Auckland Ambient Air Quality Trends for $PM_{2.5}$ and PM_{10} – 2006-2015

Nick Talbot, Nick Reid, Paul Crimmins

October 2017 Technical Report 2017/029

Auckland Council
Te Kaunihera o Tāmaki Makaurau

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Executive summary

Airborne particulate matter has been measured in the Auckland region since the 1960s, driven by public complaints about dust in the urban atmosphere. As the understanding of health implications of exposure to inhalable particulates increased, national statutory obligations for local authorities were introduced. These regulations led to the establishment of a network of monitoring stations across Auckland.

The Resource Management (National Environmental Standards for Air Quality) Regulations 2004 (NES-AQ, 2004) imposed a national standard for ambient concentrations of PM_{10} (particles of 10 micrometres and smaller). In addition to the national standard, Auckland regional targets have been introduced that also include targets for $PM_{2.5}$ (particulate matter of 2.5 micrometres and smaller). The $PM_{2.5}$ targets reflect current knowledge on the increased health effects of inhaling smaller particulates.

The Auckland monitoring network stations provide quality assured emissions data to assess compliance with regional and national guidelines. The stations are at representative locations – roadside, urban background, regional background sites – throughout the Auckland region. These stations provide a stable continuous dataset over years so that trends in emissions can be obtained. These trends help assess air quality improvement or degradation over time and inform Auckland Council's five-yearly state of the environment report, which requires a review of emission trends.

A GNS Science report for Auckland Council (Davy et al., 2017) describes trends in emission sources obtained from eight years of filter measurements collected every three days from five locations across Auckland. Elemental compositions of particulate matter from particle size ranges $PM_{2.5}$ and PM_{10} were obtained and changes in trends in different man-made and natural emission sources were identified.

This report expands the trend analysis carried out by GNS Science to evaluate the dataset for the same period for all Auckland PM_{10} and $PM_{2.5}$ monitoring sites. Long-term trends in mass concentrations of particulate matter are described and discussed in relation to the changes in the emissions of different sources from the Auckland region. These findings are then compared to those reported in the GNS Science report.

Main findings

- Annual average $PM_{2.5}$ and PM_{10} concentrations at monitoring sites are improving (declining) and meet relevant standards and guidelines.
- Statistically significant decreases in PM_{10} concentrations (at both entire dataset and seasonal scales) were reported at five of the twelve sites.
- Concentrations at peak monitoring sites have declined quickest while concentrations at background monitoring sites remain stable or have stabilised.
- Peak motoring site concentrations (Takapuna, Khyber Pass) declined rapidly before 2011, since then, annual concentrations have stabilised.
- The Glen Eden site shows slight increasing trends over the period, indicative of increases in wood smoke emissions over the period 2006-2015 as reported by GNS Science.

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1. Introduction

Airborne particulate matter has been the subject of investigation in the Auckland region since the late 1960s. Initially, the motivation to commencing monitoring was primarily due to the nuisance value of dust. Today, there is a greater understanding of the impacts particulate matter has on climate, visibility, ecology (such as arable farming) and increased degradation of architecture and antiquities. However, the greatest concern of airborne particulate matter is due to health implications. The World Health Organisation (WHO) attributed 3.6 million premature deaths that occurred world-wide in 2012 to outdoor exposure to fine particulate air pollution (WHO, 2014). International research now provides compelling evidence linking airborne particulate matter with numerous chronic and acute impacts (Section 2.1). Particulate matter, general urban air pollution and diesel emissions have each been determined as carcinogenic, in the same evidence-category as smoking (WHO, 2013C).

In typical urban atmospheres, particulate matter sizes range from 10 nanometres to 100 micrometres in aerodynamic diameter, depending on the prevalence of key emission sources. The size of airborne particulate matter is important to understand due to their possible negative health impacts. These impacts are caused, to a large degree, by inhalation and deposition mechanisms during personal exposure. Different emission sources produce differing amounts and characters of particulate matter, including variances in the shape, size and chemical composition. Naturally emitted particulates largely derive from mechanical erosion, abrasion or oceanic bubble burst. These particulates dominate the larger size fraction and disproportionately affect mass measurements. Anthropogenic sources are typically released by combustion processes, are smaller but more numerous, and therefore tend to be underrepresented by mass measurements. To try and address this measurement imbalance standard measurement methodologies now separate particles into two over-lapping size fractions, PM_{10} and $PM_{2.5}$. The smallest size fraction, $PM_{2.5}$ comprises of particles up to 2.5 micrometres (µm) in aerodynamic diameter. PM_{10} accounts for all particles up to 10 µm in aerodynamic diameter, including those within the $PM_{2.5}$ size fraction.

Particulate matter emissions and outdoor concentrations are regulated by the Resource Management Act 1991 (RMA). Under the RMA, the Resource Management (National Environmental Standards for Air Quality) Regulations 2004 (NES-AQ) were established which set maximum permissible concentrations of PM_{10}. Additional to the NES-AQ standards, regional guidelines have been promulgated for Auckland by the Auckland Ambient Air Quality Targets (AAAQT) as part of the Auckland Unitary Plan (AUP).

To monitor compliance with these air quality criteria; Auckland Council operates an extensive monitoring network across the Auckland region in locations that are regarded as representing a typical level of pollutants, depending on the proximity to major polluting source and pollution type. Eight sites are currently monitoring PM_{10}, and four sites are currently monitoring or have monitored both $PM_{2.5}$ and PM_{10}. These sites represent a significant, quality assured, time-series archive, with continuous data back to 1998 in the case of two locations which enables a robust statistical analysis of historical trends of ambient $PM_{2.5}$ and PM_{10} concentrations.

The anthropogenic sources of $PM_{2.5}$ and PM_{10} are quantified by Auckland Council through periodic emission inventories. These provide a detailed “stocktake” of all emitted air

pollutants from various sources based on measured emission rates and activity data such as the distance travelled by vehicles within the region. The most recent emission inventory results for 2006 estimated that 4.4 tonnes of PM_{10} were emitted into the air on a typical summer's day. During winter, this increased to 15.1 tonnes per day (Auckland Council, 2014). The seasonality of home heating accounts for the majority (72%) of the wintertime increase. An updated emission inventory is due in 2018.

Complementary to the emission inventory work, source apportionment research has been carried out in Auckland since 2006. This top-down assessment uses elemental analysis of $PM_{2.5}$ and PM_{10} particulate matter collected on filters at five urban sites. The longevity of the dataset enables comprehensive trends analysis that details the changes in sources that make up the composition of particulate matter over Auckland (Davy et al., 2017). Given these previous analyses of source-specific emissions, this report will not go into detail linking changes in emission sources to the observed trends over time. However, it is appropriate for this report to acknowledge the overarching trends that have the greatest impacts of particulate matter patterns. Davy et al., (2017) describe a downward trend of both PM_{10} and $PM_{2.5}$. These reductions are from improvement in vehicle fuel such as the reductions in sulphur content in diesel, modernisation of the transport fleet, and as the reduction in PM_{10} and $PM_{2.5}$ due to the move away from heavy industry and coal burning (Davy et al., 2017).

1.1 Report objectives

The objectives of this report are to:

- describe the rationale for monitoring $PM_{2.5}$ and PM_{10}
- deliver a trend analysis of all historical $PM_{2.5}$ and PM_{10} datasets for current ambient air quality monitoring sites
- assess overall trends and seasonal patterns and describe the findings of source apportionment trends (Davy et al., 2017)
- forecast annual average $PM_{2.5}$ and PM_{10} concentrations into the future.

2. Background

2.1 Health effects of $PM_{2.5}$ and PM_{10}

Exposure to PM_{10} is hazardous to human health as it is easily-inhaled (Pope 2000; WHO 2017). Larger particles with diameters between 2.5 and 10 µm ($PM_{10\text{-}2.5}$) lodge in the upper airway and have been found to cause and exacerbate a range of respiratory conditions. Smaller particles of less than 2.5 µm ($PM_{2.5}$) can deposit in the very small airways in the lung (Figure 1). Moreover, inhaled particles less than 0.1 µm in diameter are small enough to enter the bloodstream through the cell membranes in the alveoli. Evidence of this deposition process has been recently proven with observations of ultrafine particles of metal elements in brain tissue (Plascencia-Villa et al., 2016).

The key health concerns of $PM_{2.5}$ and PM_{10} exposure are the causation and exacerbation of respiratory and cardiovascular degradation and diseases, cancers, strokes and increased mortality (WHO, 2013b). There is increasing evidence of further wide-ranging health effects, including reduced birth weights, increased infant mortality, and reduced neurodevelopment and cognitive function (WHO, 2004).

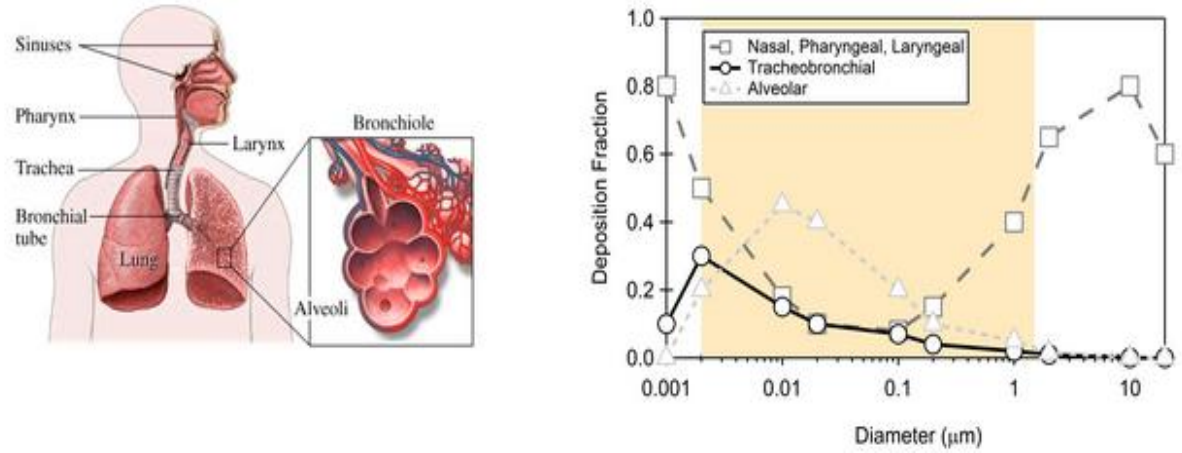


Figure 1 Graphical depiction of particle deposition as a function of particle size, expressed here in micrometres in log scale. Particles larger than $PM_{2.5}$ (white background) tend not to penetrate past the trachea, while $PM_{2.5}$ (yellow shading) can penetrate deep into the alveoli (ICRP, 1994).

Exposure to $PM_{2.5}$ and PM_{10} affects all exposed groups; however pre-existing conditions (asthma, cardiovascular issues, and diabetes) predispose individuals to more severe effects. The elderly, young children and those with respiratory and cardiovascular conditions are considered as the most vulnerable. The WHO recently published two major reviews of the health effects of air pollution (REVIHAAP and HRAPIE projects) WHO (2013a, b), which state that ambient particle matter concentrations pose a significant health risk to communities. The WHO reported their concern regarding $PM_{2.5}$ and confirmed their rationale for the setting of a $PM_{2.5}$ Guideline in 2005 (WHO, 2013). The WHO's summary of recent epidemiological studies concludes that there is significant evidence for increased morbidity and mortality caused by both short-term and long-term exposure to $PM_{2.5}$ and PM_{10} (WHO, 2013b).

Studies indicate that there is a role in related health effects for both the chemical composition and physical size of $PM_{2.5}$ and PM_{10} components. This potentially means that

there is a wider range of health effects than initially suspected, given the diversity of $PM_{2.5}$ and PM_{10} composition (WHO, 2013a). The particulate shape and chemical composition result from the production and emission of these particles. The resulting characteristics of the particulate also determine their potential impacts. Carbonaceous particles are agglomerates in their structure. This means that they have a very large surface area when compared to their tiny size (less than 0.1 µm). This large size can then host various condensable volatile organic compounds which can be very toxic to humans (Cassee, Heroux, Gerlogs-Nijland, & Kelly, 2013).

A final consideration is that the WHO (2013 a, b) states that there is no "safe level" for particulate air pollution. They note that significant health impacts can occur at ambient concentrations significantly below existing regulatory guidelines. Accordingly, the WHO states that despite the implementation of guidelines and standards world-wide, there are no 'safe' levels for ambient pollutant concentrations (WHO, 2013a.b).

Health effects (including the resulting economic burdens) from PM_{10} exposure within Auckland and New Zealand were quantified by the Health and Air Pollution in New Zealand study (HAPINZ, Kuschel, et al., 2012). HAPINZ estimated that exposure to ambient PM_{10} was associated with 611 premature deaths and $2.25 billion social costs within the Auckland region in 2006 (Kuschel et al., 2012). It is important to note that HAPINZ focussed on PM_{10} rather than $PM_{2.5}$ as it was the default priority pollutant for New Zealand. Data from monitoring stations provide a useful representation of air pollutants in open areas of the Auckland airshed, rather than a person's actual exposure to local or micro-scale pollution plumes (such as from a car exhaust when commuting on or alongside a road). It can, therefore, be considered likely that these figures underestimate the actual health impacts in densely populated areas such as Auckland.

2.2 Characteristics of $PM_{2.5}$ and PM_{10} in Auckland

Due to its geographical location, Auckland has a mild and windy climate. These conditions are conducive to the dispersal of air pollutants providing Auckland with good air quality when compared with other international cities of similar sizes. However, despite this fortuitous position, PM_{10} and $PM_{2.5}$ concentrations at monitoring sites throughout urban Auckland have intermittently exceeded ambient air quality standards and guidelines. These exceedances generally occurred on cool clear winter's mornings when stable atmospheric conditions prevail. The high pollution levels are often visible through the appearance of a brown haze over the city skyline.

The seasonality of emissions of PM_{10} is shown in Figure 2. Daily PM_{10} emissions are higher in winter due to the use of solid fuels for domestic heating. In summer, transport is the main source of daily PM_{10} emissions. This pattern of higher emissions during the winter season is common throughout New Zealand and is largely due to use of wood and coal for home heating. Meteorology can also help increase air pollution levels in winter. Cold winter nights under high atmospheric pressure can create temperature inversions close to the ground; these inversions greatly reduce the dispersal of pollutants (Ancelet et al., 2014; MfE, 2014).

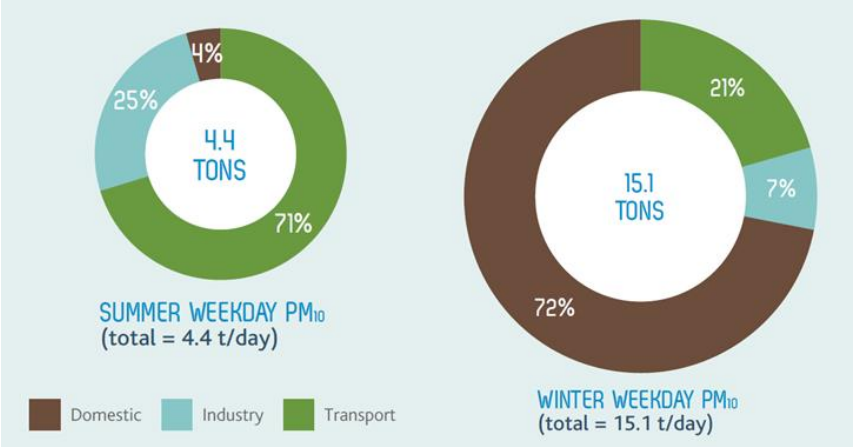


Figure 2 Daily PM_{10} emissions in summer and winter (Xie et al., 2014).

Davy et al. (2017) find that the key contributing influences on ambient PM_{10} concentrations in Auckland are (in decreasing degrees of importance): sea salt, motor vehicle exhaust emissions, residential wood burning, and crustal matter (Figure 3). The key sources of $PM_{2.5}$ are more-limited to anthropogenic sources such as motor vehicle exhaust emissions and residential home heating, but still show some influence from natural sources such as sea salt.

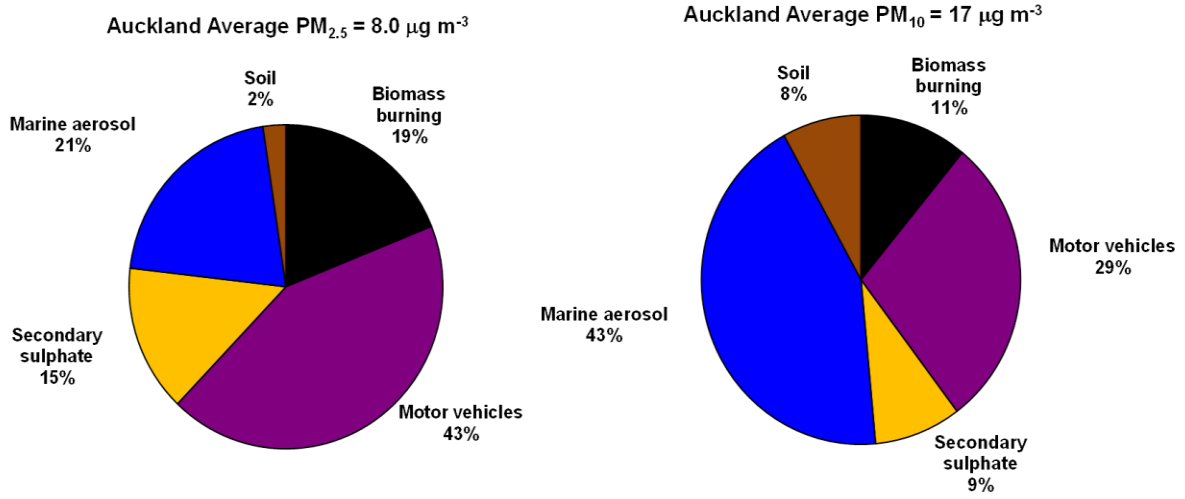


Figure 3 Source contribution for $PM_{2.5}$ (left) and PM_{10} (right) particulate (Davy et al., 2017)

$PM_{2.5}$ and PM_{10} concentrations can vary over time, according to emission source, meteorology and human behaviour. For most Auckland measurement sites, concentrations peak in the morning largely due to a 'rush hour' traffic peak, evident in Figure 4 with the increase between 07:00 and 09:00. Afternoon concentrations are generally lower than those of the morning due to increased mixing in the atmosphere. As the ground cools in the evening, so the atmosphere becomes more stable and concentrations increase with less dispersion. In winter, this natural process is exacerbated with the increase in home heating emissions. Weekday concentrations are higher than weekends due to the timing of peak traffic hours.

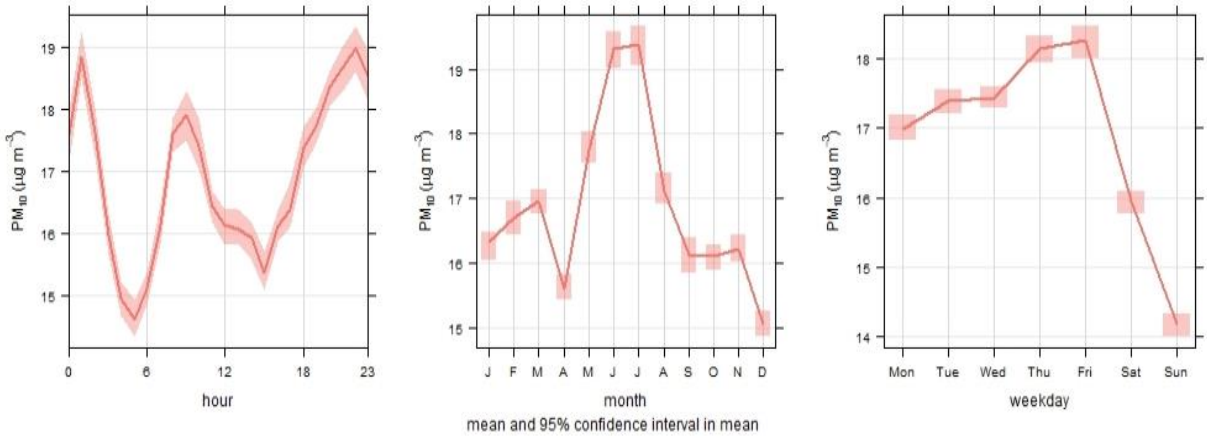


Figure 4 Arithmetic mean hourly PM_{10} concentrations for a range of timescales including Hour (left) month (middle) and weekday average (right).

2.3 Ambient Air Quality Guidelines and Standards

The Ministry for the Environment (MfE) introduced National Environmental Standards for Air Quality (NES-AQ) to provide regional councils with emission targets over defined airsheds. The NES-AQ follows recommendations set out by the WHO (2006) for short-term guidelines for PM_{10}. The current NES-AQ threshold for PM_{10} is 50 µg/m^3 (24-hr average), which covers short-term exposure. This value may not be exceeded more than once (one 24-hr period) in a 12 month period. If there is an exceedance of the standard, councils must report this to both the public and MfE. Longer-term exposure to PM_{10} is covered by the Auckland Ambient Air Quality Targets (AAAQT) within the AUP, with a value of 20 µg/m^3 (annual average). Currently, there is no national environmental standard for $PM_{2.5}$. However, $PM_{2.5}$ is now being measured in several towns and cities around New Zealand and is controlled at both short and long-term averaging periods by AAAQT.

The PM_{10} and $PM_{2.5}$ criteria applicable in Auckland are based on international best-practice, reflecting the WHO guidelines (2006) and the recommendations of more recent population health assessments (WHO, 2013B), and are summarised in Table 1.

Table 1 Standards, guidelines and targets for particulate matter in Auckland

Particle size	**PM_{10}**		**$PM_{2.5}$**	
Averaging time	**24 hour**	**Annual**	**24 hour**	**Annual**
Auckland Ambient Air Quality Targets (AUP)		20 µg m^{-3}	25 µg m^{-3}	10 µg m^{-3}
National Environmental Standard	50 µg m^{-3}			
NES – allowable exceedances per year	1			

3. Methodology

3.1 Overview of the methodology used in this report

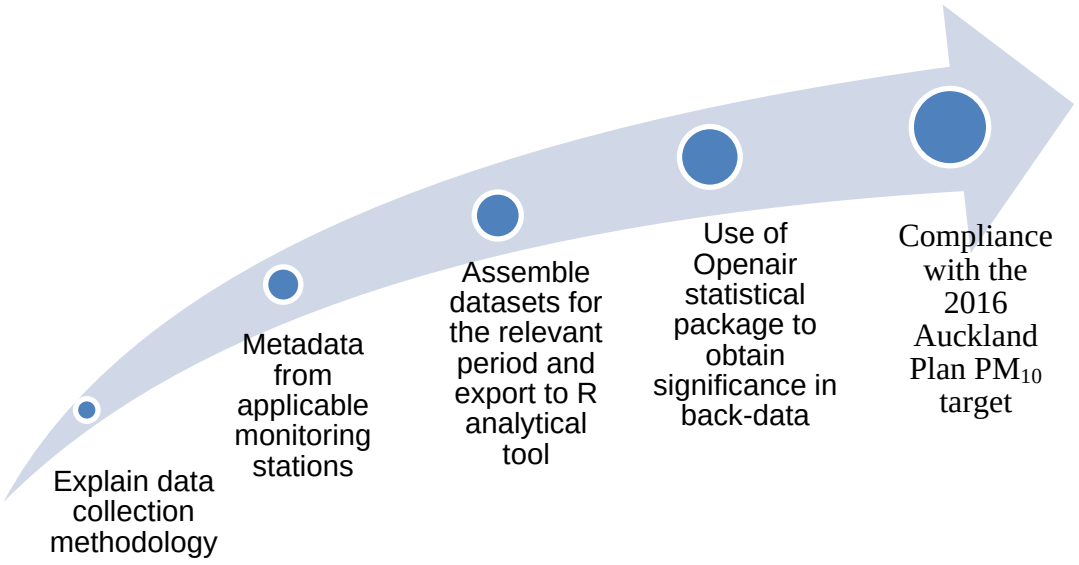


Figure 5 Flow diagram to describe the methods used to construct this trends report

3.2 Description of data collection methodology

Auckland Council measures ambient $PM_{2.5}$ and PM_{10} concentrations using Beta Attenuation Monitors (BAM), an internationally recognised instrument that yields high-quality data over long time periods. These instruments sample ambient air through a size-selective (i.e. PM_{10} or $PM_{2.5}$) inlet at a flow rate of 16.7 litres per minute. The monitoring heads are typically located no more than 5 m above ground level. The exact height depends on the monitored location and height of the monitoring station.

$PM_{2.5}$ and PM_{10} methods used by Auckland Council adhere to the standards required by the MfE (2009) and the NES-AQ which reflect the relevant Australia and New Zealand Standards. Data management is undertaken in accordance with MfE guidance (2009) and under an International Accreditation New Zealand (IANZ) quality management system. These processes ensure that the Auckland Council $PM_{2.5}$ and PM_{10} data are robust and reliable.

In accordance with the MfE guidance (2009), representative locations free from localised influences (such as obstructed wind-flows) are chosen to monitor regional air quality. The NES-AQ requires monitoring to be undertaken in a location where people are likely to be present and air quality is likely to be worst. This means that the monitors are typically located near to known major pollutant sources such as major roads (with the exception of the rural background monitoring sites at Patumahoe and Whangaparoa).

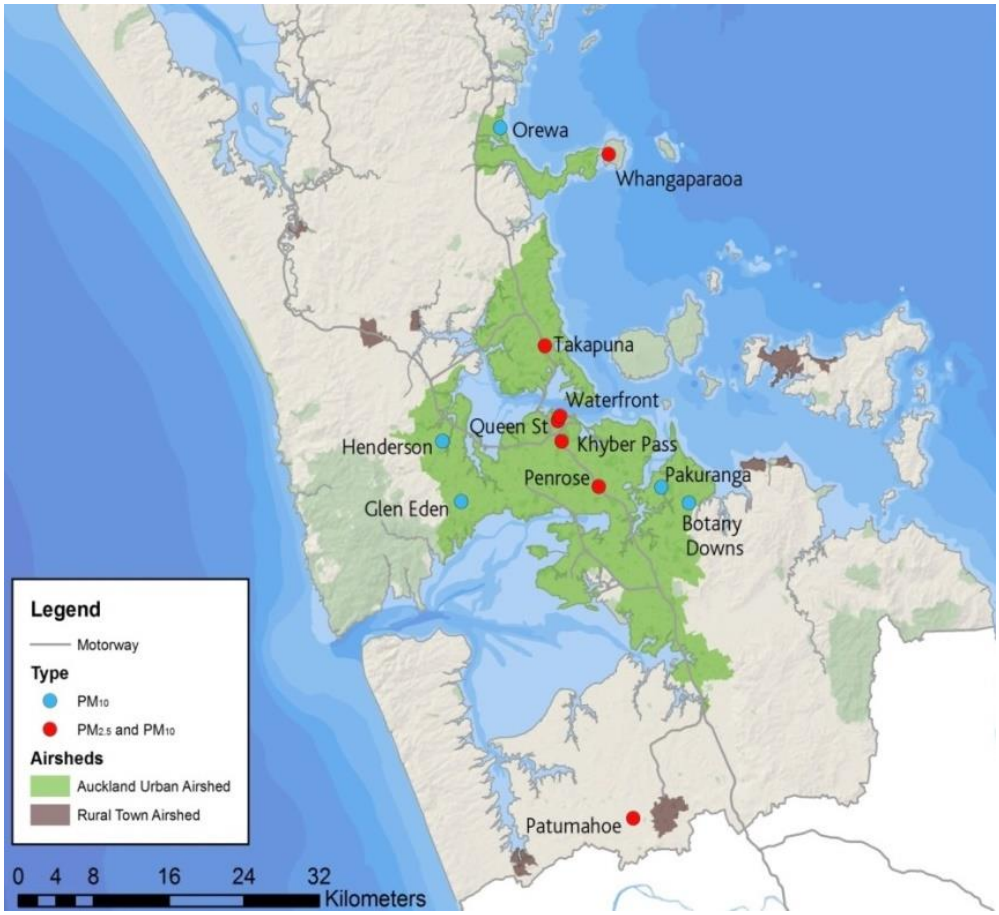


Figure 6 Locations of monitoring sites that provided data to this report (Davy et al., 2017).

Table 2 Metadata for all monitoring sites including the number of measurement points included (n) and the percentage of valid data considered.

	Site	Site class	Data start	Data end	n	% Valid data
$PM_{2.5}$	Takapuna	Urban Background	15/06/2007	31/12/2015	73254	96.7
	Penrose	Industrial / Traffic	09/08/2006	31/12/2015	95543	84.4
	Patumahoe	Rural Background	01/04/2008	31/12/2015	65523	97.4
	Whangaparoa	Rural Background	11/04/2008	30/06/2014	52883	91.1
	Waterfront	Traffic Peak	21/02/2011	01/12/2014	31696	98.2
PM_{10}	Penrose	Traffic / Industrial	01/01/2006	31/12/2015	107357	82.6
	Takapuna	Urban Background	01/01/2006	31/12/2015	103290	97.5
	Pakuranga	Urban Background	01/01/2006	31/12/2015	93230	97.4
	Botany Downs	Urban Background	01/01/2006	24/11/2014	79351	93.6
	Patumahoe	Rural Background	01/01/2006	31/12/2015	92582	96.8
	Glen Eden	Urban Background	01/01/2006	31/12/2015	87380	99.0
	Orewa	Urban Background	13/09/2007	01/09/2014	57747	94.8
	Whangaparoa	Rural Background	01/04/2008	18/11/2014	53636	92.5
	Waterfront	Traffic Peak / Port	21/02/2011	01/12/2014	31849	98.7
	Khyber Pass	Traffic Peak	01/01/2006	31/12/2015	47398	99.8
	Henderson	Traffic /Urban	01/01/2006	31/12/2015	85628	98.5

3.3 Data analysis methods

All quality assured datasets were compiled into a complete database, beginning at the start of the data period for each site. This formed the 'master' database for the project, on which usual descriptive tools (data period, % valid data, and annual averages) were calculated. Monthly averages of the hourly samples were used to calculate long-term trends for PM_{10} and $PM_{2.5}$ concentrations. All available data sampled between 1 January 2006 and 31 December 2015 were considered for the calculation of PM_{10} trends. As no sites measured $PM_{2.5}$ until later in 2006, $PM_{2.5}$ trends have been calculated using data sampled from 2008 to 2015 inclusive.

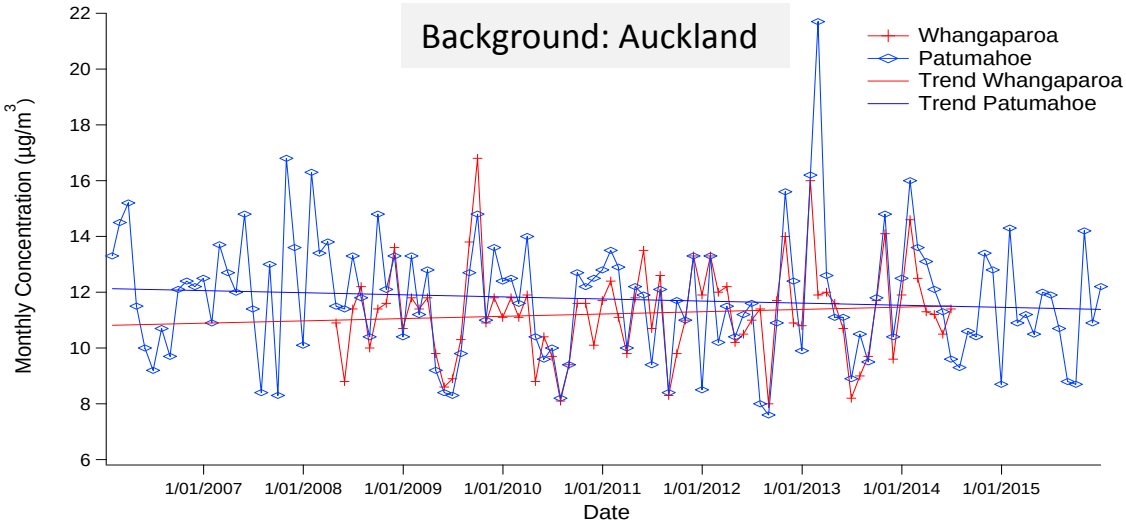
For all statistical analyses presented in this report, the *openair* package based on 'R' statistical software has been used to analyse the data for trends (Carslaw 2012). For the trend analysis and sign, the Theil-Sen function in *openair* was used (Carslaw 2012). The analysis of trends in the particulate matter concentration and source contribution data are accompanied by confidence interval estimates for the observed trends. The following paragraph describes the basis of the Theil-Sen function and is taken from Carslaw (2012).

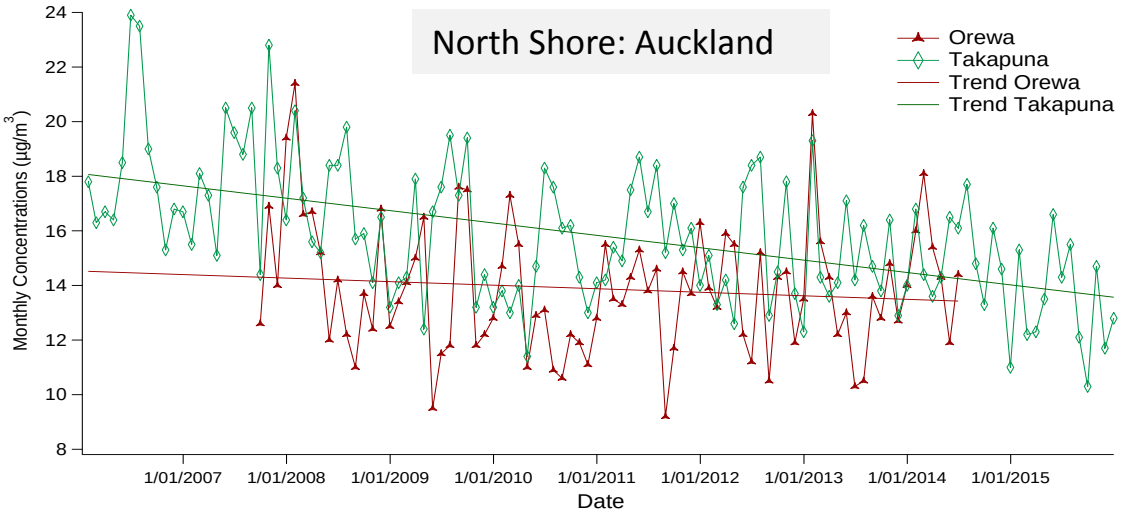
> *Given a set of n x, y pairs, the slopes between all pairs of points are calculated. The Theil-Sen estimate of the slope is the median of all these slopes. The advantage of the using the Theil-Sen estimator is that it tends to yield accurate confidence intervals even with non-normal data and heteroscedasticity (non-constant error variance). It is also resistant to outliers — both characteristics can be important in air pollution* (Carslaw, 2012).

4. Results: Measured trends

This section shows arithmetic mean concentrations of monthly data from 2006 up to and including 2015, the last full yearly dataset available at the time of writing. The graphs group sites that represent various regions of Auckland. This is designed to allow comparisons between stations located in different regions. Individual sites may measure differing levels within regions owing to different site-specific characteristics. A discussion of the key findings follows.

4.1 PM_{10} trends for Auckland by geographical location, 2006-2015





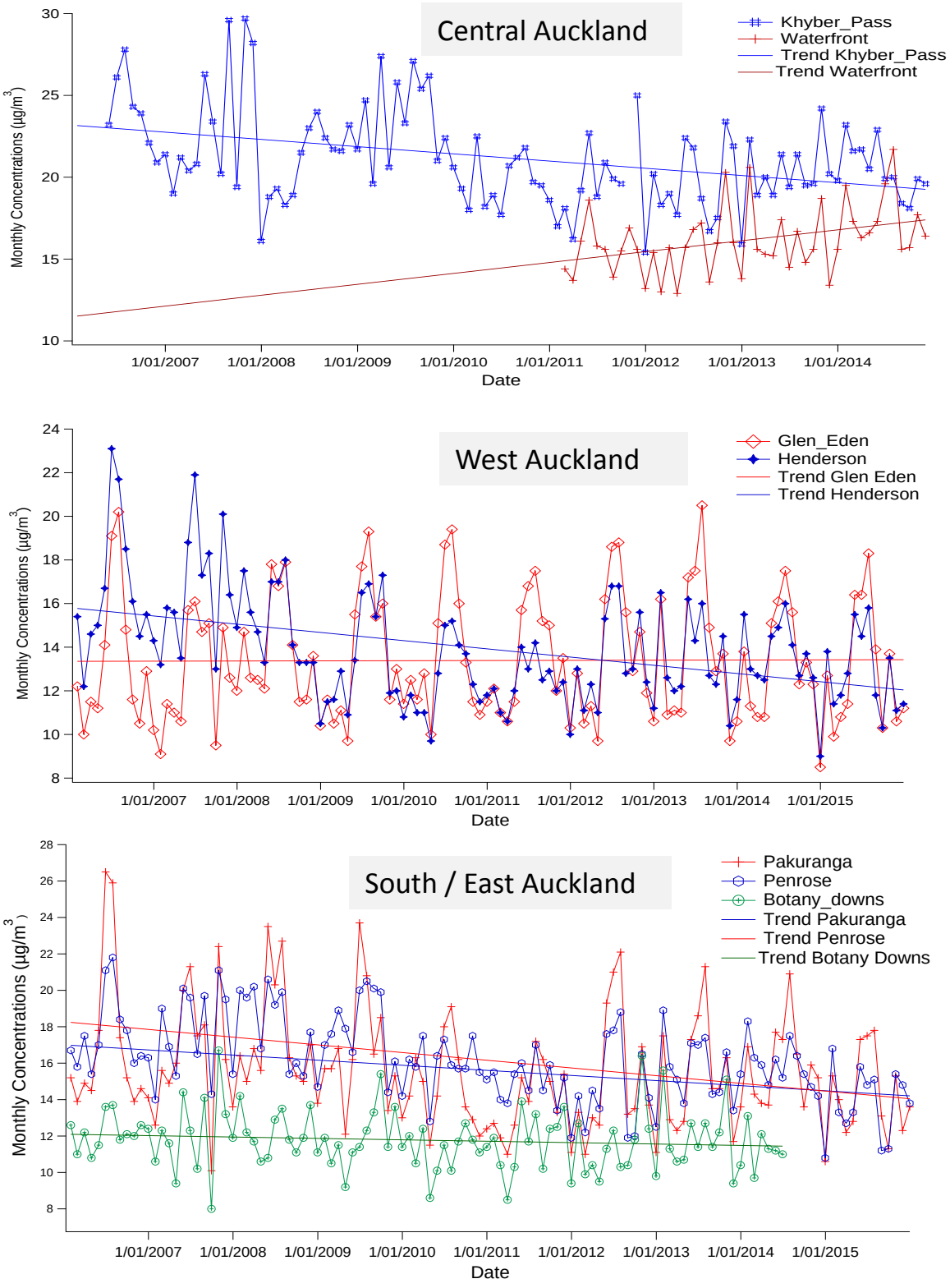


Figure 7 Monthly PM_{10} concentrations and trend lines for data from 2006 until 2015. Datasets are grouped according to their geographical and airshed coverage.

The overall trend shows declining PM_{10} concentrations over the average monthly periods. By 2015, concentrations were below the annual average guideline at all sites. Figure 6 shows the geographical location of each monitoring site.

The Background sites (Figure 7; top), are the sites located to the far north and south of the Auckland region. They show relatively consistent PM_{10} concentrations, with slight increasing trends for Whangaparoa and slight decreasing trends for Patumahoe. It has been noted in the trends report by Davy et al. (2017) that background concentrations from marine aerosol (a key source of natural PM_{10} over Auckland) have been declining slightly over a period of time, this might account for the Patumahoe trend. Whangaparoa's slightly increasing trend is most likely due to the absence of data until 2008, a period when concentrations were slightly higher. The similarity of sites that lay almost 100km away from each other is notable and indicative of the absence of local emission sources at these background sites.

Orewa and Takapuna have been graphed together under the geographical location of Auckland North Shore although their locations represent different airshed types. Takapuna sits close to Auckland CBD and a well-developed urban area, while Orewa is situated at the very north of the Auckland region and is less developed as a consequence. However, Orewa is growing rapidly and there is a major road near to the monitoring site. It is notable that PM_{10} in Takapuna shows some seasonal variability (peaks in winter, troughs in summer); however, the seasonal signal is not as clear as with $PM_{2.5}$ (Figure 8). This is explained by the increase in influence from oceanic primary and secondary sulphate found in the larger size fraction. The trend for these sources is downwards which is consistent with the findings in Davy et al. (2017).

Interestingly, Orewa does not show significant seasonal fluctuations in PM_{10} indicating that wood smoke from home heating does not strongly influence this site. The Orewa station is located close to the coast and is therefore strongly influenced by oceanic sources. Unlike Takapuna, there is less of a downward trend in PM_{10} concentrations at Orewa, which is a conflicting result with the lowering oceanic sulphate concentrations noted by Davy et al. (2017) given that oceanic sources are the likely main particle source. It should be noted that the population of Orewa increased almost 14% between the 2006 and 2013 Census (Statistics New Zealand, 2013); therefore, greater contributions from anthropogenic sources may have occurred during this time, with the effect of moderating reductions on PM_{10} concentrations.

Central PM_{10} BAM monitoring locations consist of a long-term site at Khyber Pass and a shorter-term site on the CBD waterfront. A third CBD site at 253 Queen St monitors PM_{10} and $PM_{2.5}$ by gravimetric methods, and recently by light scattering spectrometer. However, Queen Street has been excluded from this analysis given its differing monitoring methodology. The BAM sites show contrasting results. Khyber Pass PM_{10} concentrations show a definitive lowering trend, similar to that of Takapuna. This result can be explained by the large reductions in vehicle exhaust emissions recorded during this period due to a modernising fleet and traffic management strategies (Davy et al., 2017). The increases in PM_{10} during the three years of monitoring at the waterfront site show the strongest increasing trend of any site. The increases cannot be explained by the locations next to one of Auckland's busiest streets (Quay Street) as vehicle fleet emissions have reduced. Although uncertain, possible increases in port activity during this period and different land use from the port site may have contributed to these increases.

The two West Auckland PM_{10} sites show a strong correlation to each other and distinct seasonal trends. Both are suburban sites located near residences with chimney stacks. There appears to be a strong local influence from home heating sources during winter. Both

sites show a downward trend in PM_{10} since 2008. However, source apportionment work at the Henderson site indicated an increase in the contribution from biomass burning over this period (Davy et al., 2017). These increased biomass burning contributions were outweighed by greater declines of PM_{10} from other sources (including vehicle emissions).

Despite the close locality of the Botany Downs and Pakuranga sites, both the PM_{10} trends and the monthly concentration distributions show that the sites reflect different emission sources. The seasonality of Pakuranga is again indicative of the influence of home heating emissions. The monthly average concentration of Botany Downs is similar to the background sites. This indicates that there is most likely no strong local source. This is supported by the lack of a decreasing trend from 2008-2014, again in agreement with the background sites. Penrose is an industrial site in south / Central Auckland with a complex mixture of sources (Davy et al., 2017). The strong decreasing trend at this site can be explained from reducing vehicle emissions from the neighbouring Southern Motorway and increasing regulations and emissions controls for industrial PM_{10} emissions.

4.1.1 PM_{10} Statistical trend analysis

Table 3 Summary of PM_{10} trend analysis results using data from 2008 until the end of 2015 or until the station was decommissioned. Sites that show significant trends are in bold.

	Site	Method	Period (years)	Overall trend	P-Value	Significant trend(s)?
PM_{10}	**Khyber Pass**	**BAM**	**15.85**	**-0.59**	**<0.001**	**Yes**
	Henderson	**BAM**	**15.47**	**-0.36**	**<0.001**	**Yes**
	Takapuna	**BAM**	**11.73**	**-0.28**	**<0.001**	**Yes**
	Penrose	**BAM**	**10.62**	**-0.37**	**<0.001**	**Yes**
	Pakuranga	**BAM**	**8.83**	**-0.38**	**<0.001**	**Yes**
	Botany Downs	BAM	8.80	-0.12	0.6319	No
	Patumahoe	BAM	8.76	0.02	0.5245	No
	Glen Eden	BAM	8.10	0.07	0.1757	No
	Orewa	BAM	6.30	-0.08	0.9355	No
	Whangaparoa	BAM	5.73	0.17	0.7273	No
	Waterfront	BAM	2.86	0.19	0.5234	No

Statistically significant overall trends are not necessarily replicated in statistically significant seasonal trends. Henderson, Takapuna and Penrose sites all show significant decreases in concentrations of PM_{10} during the winter months of June, July and August. The high percentage contribution of home heating to winter PM_{10} contributions (64% of total source emissions of PM_{10} concentration at Takapuna in winter (Davy et al., 2017)) and the decreasing trends seen at many sites suggests that the relative contribution of home heating to ambient PM_{10} concentrations is declining. However, this appears to disagree with the findings of Davy et al. (2017) who report an increasing trend from biomass burning over the Auckland region. If the biomass burning source is increasing but the PM_{10} concentrations in winter are decreasing significantly then factors such as meteorology (warmer or windier winters) and large decreases in other sources (such as sulphate from traffic emissions, as noted by Davy et al. (2017)) may be the key drivers to the PM_{10} reductions. Table 3 also shows that the sites with the longest sampling period show the statistically significant decreases in concentrations.

4.2 $PM_{2.5}$ trends for Auckland, 2008 - 2015

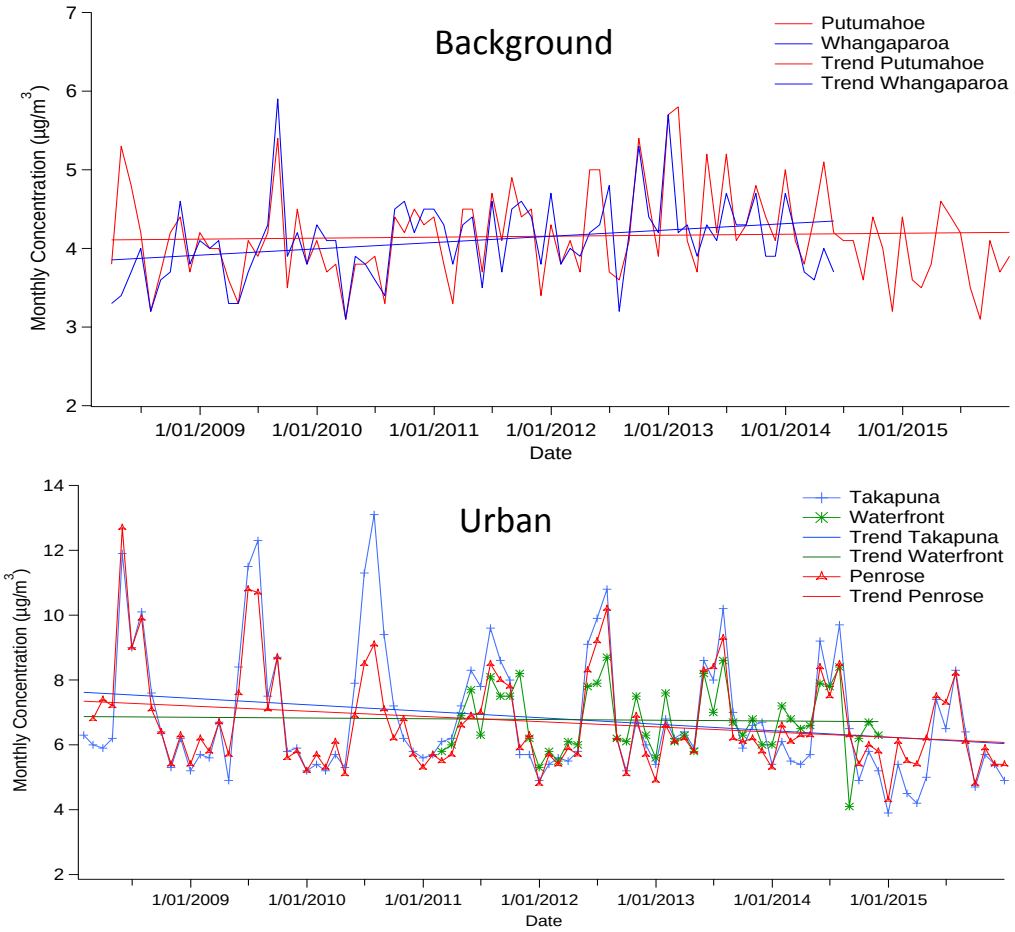


Figure 8 Monthly $PM_{2.5}$ concentrations for all Auckland monitoring sites reported upon here from 2008, rather than 2006, due to data availability. Monitoring locations have been separated into geographical region.

The trends calculated for $PM_{2.5}$ show slightly declining urban concentrations despite slight increases in region-wide background $PM_{2.5}$ (as measured at the Patumahoe and Whangaparoa monitoring sites). This demonstrates that anthropogenic $PM_{2.5}$ emissions near to the urban monitoring sites (likely to be predominantly from motor vehicles and domestic home heating) are likely to have decreased over the analysed period.

The urban sites are notable for the similarity of their monthly average $PM_{2.5}$ concentrations. The data for all urban sites show similar seasonal variability. This likely reflects increased winter-time $PM_{2.5}$ emissions from home heating and seasonal differences in meteorology, with reduced dispersion conditions more frequent in winter months, leading to higher ambient $PM_{2.5}$ concentrations each winter.

4.2.1 $PM_{2.5}$ Statistical trend analysis

Table 4 Summary of trend analysis results using data from 2008 until the end of 2015

	Site	Method	Period (years)	Overall trend		Significant trend(s)?
				± µg/m^3 / Year	P - value	
$PM_{2.5}$	Takapuna	BAM	6.55	-0.05	0.5052	No
	Penrose	BAM	7.00	-0.04	0.5313	No
	Patumahoe	BAM	7.00	0.05	0.5884	No
	Whangaparoa	BAM	5.73	0.04	0.0583	No
	Waterfront	BAM	2.86	0.10	0.8183	No

None of the five $PM_{2.5}$ sites analysed for trends shows statistically significant ($p < 0.001$) declining or increasing trends over the 2008 to 2015 period, suggesting generally stable concentrations. Of the 12 PM_{10} datasets analysed for trends, five urban sites (Khyber Pass, Henderson, Takapuna, Penrose and Pakuranga) all had significant ($p < 0.001$) declining trends across their periods of record. There is a clear delineation between the air quality sites near to major roads and those located at more suburban sites. The locations with vehicle emission sources close to them all show significant decreases in concentration over the measurement period while the sites away from direct sources overall show no significant trend, or a small increasing trend.

5. Compliance with the 2016 Auckland Plan PM_{10} target

Strategic direction 7 of the Auckland Plan titled *"Acknowledge that nature and people are inseparable"* has a specific PM_{10} concentration reduction target:

> *"to reduce air pollutant emissions (PM_{10}) by 50% by 2016 (based on 2006 levels) in order to meet national and international ambient air quality standards and guidelines, and achieve a further 20% reduction by 2040"*

Strategic direction 7 is an emission target rather than a concentration limit. This is an important distinction as a 50% reduction in PM_{10} emissions would not be reflected in a 50% reduction in PM_{10} concentrations due to factors such as non-anthropogenic sources. To determine compliance with this emission reduction target, a separate analysis of PM_{10} emission sources is required. Emission inventories are regularly carried out for this purpose by Auckland Council with the next inventory due to be released late 2017.

This report does not attempt to directly assess PM_{10} emissions but focuses on concentration reductions in PM_{10} to estimate how anthropogenic emissions may have changed over the last decade for comparison against the Auckland Plan target.

Natural sources of PM_{10} such as sea salt contribute approximately 60% to Auckland's urban PM_{10} mass concentration over a year (with seasonal variation) (Davy et al., 2017). Therefore, if the Auckland Plan's PM_{10} emissions reduction target is achieved, measured concentrations should show a 20% reduction, given a 50% reduction in the 40% portion of the human-made emissions and assuming constant meteorological factors.

Table 4 Percentage change between 2006 annual averages and 2016 annual averages (PM_{10}).

Site	2006 annual average	2016 results	Difference	Difference
	($\mu g/m^3$)	($\mu g/m^3$)	($\mu g/m^3$)	(%)
Henderson	16	13	-4	-25
Glen Eden	13	13	0	0
Takapuna	18	14	-4	-22
Penrose Gavin St	18	16	-2	-11
Pakuranga	17	15	-2	-12
Average	16.4	14.2	-2.2	-13

It appears that based on the annual-average ambient PM_{10} concentrations for 2016 the target to reduce anthropogenic PM_{10} emissions by 50% by the end of 2016 were not met at an airshed scale. However, it is clear from Table 5 that both Henderson and Takapuna met the estimated required reduction in ambient PM_{10}. Glen Eden, which has no notable vehicle sources nearby and is impacted by residential wood burning did not show any decline in ambient PM_{10}. As previously discussed, the high traffic signal sites show the largest reductions due to modernising fleets and regulatory improvements in fuel quality. New vehicles, including the bus fleet, have to meet increasingly stringent vehicle emission targets. It is therefore apparent that much of the reduction in ambient PM_{10} is due to vehicle emission controls (Davy et al., 2017. Xie et al., 2017).

5.1 Trends in National Environmental Standards exceedances for PM_{10}

Despite the general decline in concentrations of PM_{10} and $PM_{2.5}$, the Auckland Airshed has still periodically exceeded the NES-AQ for PM_{10} in recent years. The bulk of these exceedances were caused by home heating emissions in winter.

The NES-AQ requires that airsheds meet the Ambient Air Quality Standard for PM_{10} of 50 µg/m³ as a 24-hour average before varying dates depending on their past compliance history. This variation of compliance due dates was a pragmatic allowance so that airsheds which had poor records of compliance had longer to reduce PM_{10} emissions to be able to maintain compliance with the standard.

In the five-year period prior to the 2011 amendments of the NES-AQ coming into force, the Auckland Urban Airshed averaged 4.2 exceedances of the 24-hour average PM_{10} standard per year. This starting level of compliance required Auckland to have no more than one 24-hour period of PM_{10} in excess of 50 µg/m³ per 12-month period by 1 September 2016.

Based on the lack of exceedances recorded in 2014 to 2016, it appears that the Auckland Urban Airshed is on track to comply with this requirement. However, the highly variable nature of short term PM_{10} concentrations means that compliance with the NES-AQ cannot be assured into the future. Less favourable meteorological conditions could still result in periodic exceedances of the standard, particularly in winter when greater PM_{10} emissions occur.

Airsheds, where there was a history of non-compliance, are also defined by the NES-AQ as 'polluted' for a period of five years from the date of the most recent breach of the PM_{10} standard. The Auckland Urban Airshed is therefore currently defined as 'polluted', meaning that there are additional restrictions for the granting of industrial air discharge consents. These restrictions are scheduled to end in October 2018, being five years after the date of the most-recent PM_{10} exceedance (which occurred in October 2013 at the Khyber Pass monitor), unless a further breach of the standard occurs prior to this date.

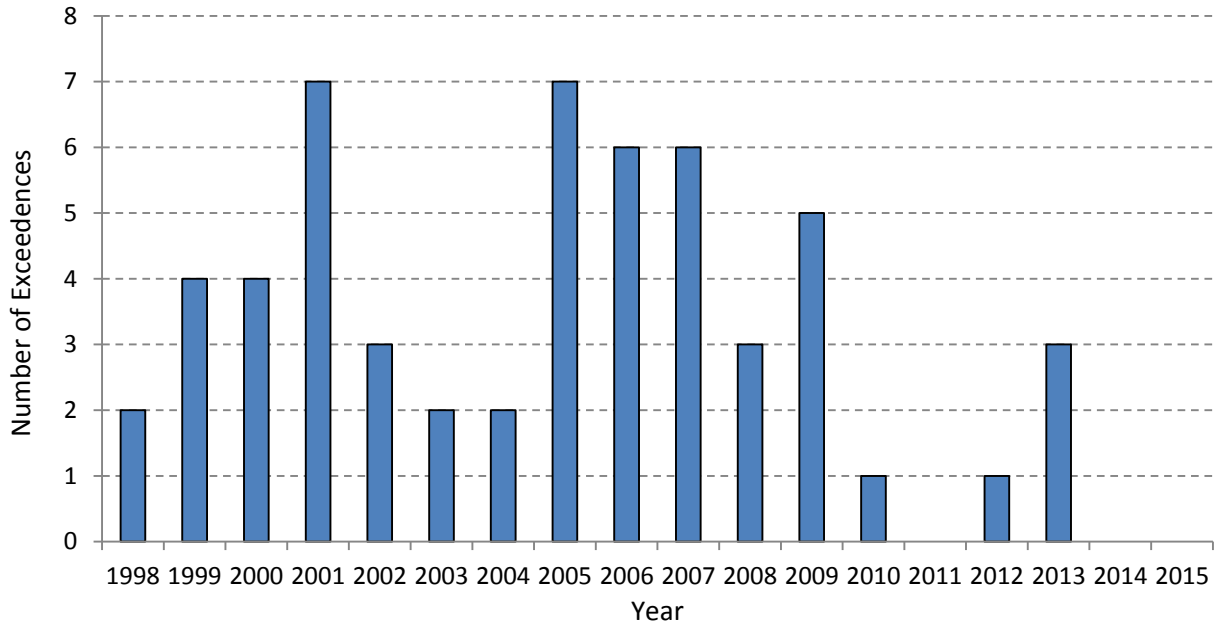


Figure 9 The number of days where NES-AQ for PM_{10} was exceeded in the Auckland airsheds, 1998 - 2015.

6. Conclusions

$PM_{2.5}$ and PM_{10} concentrations at Auckland's urban monitored sites have declined since 2006; five of the 12 PM_{10} monitoring sites showed statistically significant declining trends. No site reported a statistically significant increasing trend. Peak traffic sites, with highest concentrations, reported the strongest declining trends. Background sites reported no statistically significant trends. Annual average $PM_{2.5}$ and PM_{10} concentrations are below relevant standards and guidelines, and in general, these are also declining. The decline in particulate matter concentrations at monitored sites is positive for the health of people in Auckland. However, with the increase in road traffic, growing urban population and density throughout Auckland, the number of people exposed to locally emitted particulate matter 'plumes' will increase, and with it, the possibility of health impacts. There is no safe level of particulate matter exposure.

Under the current NES-AQ, there is no standard for $PM_{2.5.}$ However, with concern growing internationally over the health effects of $PM_{2.5}$, it is probable that $PM_{2.5}$ may be included in the NES-AQ in the future; therefore it remains important to continue to focus on $PM_{2.5}$ concentrations considering the well documented detrimental impacts on human health.

At present, the Auckland urban airshed must comply with the NES-AQ requirement of one or fewer exceedances of the 24-hour average PM_{10} standard per year. Based on recent years, compliance with this requirement appears likely into the future, although given the highly variable nature of short-term peak PM_{10} concentrations, it is possible for exceedances to occur against a background of declining concentrations. Further efforts to reduce the PM_{10} peaks predominantly caused by home heating emissions in winter will further reduce overall PM_{10} concentrations and the potential for exceedances of the NES-AQ.

Source apportionment trends reported by Davy et al., (2017) reveal increased emissions from home heating over the reported period. This increase in emission has been offset by a greater reduction from vehicle emissions due to improvements in the quality of fuel. Cleaner fuel emits less $PM_{2.5}$ and PM_{10} emissions resulting in cleaner air. This provides a clear example of achievement using regulatory bodies to drive change. Recently, total emissions of pollutants from vehicle exhaust have levelled off, and due to the increasing number of vehicles on Auckland's roads, total emission values could start to increase again in the near future. Regulatory policy to decrease emissions from home fires have been less successful, with Aucklanders seemingly unwilling, or unable to move away from using high polluting domestic fires to heat houses instead of modern, low polluting methods. This is despite evidence of the inefficiency of old fireplaces and the prevalence of asthma due to cold, damp homes.

Compared to other large (million plus population) cities around the world, Auckland has very good air quality. This is because of our fortuitous geographical location, and increasingly, due to decreases in transport emissions. However, there is no safe threshold for exposure to $PM_{2.5}$ and PM_{10}. With a rapidly increasing urban population, the total burden of air pollution exposure could increase despite decreasing emissions. Auckland offers good air quality throughout the majority of the region, but further improvements are required to continue the downward trend in concentrations of airborne particulate observed over the past 10 years.

Main results:

- Annual average $PM_{2.5}$.and PM_{10} have declined and are below relevant standards and guidelines.
- Statistically significant declines in $PM_{2.5}$ concentrations (both considering the entire dataset and the seasonal scales) were reported at two of seven sites.
- Statistically significant declines in PM_{10} concentrations (at both entire dataset and seasonal datasets) were reported at six sites.
- Concentrations at peak monitoring sites are declining.
- Concentrations at background monitoring sites are stable.
- Between 1998 and 2014 the number of exceedances of the national short-term PM_{10} standard declined by 0.2 exceedances per year. Based on this trend we should continue to see a decline in the number of exceedances recorded.

7. Acknowledgements

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9. Appendix A: Methodology

Figure 10. BAM instrument at Khyber Pass.

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9.1 Site descriptions and data availability

$PM_{2.5}$ and PM_{10} from 12 existing Auckland Council ambient air quality monitoring sites are used in this report. Auckland Council has previously monitored in other locations, however, for the purposes of the Auckland Ambient Air Quality Targets it is more useful to use sites which will continue to operate for the foreseeable future. Table 2 summarises the sites used. Further information is available in Petersen and Smith, (2006).

The sampling mechanics work as follows; PM passes through the intake system and is deposited on a glass fibre filter tape, sandwiched between a radioactive source and a detector. Beta-rays from the radioactive source pass through the filter (and thus the PM), with higher levels of PM causing a lower beta-ray reading. This is corrected against an on-board correction chamber, with the same absorptivity as clean filter tape. As PM collects on the filter, and the difference between the filter and correction chamber reading changes, the instrument converts this into PM concentrations, corrected for flow rate, and a suite of relevant temperature measurements from the installation. This means that BAM data has a higher resolution, as data are collected continuously.

Some sites in the Auckland Council network monitor $PM_{2.5}$ and PM_{10} by both BAM and Partisol, often for differing lengths of record. Since trend analysis is strongest when long periods of data are analysed, the longest continuous records available at each site were selected for analysis. Partisol data were used preferentially when similar records of BAM and Partisol data were available. Partisol data however does yield a lower resolution dataset, as it runs as a 24hr average for 1 day in 3[1]. This lower resolution is countered by longer periods of data being available.

Table 2 details the final methods used for analysis by this report. Importantly, it highlights the quality of the Auckland Council $PM_{2.5}$ and PM_{10} data, with no site having less than 82% valid data for the study period (MfE recommends that datasets should have more than 75% valid data for averaging and long term analysis (MfE, 2009)). Out of the 19 $PM_{2.5}$ and PM_{10} datasets analysed in this report, 7 datasets are longer than 10 years. It is anticipated that these longer datasets will yield more robust trends

[1] With the exception of the Sequential Partisol instrument at Queen St which measures daily averages.

10. Appendix B: $PM_{2.5}$ Trend analysis

This appendix presents trend analysis figures for $PM_{2.5}$. For each figure, the top pane is annual average concentration. The middle pane is deseasonalised Theil-Sen analysis. The bottom pane is seasonal Theil-Sen analysis. For each Theil-Sen output, the green number is overall trend, with 95% confidence intervals in brackets. The *** after the trend denotes statistical significance (*p*-value) using the following notation:

$p < 0.001 = ***$, $p < 0.01 = **$, $p < 0.05 = *$ $p < 0.1 = +$.

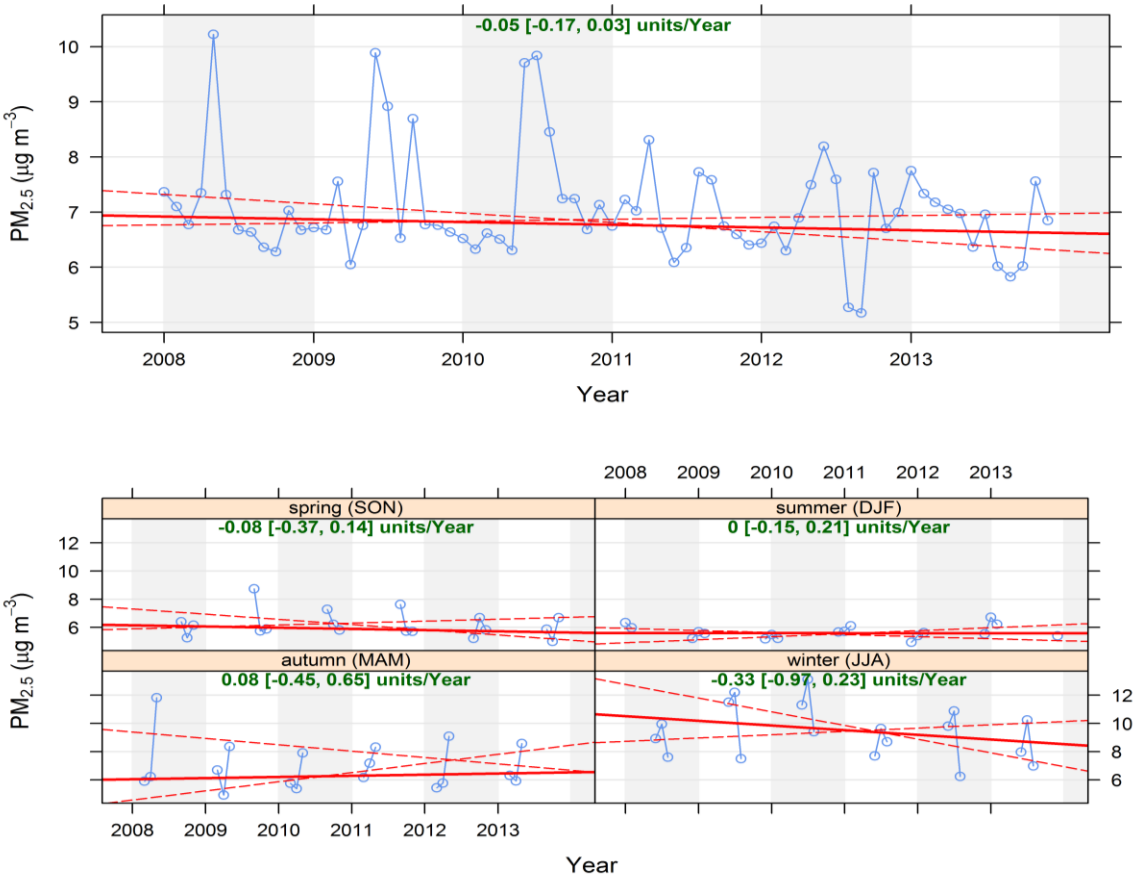

Figure 11. $PM_{2.5}$ Trends at Takapuna.

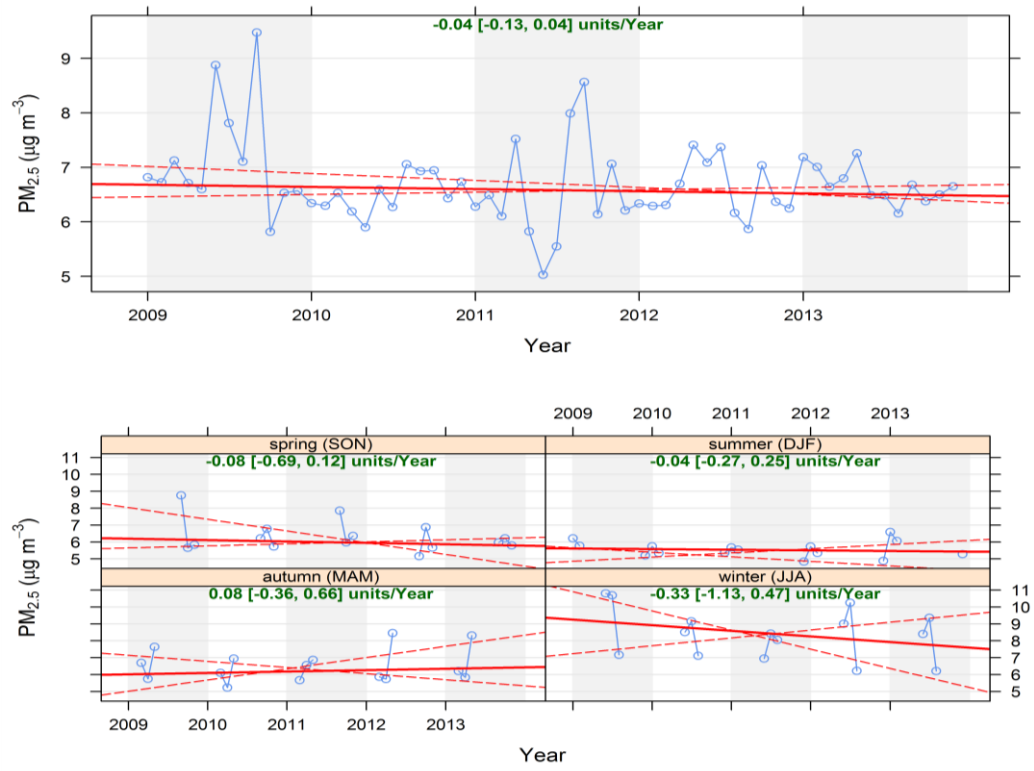

Figure 12. $PM_{2.5}$ Trends at Penrose.

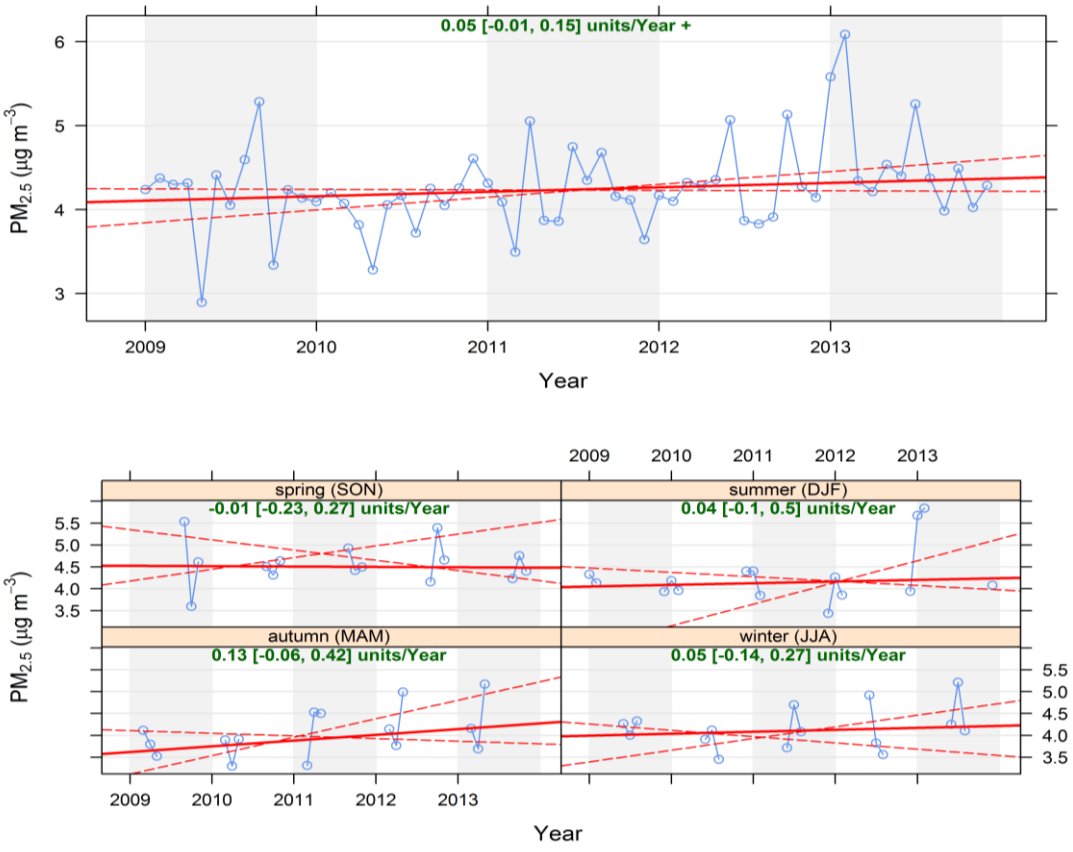

Figure 13. $PM_{2.5}$ Trends at Patumahoe.

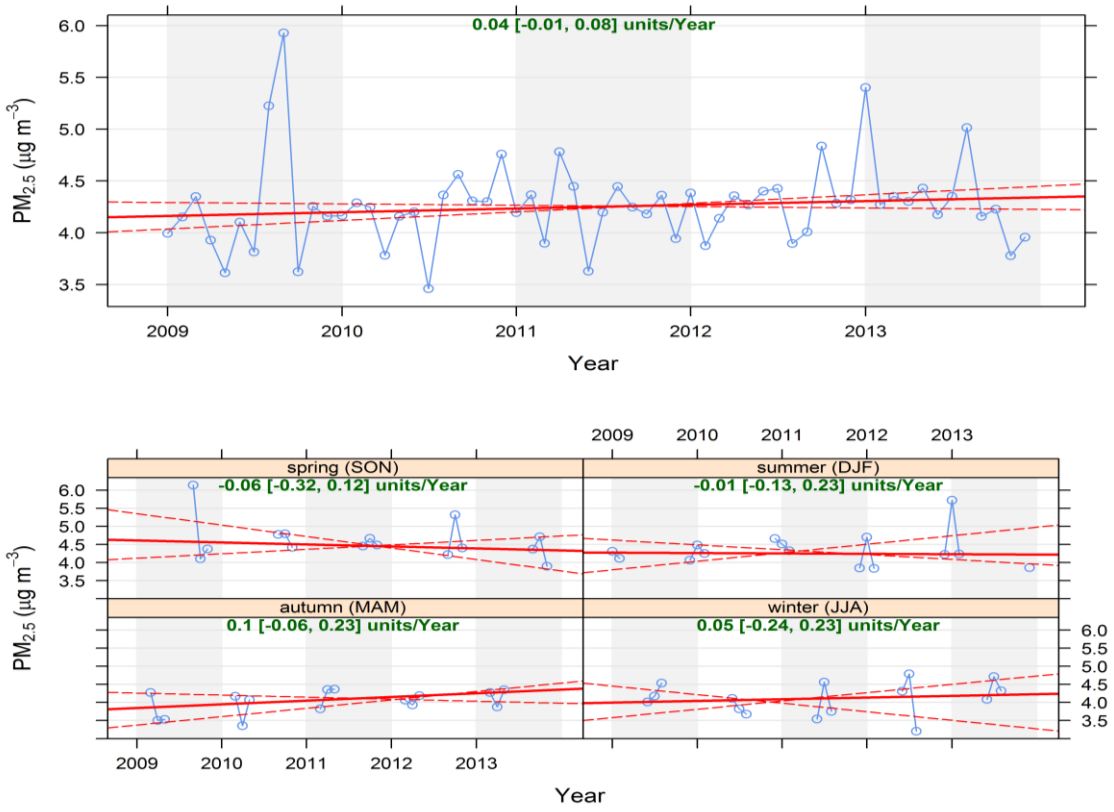

Figure 14. $PM_{2.5}$ Trends at Whangaparoa.

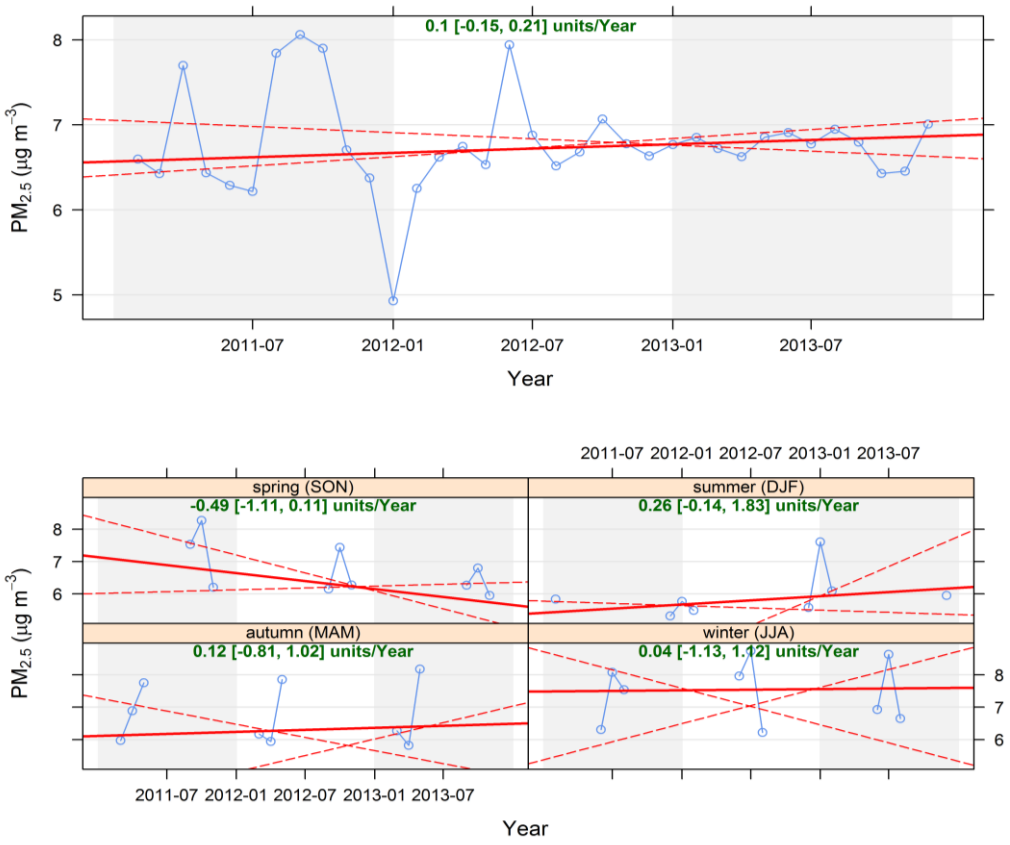

Figure 15. $PM_{2.5}$ Trends at Waterfront.

11. Appendix C: PM_{10} Trend analysis

This appendix presents trend analysis figures for $PM_{2.5}$. For each figure, the top pane is annual average concentration. The middle pane is deseasonalised Theil-Sen analysis. The bottom pane is seasonal Theil-Sen analysis. For each Theil-Sen output, the green number is overall trend, with 95% confidence intervals in brackets. The *** after the trend denotes statistical significance (*p*-value) using the following notation:

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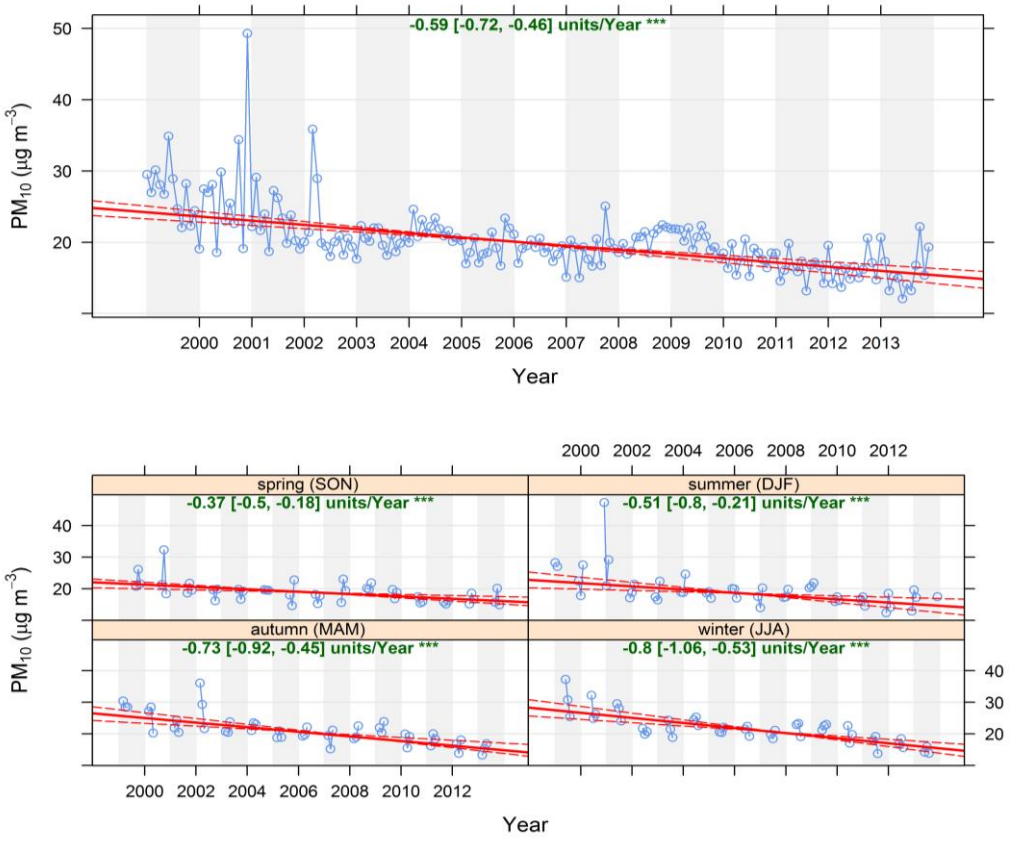

Figure 16. PM_{10} Trends at Khyber Pass.

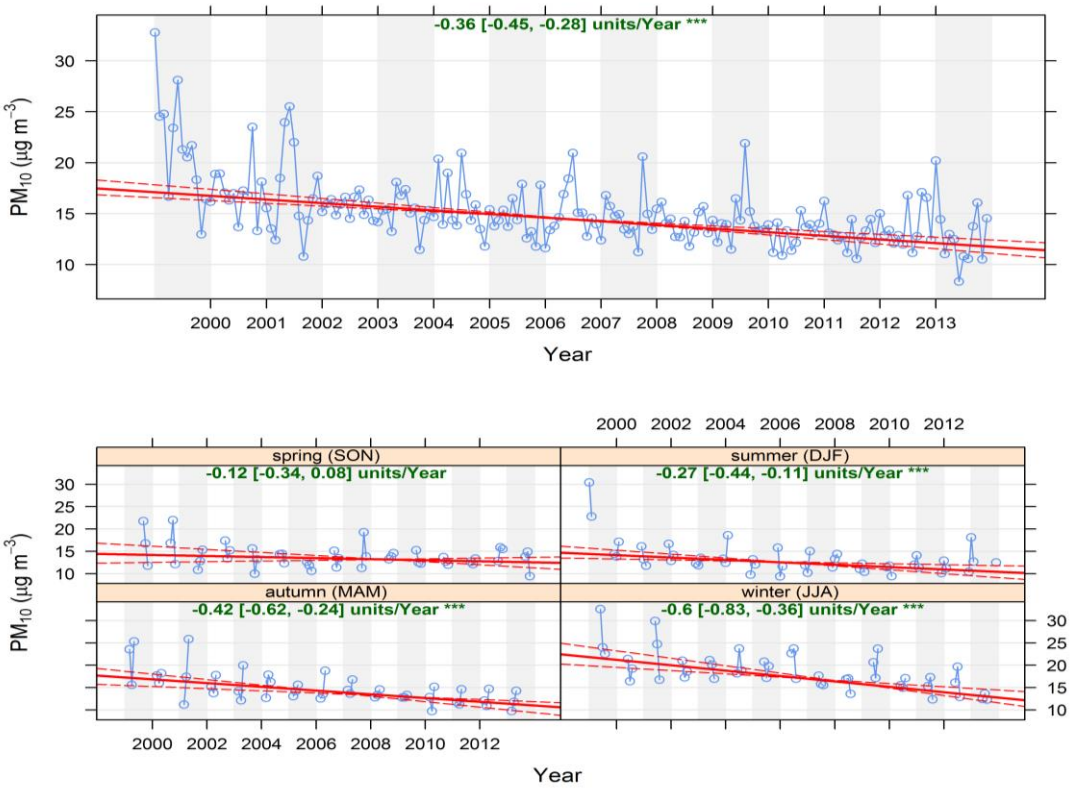

Figure 17. PM_{10} Trends at Henderson.

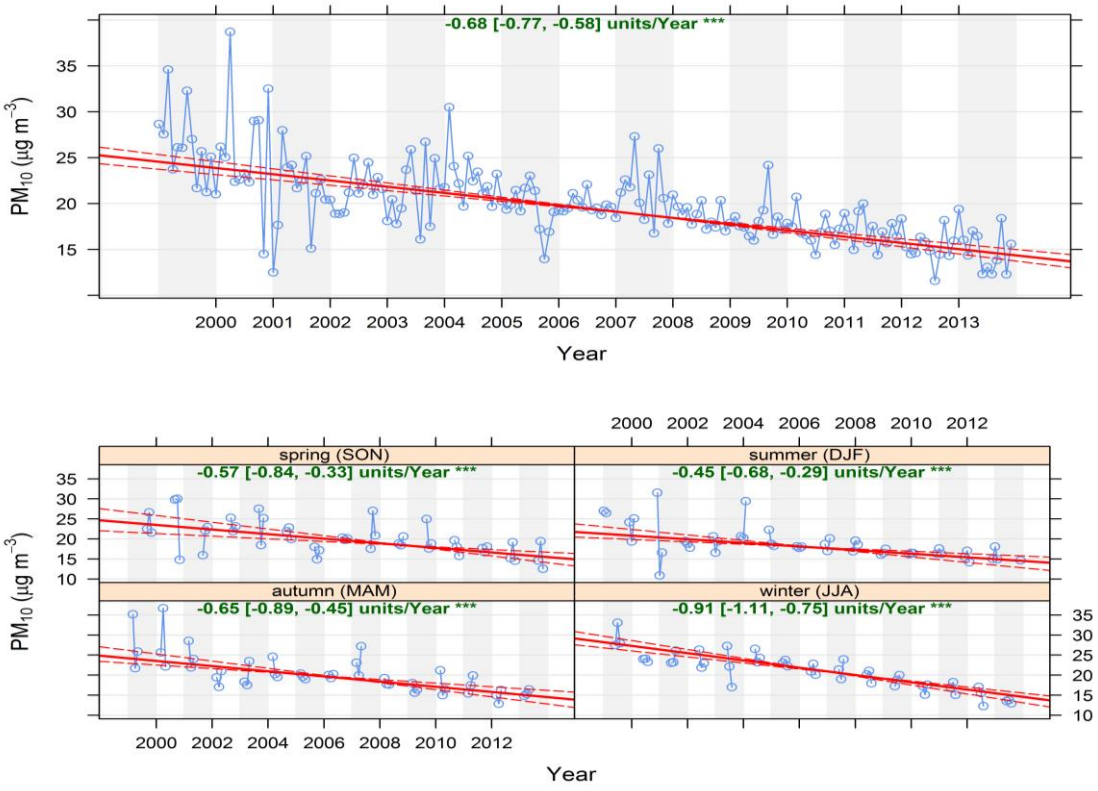

Figure 18. PM_{10} Trends at Queen St.

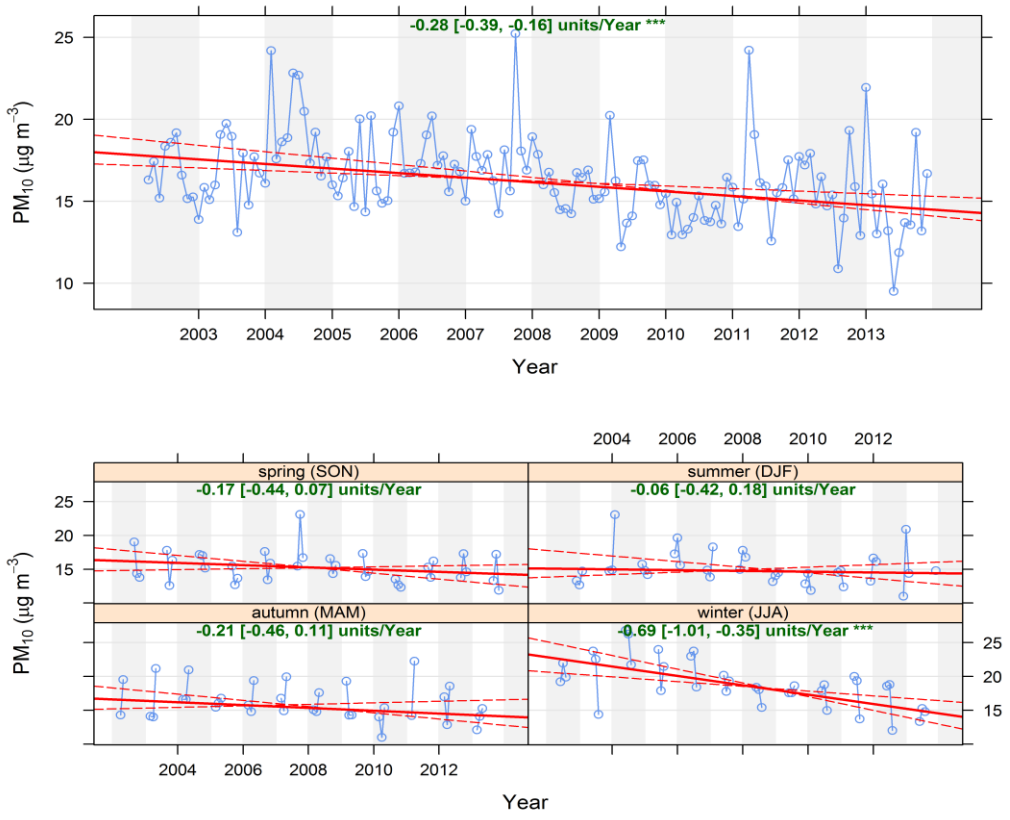

Figure 19. PM_{10} Trends at Takapuna.

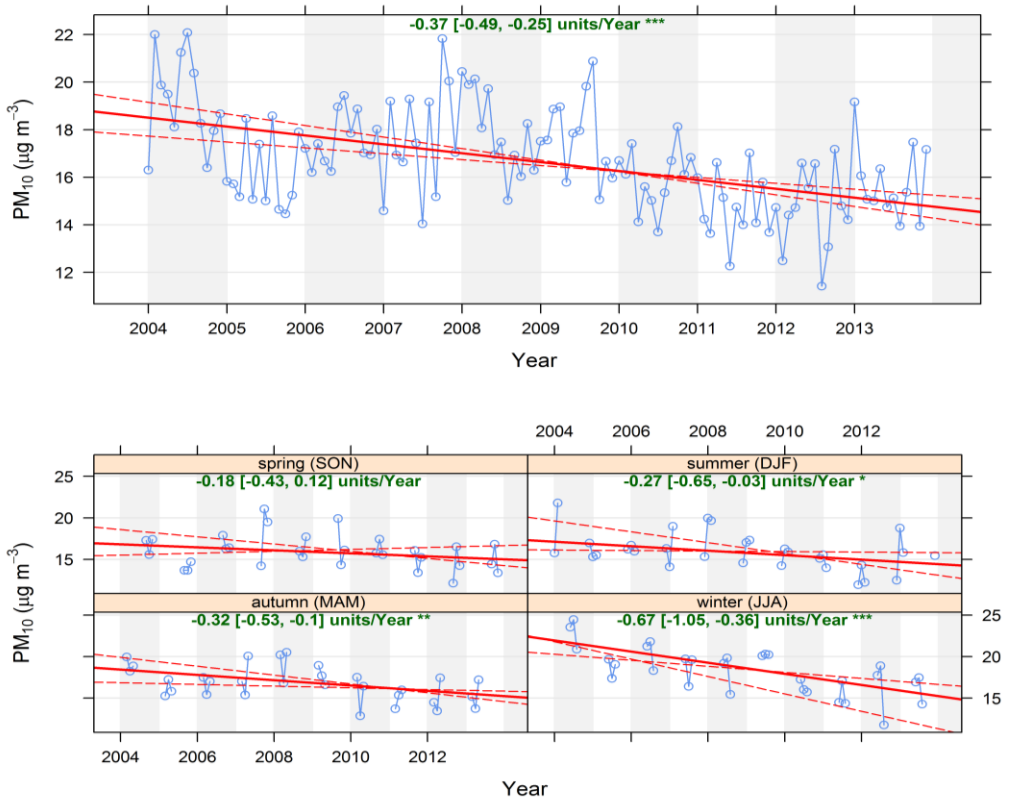

Figure 20. PM_{10} Trends at Penrose.

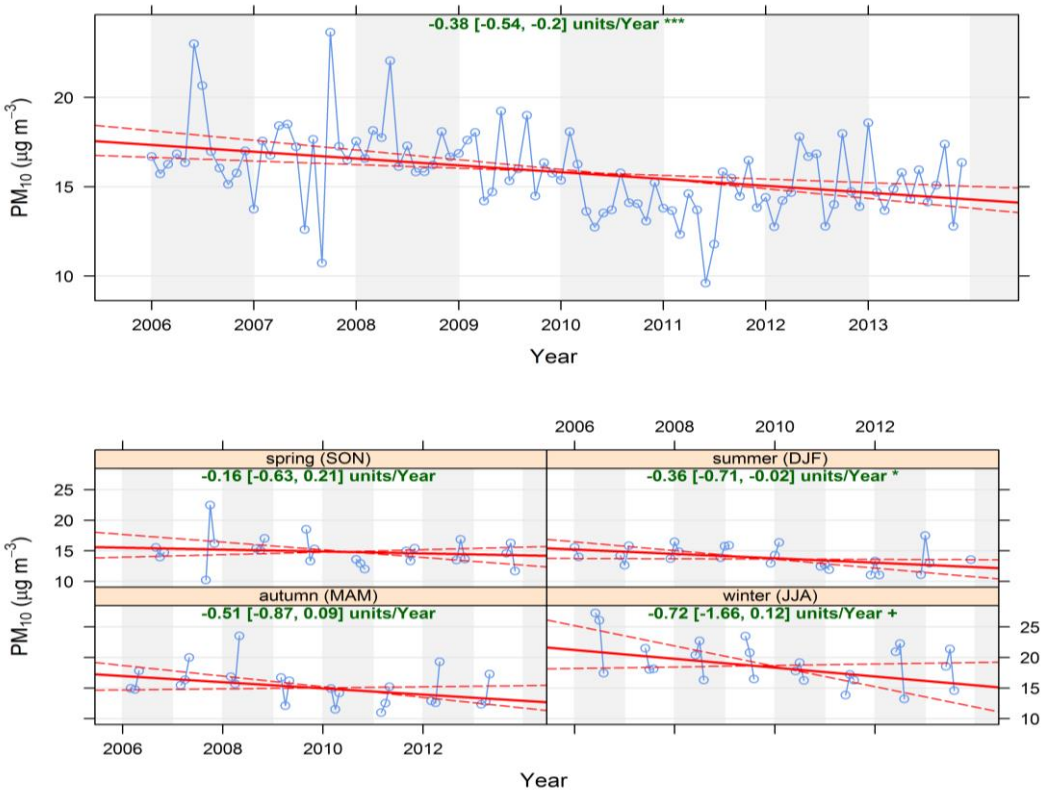

Figure 21. PM_{10} Trends at Pakuranga.

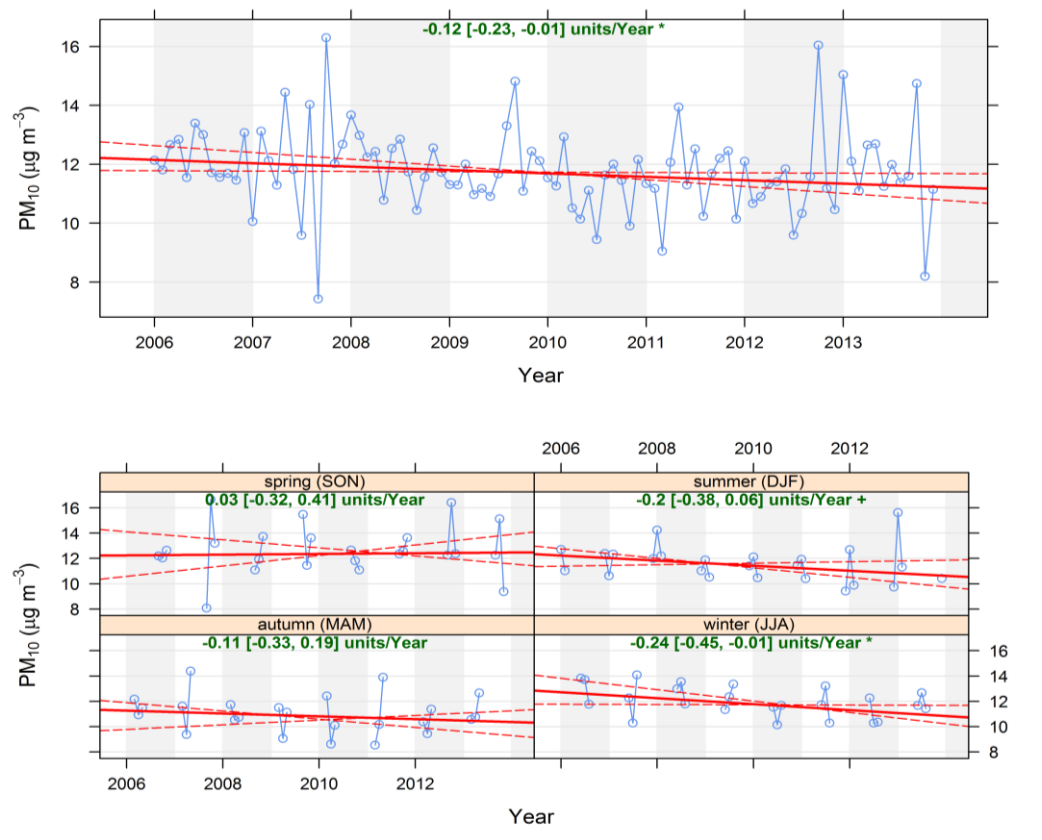

Figure 22. PM_{10} Trends at Botany Downs.

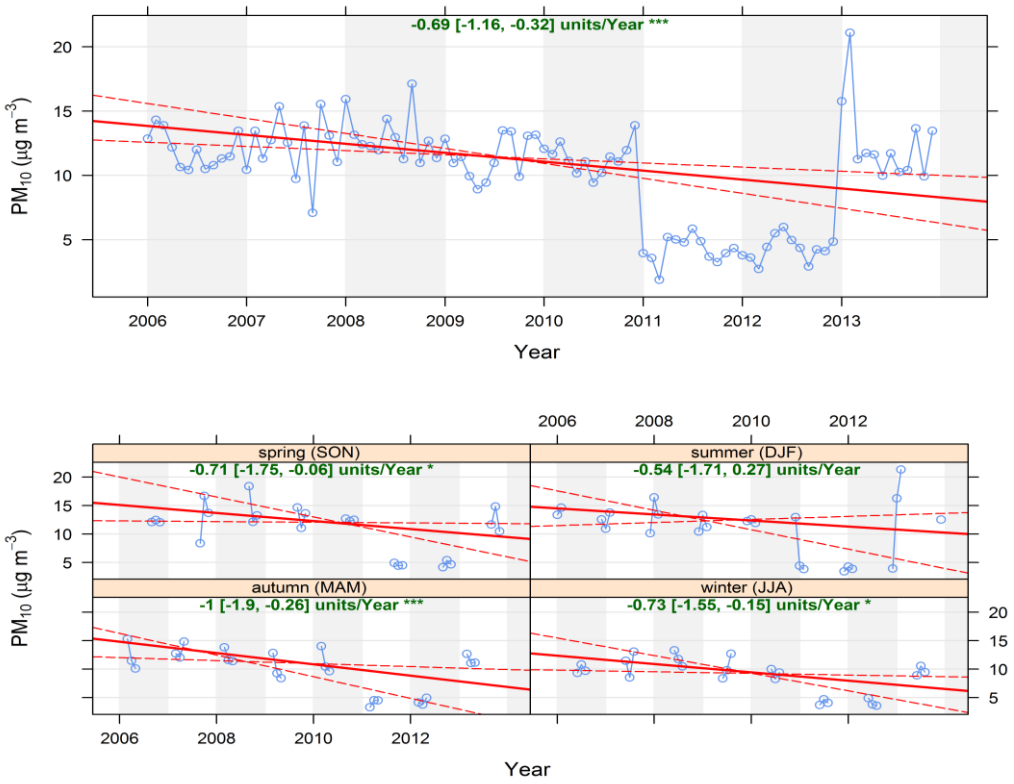

Figure 23. PM_{10} Trends at Patumahoe.

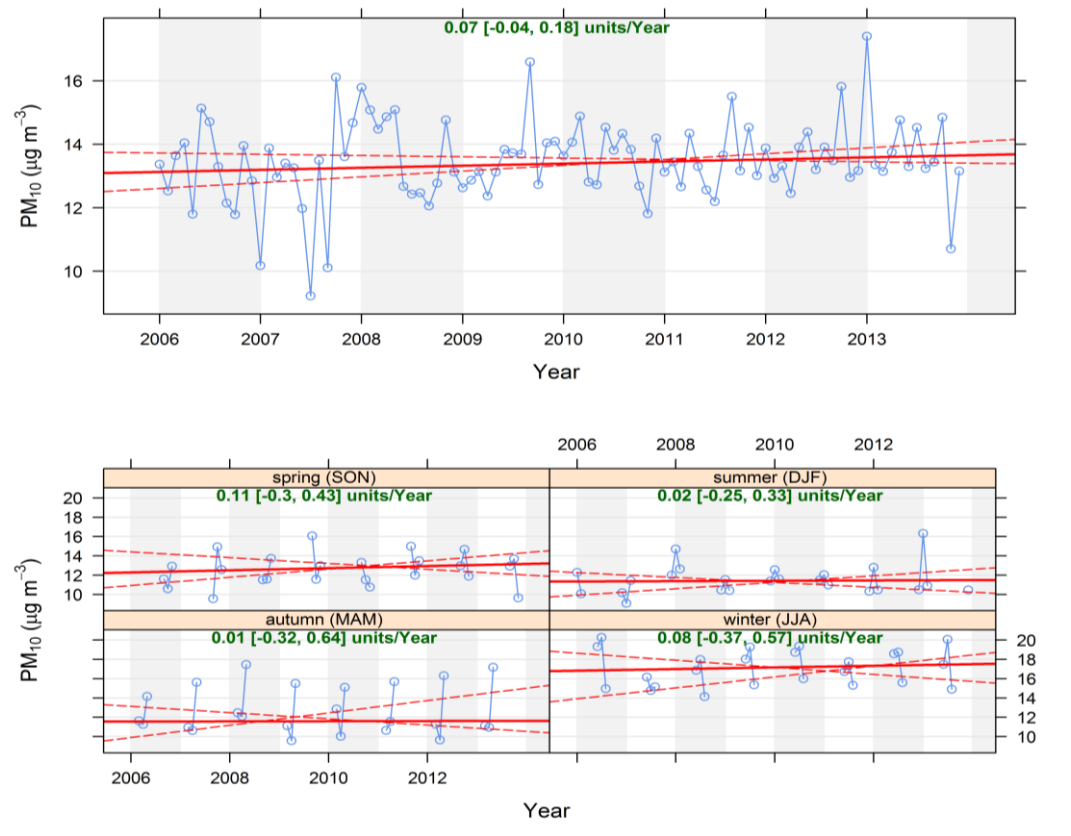

Figure 24. PM_{10} Trends at Glen Eden.

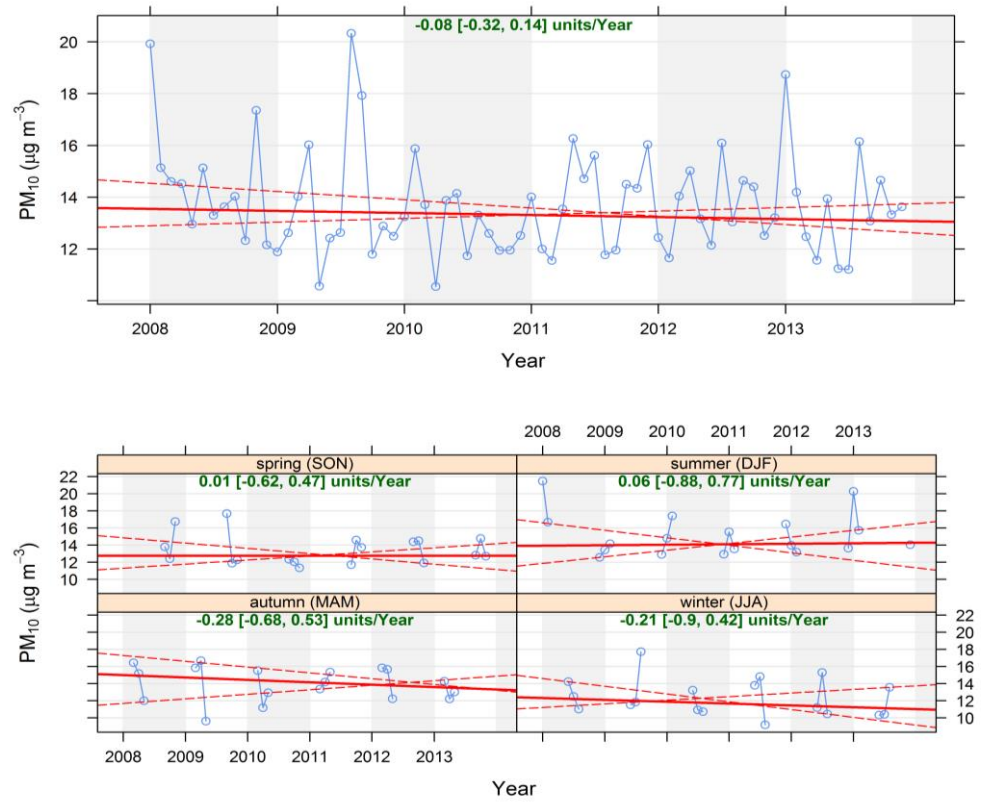

Figure 25. PM_{10} Trends at Orewa.

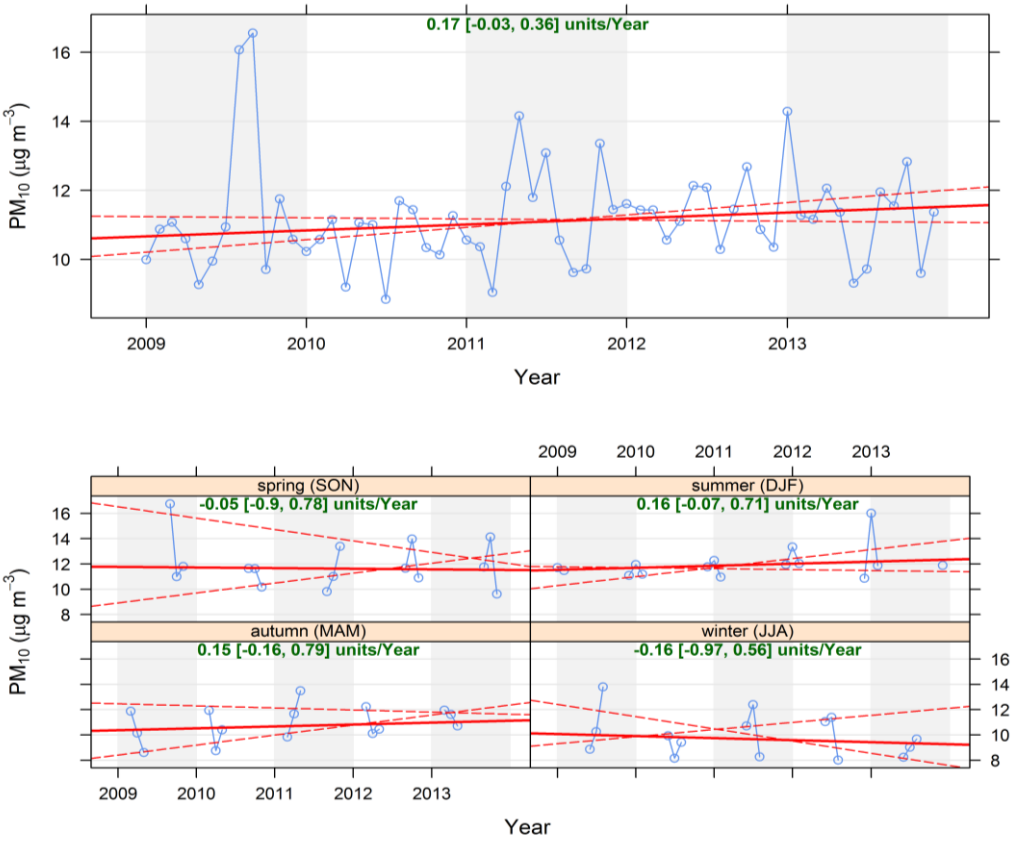

Figure 26. PM_{10} Trends at Whangaparoa.

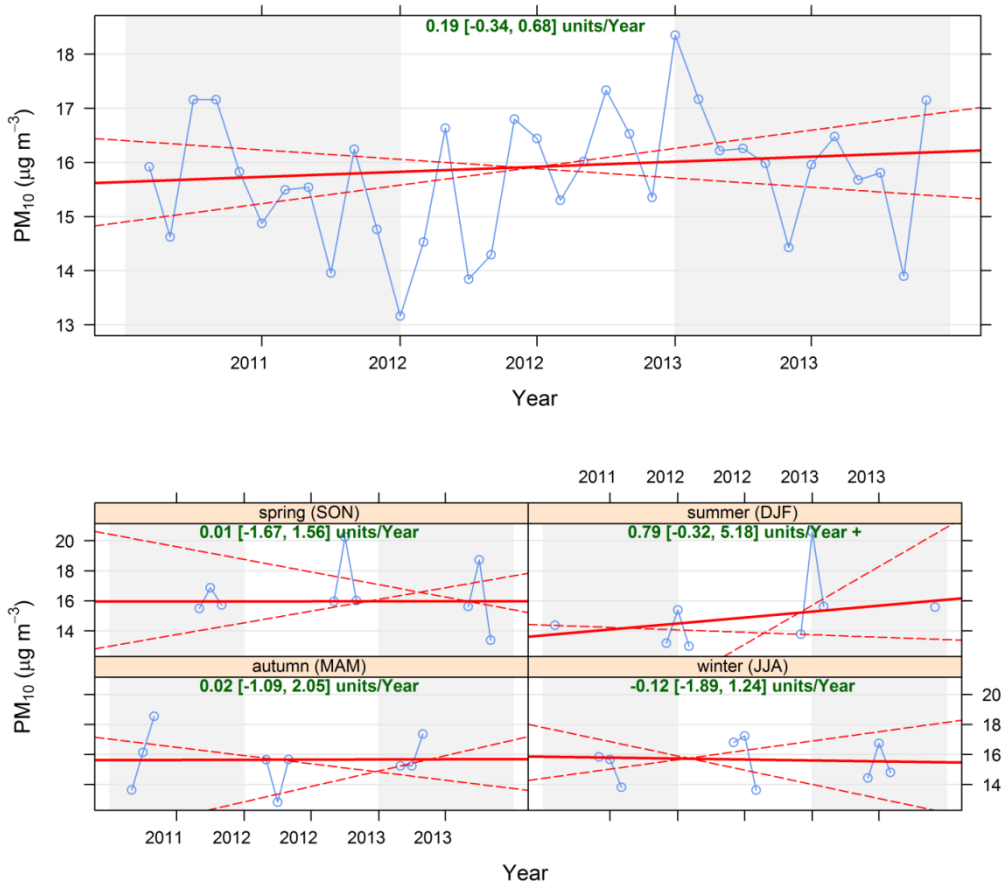

Figure 27. PM_{10} Trends at Waterfront**.**

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