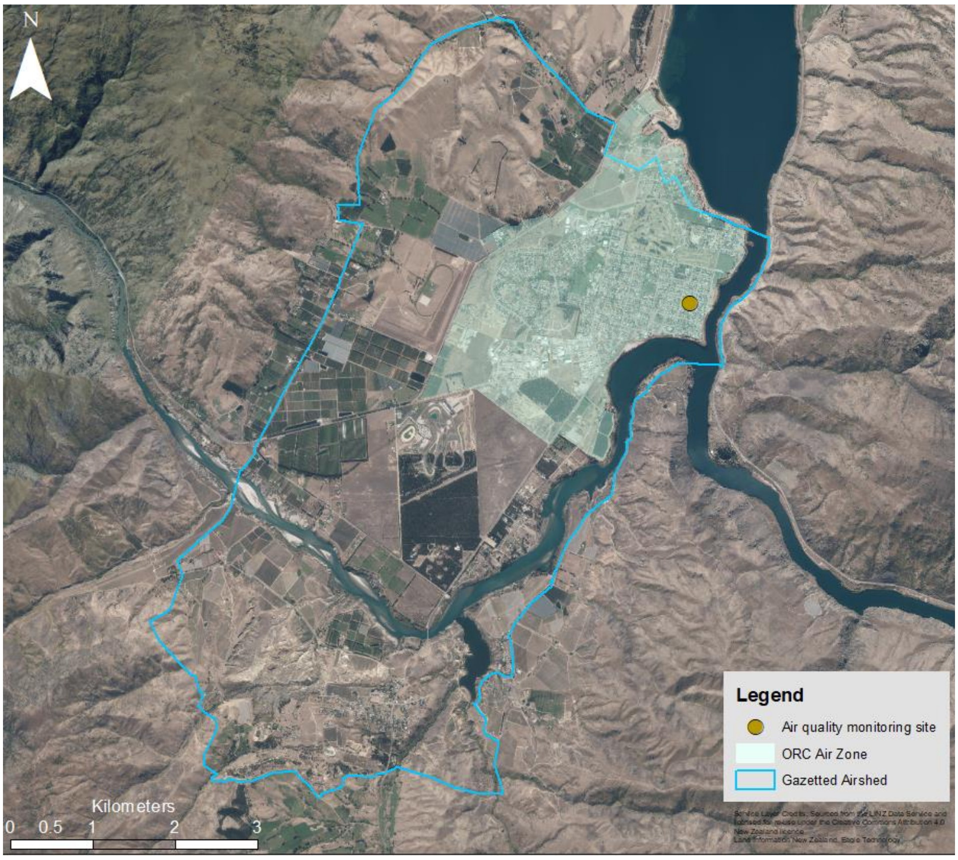


Alexandra

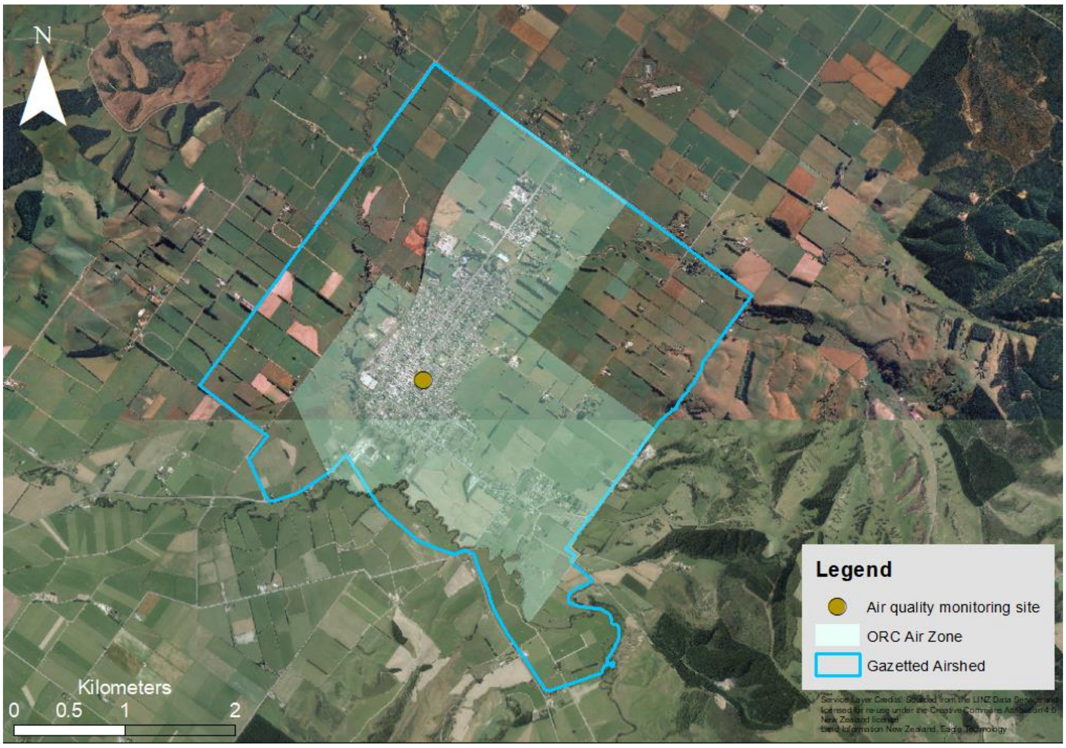


Central Dunedin

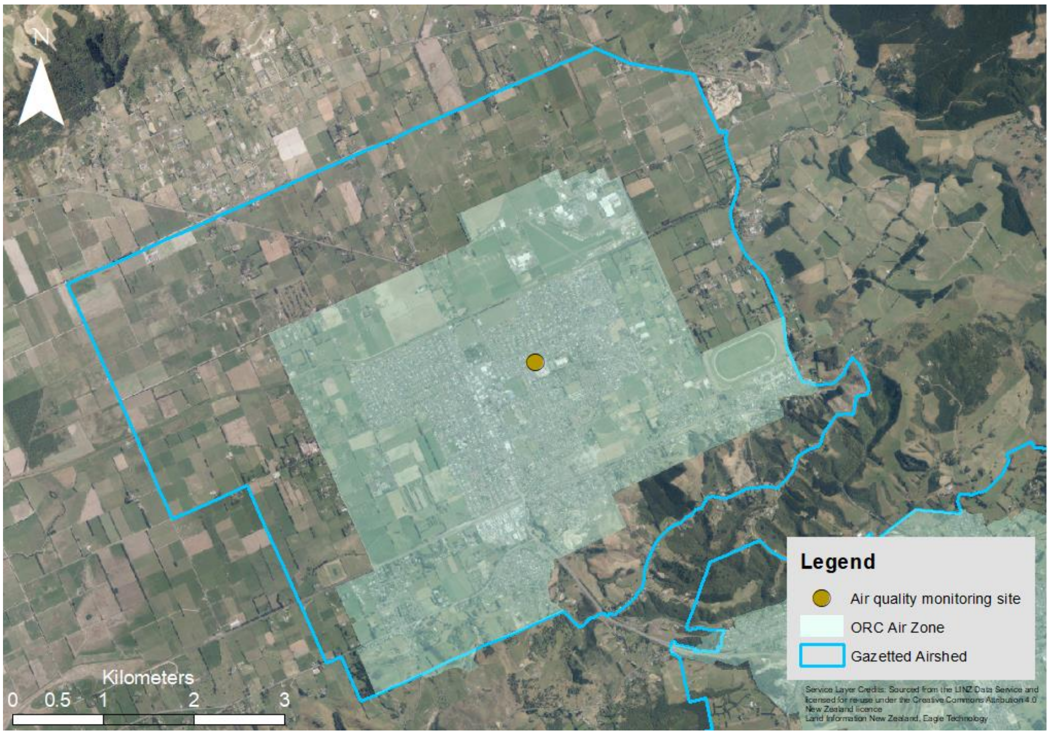
Clyde



Cromwell



Milton


N
Legend
Air quality monitoring site
ORC Air Zone
Gazetted Airshed
Kilometers
0 0.5 1 2 3

Mosgiel