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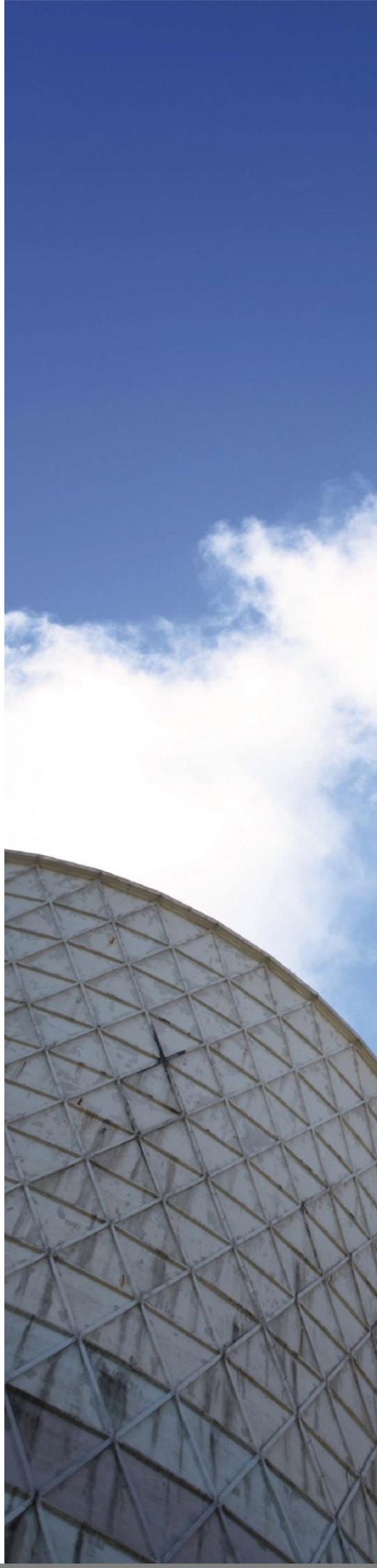
Consulting • Technologies • Monitoring • Toxicology

FINAL REPORT

UPPER HUNTER AIR QUALITY PARTICLE MODEL

Prepared for:

NSW Environment Protection Authority



PROJECT TITLE:	Upper Hunter Air Quality Particle Model
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EXECUTIVE SUMMARY

Purpose of the study

This study was commissioned to investigate primary anthropogenic particulate matter (PM) emission sources and their contribution to annual average PM_{10} and $PM_{2.5}$ concentrations in Singleton and Muswellbrook.

The principal objective of this study was to investigate the effects of potential emission reductions to inform the achievability of a target for reducing long term average PM_{10} and $PM_{2.5}$ concentrations in Singleton and Muswellbrook by answering the following questions:

1. What contribution do primary PM emissions from coal mines, domestic wood heaters, electric power generation and non-road diesel exhaust make to annual average PM_{10} and $PM_{2.5}$ concentrations in Singleton and Muswellbrook in 2012 (base case) and in business as usual (BAU) projections for the years 2016, 2021, 2026 and 2031?

2. How sensitive are annual average ambient PM_{10} and $PM_{2.5}$ concentrations in Singleton and Muswellbrook for the years 2016, 2021, 2026 and 2031 to reductions in primary PM emissions from coal mines, domestic wood heaters, electric power generation and non-road diesel exhaust?

Overview of methodology

The study methodology was developed in accordance with the NSW EPA's Terms of Reference (ToR) for the study and summarised as follows.

Meteorological modelling

The modelling for this study used a combination of TAPM, CALMET and CALPUFF. Surface observations from 10 meteorological monitoring sites were included in the modelling (data assimilation). Two options for data assimilation were investigated:

- Option 1: Data assimilation of observations in TAPM with no observations in CALMET.
- Option 2: Data assimilation of observations in CALMET with no observations in TAPM.

Four meteorological monitoring sites were excluded from the modelling and used for model evaluation (comparison of observed and predicted). Overall, it was concluded that both CALMET options simulate the meteorology with an acceptable degree of accuracy.

Emission estimates

Detailed coal mine emissions inventories were developed for PM_{10} and $PM_{2.5}$ for the base year 2012 and for BAU projections for years 2016, 2021, 2026 and 2031. Hourly emissions files were developed for modelling and spatial variation in activities and emissions across each year were captured. Emissions from diesel use at coal mines were estimated based on recent survey data provided by the EPA. Emissions from wood heaters, power stations and all other sources were derived from data provided by the NSW EPA, based on the Air Emission Inventory for the Greater Metropolitan Region (GMR) in NSW.

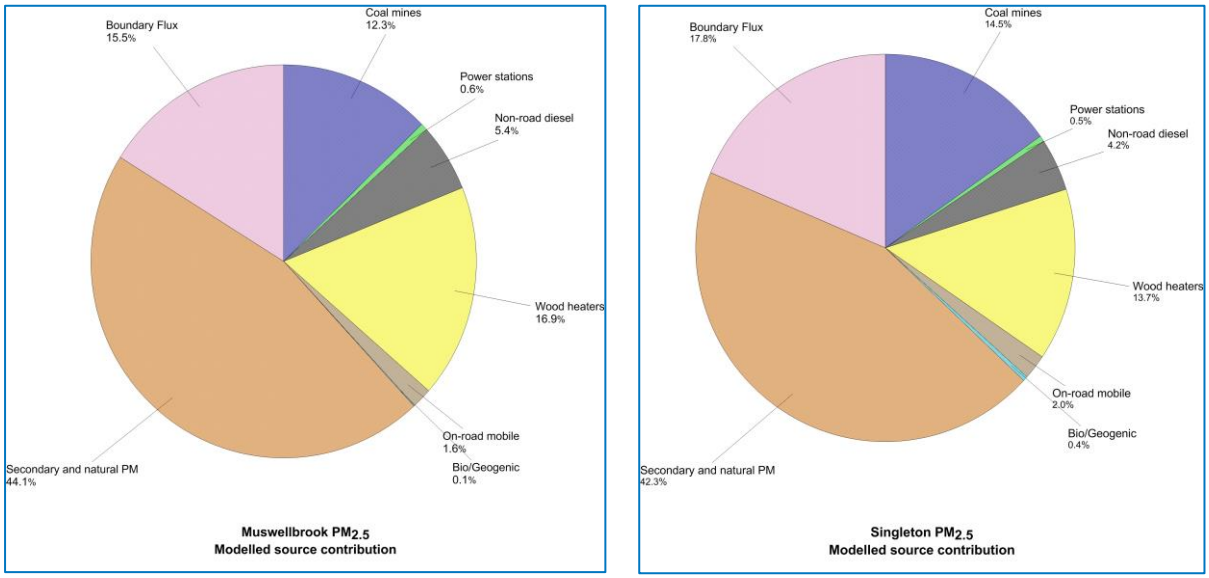
Dispersion modelling

Dispersion modelling for all sources was completed for base year 2012 and analysis of model performance was based on comparison with 2012 monitoring data for PM_{10} and $PM_{2.5}$. Following validation of base year predictions, dispersion modelling was completed for coal mines and diesel emissions for BAU projections, with a focus on annual average PM_{10} and $PM_{2.5}$ in Singleton and Muswellbrook. BAU projections for other sources were scaled based on 2012 modelling results. Emission reduction analysis is presented for BAU projections based on illustrative percentage reductions for coal mines, wood heaters, electric power generation and non-road diesel exhaust.

Study results and conclusions

Source contribution

The modelled source contributions to annual average $PM_{2.5}$ concentrations in 2012 are summarised in **Figure 1**. The non-modelled (estimated) contribution from secondary and natural PM and boundary flux (background) is also shown. Wood heater emissions are the largest single (primary anthropogenic) contributor to annual average $PM_{2.5}$ concentrations for Muswellbrook (16.9%) and coal mine emissions are the largest single contributor in Singleton (14.5%). The combined contribution from coal mines and non-road diesel exhaust is higher than wood heaters in Muswellbrook. Source contribution to annual average PM_{10} concentrations in 2012 is shown in the body of the report.



Muswellbrook *Singleton*

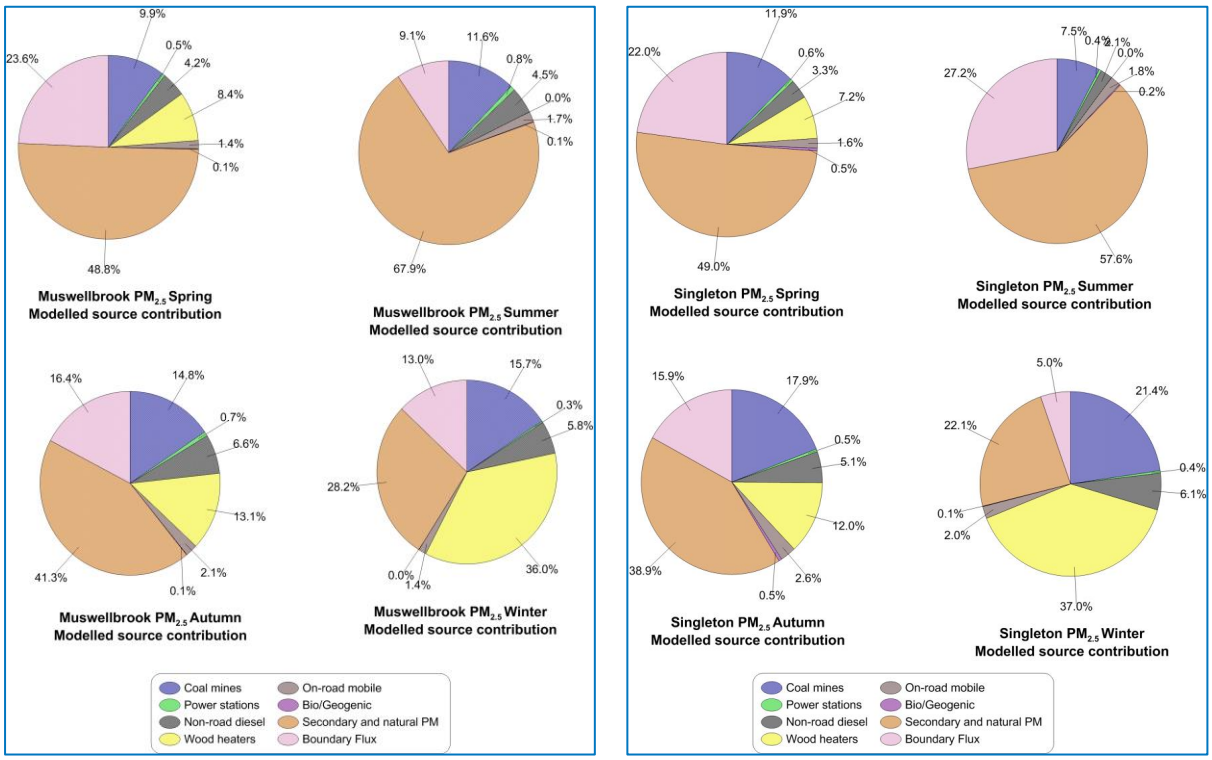
Figure 1: Predicted source contribution to $PM_{2.5}$ base year 2012

Seasonal variation

Significant seasonal variation is evident in source contribution to annual average $PM_{2.5}$ concentrations, as shown in **Figure 2**.

Wood heater emissions dominate in winter for both Muswellbrook (36%) and Singleton (37%). In other seasons, coal mine emissions are the largest (primary anthropogenic) contributor for both Muswellbrook (10% - 16%) and Singleton (7% - 21%). Wood heater emissions also significantly contribute in Spring and Autumn.

The seasonal variation in source contribution to annual average PM_{10} concentrations in 2012 is shown in the body of the report.

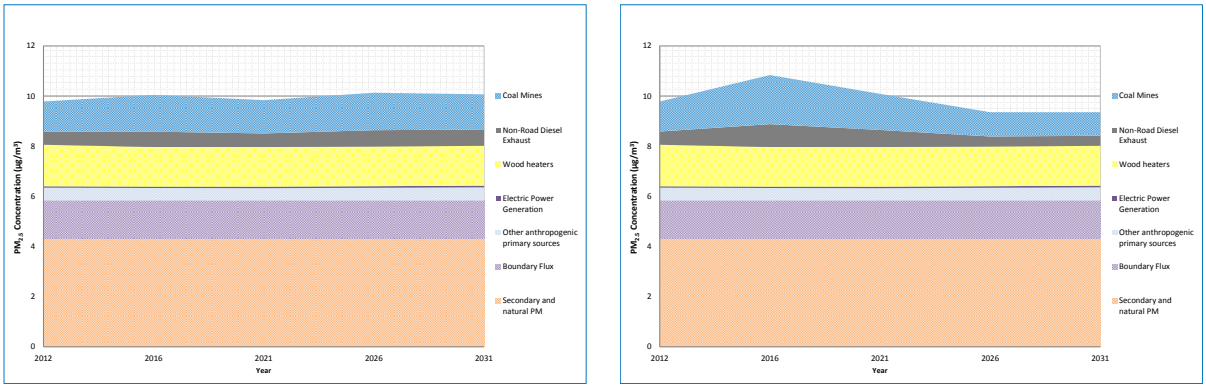


Muswellbrook Singleton

Figure 2: Predicted seasonal variation in source contribution to $PM_{2.5}$ base year 2012

Business as usual projections

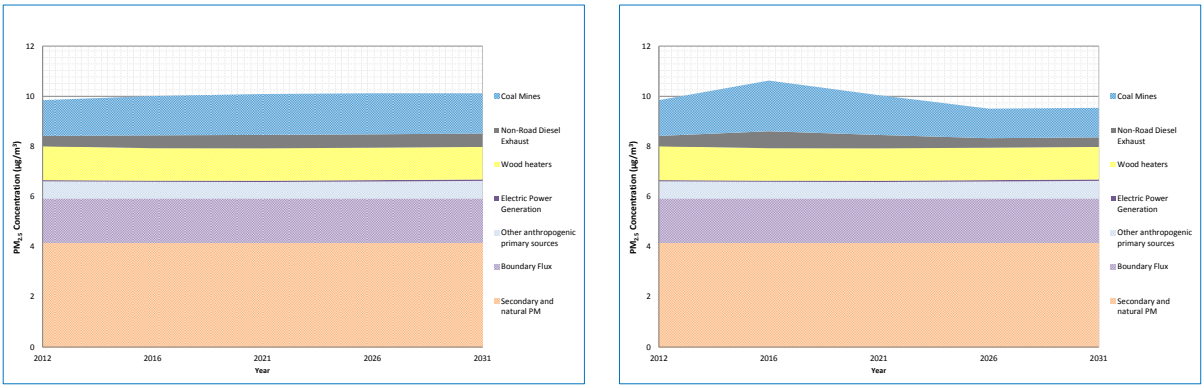
The annual average $PM_{2.5}$ concentration in Muswellbrook for BAU scenarios is presented in **Figure 3**. Under the BAU "likely" scenario, the annual average $PM_{2.5}$ concentrations in Muswellbrook increase in 2016 but drop in 2021. This is a result of certain mining activity moving away from Muswellbrook, for example Drayton mine finishing and being replaced by Drayton South. The annual average $PM_{2.5}$ concentrations in Muswellbrook increase again in 2026, as new mines are established, before dropping slightly in 2031.



Likely Scenario Consent Scenario

Figure 3: BAU annual average $PM_{2.5}$ concentration in Muswellbrook

The annual average $PM_{2.5}$ concentration in Singleton for both BAU scenarios (likely and consent) is presented in **Figure 4**. Under the BAU "likely" scenario, the annual average $PM_{2.5}$ concentrations in Singleton increase very slightly (~0.1 µg/m^3) each year to 2026, from a combination of coal mines and non-road diesel increasing slightly.

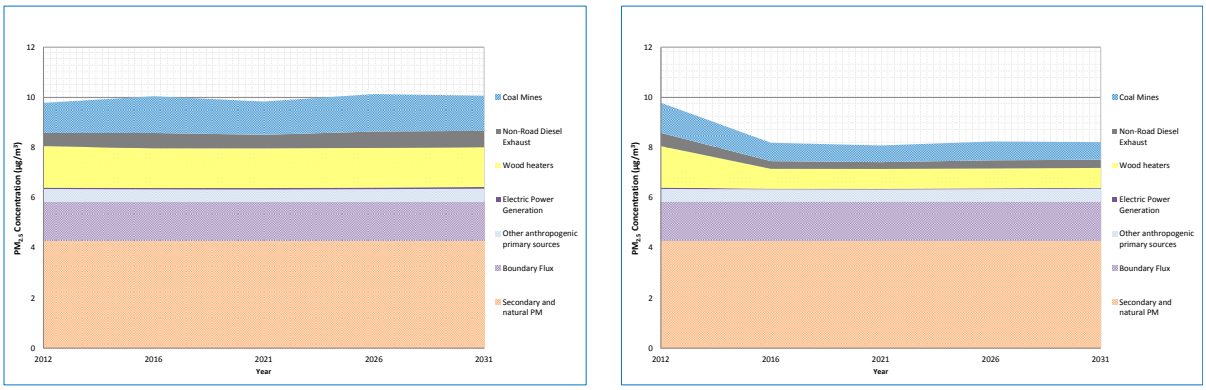


Likely Scenario | Consent Scenario

Figure 4: BAU annual average $PM_{2.5}$ concentration in Singleton

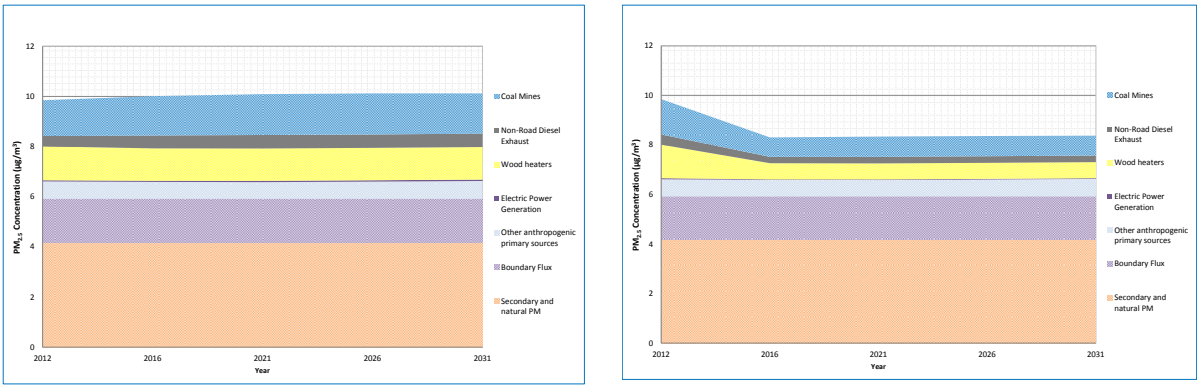
Emissions reductions

The effect of a 50% emission reduction, applied to each of the four key sources for the likely scenario is presented in **Figure 5** for Muswellbrook and **Figure 6** for Singleton. The plots compare annual average $PM_{2.5}$ concentrations for BAU likely scenario (left panel) with a 50% emission reduction applied across all four key sources (right panel).



BAU – Likely Scenario | 50% emission reduction for four key sources

Figure 5: BAU "likely" scenario compared with 50% emissions reduction for Muswellbrook



BAU – Likely Scenario | 50% emission reduction for four key sources

Figure 6: BAU "likely" scenario compared with 50% emissions reduction for Singleton

The annual average PM_{10} concentration in Muswellbrook and Singleton for both BAU scenarios and the emissions reduction scenarios are presented in the main body of the report.

It is noted that the BAU projections are very sensitive to assumptions made in estimating emissions for future years. Modelling uncertainty is considered to increase for future years and results should be interpreted with this in mind.

Recommendations for future work

The two most significant sources of uncertainty identified in this study relate to estimates of background/boundary flux from outside the modelling domain and the contribution from secondary particles. The uncertainty is increased in applying these estimates for BAU projections.

Recommendations are made for future work to reduce this uncertainty, including:

- Better representation of regional background or boundary flux.
- Refining the approach for consideration of secondary particles, for example by developing a secondary particle model for the Upper Hunter.

Other recommendations for reducing uncertainty in the modelling presented in this study are:

- Refinement of the approach to prognostic meteorological modelling.
- Improving the spatial resolution of other source contributions from gridded GMR emission inventories.
- Further refinement of the approach for wood heater modelling.

CONTENTS

TABLES

FIGURES

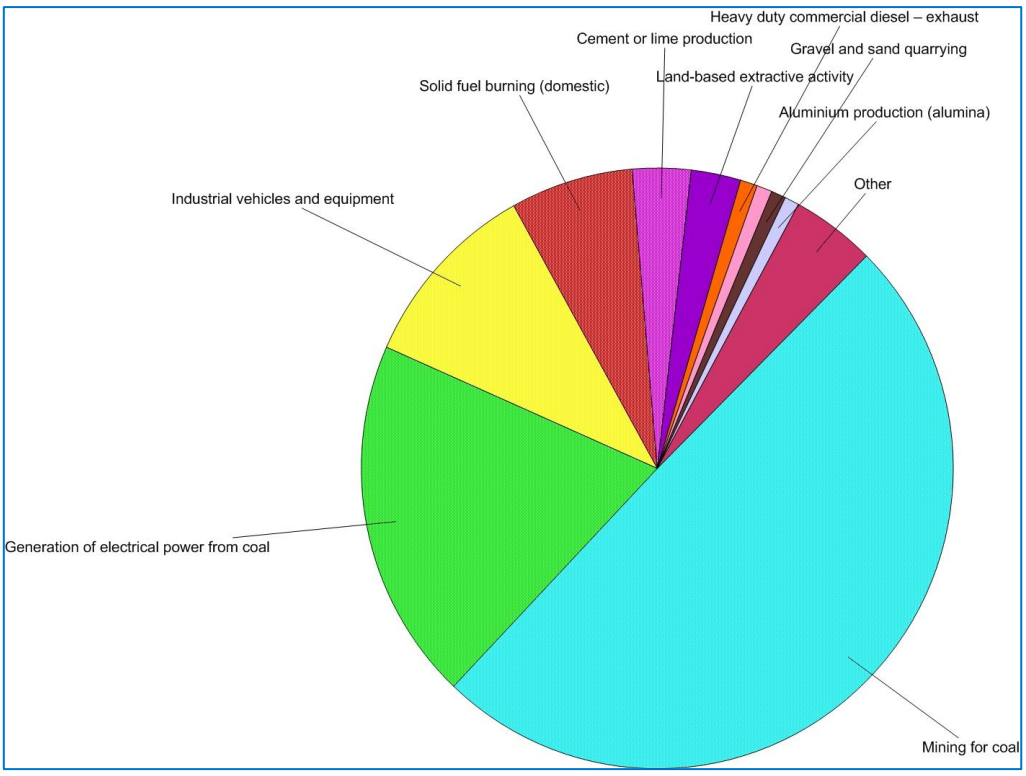
1 INTRODUCTION

The New South Wales (NSW) Environment Protection Authority (EPA) has commissioned Pacific Environment to investigate how primary anthropogenic[a] particulate matter (PM) emission sources contribute to annual average PM_{10}[b] and $PM_{2.5}$[c] concentrations in the Upper Hunter Valley of NSW.

The outcomes of the study will be used to inform the achievability of PM-reduction targets for the Upper Hunter Valley. The setting of targets is based on predicted future changes in annual average $PM_{2.5}$ concentrations in Singleton and Muswellbrook that result from emission-reduction scenarios for each source. The study focuses on the largest sources of primary anthropogenic PM emissions for the area (**NSW EPA, 2012a, 2012b**), as follows:

- Coal mines
- Domestic wood heaters
- Electric power generation
- Non-road diesel exhaust

The relative contribution of these sources is demonstrated in **Figure 1.1** by comparing the top 10 human made sources of $PM_{2.5}$ emissions in non-urban areas of the Greater Metropolitan Region (GMR).



Source: NSW EPA (2012a)

Figure 1.1: Top ten human made sources of $PM_{2.5}$ in non-urban areas of GMR

[a] Primary natural PM is emitted directly into the atmosphere as a result of processes such as wind erosion (mineral dust) and the production of marine aerosols (sea salt). Primary anthropogenic particles result from processes involving either combustion (e.g. industrial activity, domestic wood heaters, vehicle exhaust) or abrasion (e.g. mining for coal, road vehicle tyre wear). Secondary PM is not emitted directly, but is formed by chemical reactions involving gas-phase components of the atmosphere. The origin of secondary PM may be natural or anthropogenic.

[b] Particulate matter with an aerodynamic diameter of less than 10 micrometres

[c] Particulate matter with an aerodynamic diameter of less than 2.5 micrometres

1.1 Background and context

Airborne PM in the Upper Hunter Valley is a key issue for the NSW EPA, as outlined in the document *NSW 2021: A plan to make NSW number one,* the Government's 10 year plan for the state. Goal 22 of *NSW 2021 (Protect Our Natural Environment* (**NSW Department of Premier and Cabinet, 2011**)) aims to provide more information to local communities on air quality. This has led to the establishment of the Upper Hunter Ambient Air Quality Monitoring Network (UHAQMN), a regional air quality monitoring network which consists of fourteen monitoring sites at strategic locations, including the population centres of Singleton and Muswellbrook.

NSW 2021 has also led to the establishment of the Upper Hunter Air Particles Plan which outlines the measures currently in place, or being developed, to improve air quality in the Upper Hunter. The EPA has set up a high-level inter-agency air quality taskforce aimed at improving air quality in the Upper Hunter.

This study forms part of the Upper Hunter Air Particles Plan and complements the related Upper Hunter Fine Particle Characterisation Study (a joint effort between CSIRO and ANSTO) (**Hibberd et al, 2013**). The objective of the Upper Hunter Fine Particle Characterisation Study was to determine the major components and sources of $PM_{2.5}$ in Singleton and Muswellbrook. The study is not limited to primary anthropogenic PM and characterises $PM_{2.5}$ in terms of:

- Elemental composition (using ion beam analysis).
- Water soluble ions (using ion chromatography).
- Organic, elemental and black carbon.
- Source contribution (using positive matrix factorisation).

The reduction of PM from coal mines in particular is a priority for the NSW EPA, as reflected in the '*Dust Stop*' program. This is being implemented through Pollution-Reduction Programs (PRPs) that require coal mines to identify and implement best practice measures to reduce particle emissions from their operations. The PRPs form a component of each coal mine's Environment Protection Licence (EPL).

Initiatives for non-road diesel emissions, including actions specific to coal mines, are also a priority for the EPA (**NSW EPA, 2014**).

1.2 Objectives of the study

The principal objective of this study was to quantify the contribution of primary anthropogenic PM emissions to annual average ambient PM_{10} and $PM_{2.5}$ concentrations in Singleton and Muswellbrook. The study investigates the effects of potential emission reductions to inform the achievability of a target for reducing long term average $PM_{2.5}$ concentrations in Singleton and Muswellbrook.

The study seeks to answer the following questions:

1. What contribution do primary PM emissions from coal mines, domestic wood heaters, electric power generation and non-road diesel exhaust make to annual average PM_{10} and $PM_{2.5}$ concentrations in Singleton and Muswellbrook in 2012 (base case) and in business as usual (BAU) projections for the years 2016, 2021, 2026 and 2031[d]?

2. How sensitive are annual average ambient PM_{10} and $PM_{2.5}$ concentrations in Singleton and Muswellbrook for the years 2016, 2021, 2026 and 2031 to reductions in primary PM emissions from coal mines, domestic wood heaters, electric power generation and non-road diesel exhaust.

[d] The BAU projection years were chosen to be consistent with the projection years for the NSW EPA GMR emissions inventory.

This is the first known study to develop a regional scale primary particle model for the Hunter Valley.

2 STUDY APPROACH

The study methodology has been developed in accordance with the NSW EPA's Terms of Reference (ToR), and is consistent with Australian and International best practice for the modelling and assessment of air pollutants. Detailed methodology is provided in subsequent sections, as follows:

- **Section 3** – overall modelling approach.
- **Section 5** and **6** – emissions estimation.
- **Section 8** – model sensitivity tests.
- **Section 9** – source apportionment modelling.

The ToR included a requirement for an independent expert peer review of a methodology paper. The independent peer review was conducted by Joseph Scire, Principal Scientist at Exponent. Mr. Scire has more than 30 years' experience in the design, development, and application of research and regulatory air quality models. He has played a major role in the development of several widely used models, including the CALPUFF modelling system. All recommendations from the independent peer review are incorporated into the study where possible and practical. The overall approach to the study is outlined in the following steps:

- **Step1 – Coal mine emissions**: Develop detailed coal mine emissions inventories (PM_{10} and $PM_{2.5}$) for the base year 2012 plus BAU projections for years 2016, 2021, 2026 and 2031. Hourly emissions files are developed for modelling and spatial variation in activities and emissions across each year captured based on publicly available mine plan information.
- **Step 2 – Non-road diesel emissions**. Develop detailed emission inventories for non-road diesel (PM_{10} and $PM_{2.5}$) for the base year 2012 plus BAU projections for years 2016, 2021, 2026 and 2031. Emissions are based on recent mine survey information gathered by the EPA. Spatial variation across each year is captured similar to the approach for coal mine emissions.
- **Step 3 – Emissions from wood heaters and power stations**. Using the Air Emission Inventory for the GMR, emissions data (PM_{10} and $PM_{2.5}$) are collated and analysed and hourly emission files developed for modelling for the base year 2012.
- **Step 4 – Emissions from other sources**. Emissions from all other sources in the modelling domain are extracted from the GMR inventory, collated and analysed, and hourly emission files developed for modelling for the base year 2012.
- **Step 5 - Meteorological modelling**. Meteorological modelling using TAPM and CALPMET.
- **Step 6 – Meteorological model evaluation**. Analysis of model performance based on comparison with 2012 monitoring data collected at the UHAQMN.
- **Step 7 - Dispersion modelling for base year 2012**. Dispersion modelling using CALPUFF of all sources for base year 2012 for PM_{10} and $PM_{2.5}$
- **Step 8 - Dispersion modelling evaluation**. Evaluation of model performance (PM_{10} and $PM_{2.5}$) based on comparison with 2012 monitoring data collected at the UHAQMN. Model evaluation includes consideration of secondary and natural PM plus influence of background PM from outside the modelling domain.
- **Step 9 - Dispersion modelling for BAU projections**. Dispersion modelling of coal mines and non-road diesel for BAU projections for years 2016, 2021, 2026 and 2031. Results presented for Singleton and Muswellbrook for PM_{10} and $PM_{2.5}$.
- **Step 10 – Scaling 2012 modelling for other sources for BAU projection**. The predicted PM_{10} and $PM_{2.5}$ concentrations for 2012 from wood heaters, electric power generation and all other sources are scaled based on emissions estimates for BAU projections (2016, 2021, 2026 and 2031). Results are presented for Singleton and Muswellbrook for PM_{10} and $PM_{2.5}$.
- **Step 11 – Emission reduction analysis**. Presentation of nominal percentage reductions in PM_{10} and $PM_{2.5}$ concentrations for coal mines, wood heaters, electric power generation and non-road diesel exhaust.

3 MODELLING APPROACH

3.1 Introduction

The modelling for this study used a combination of TAPM, CALMET and CALPUFF modelling schemes.

The Air Pollution Model, or TAPM, is a three-dimensional meteorological and air pollution model developed by the CSIRO Division of Atmospheric Research. A detailed description of TAPM and its performance can be found in **Hurley (2008)** and **Hurley et al. (2009)**. TAPM uses fundamental fluid dynamics and scalar transport equations to predict meteorology and (optionally) pollutant concentrations. It consists of coupled prognostic meteorological and air pollution concentration components. The model predicts airflows that are important to local-scale air pollution, such as sea breezes and terrain induced flows, against a background of larger scale meteorology provided by synoptic analyses.

CALMET is a meteorological pre-processor that includes a wind field generator with treatments of slope flows, terrain effects and terrain blocking effects. The pre-processor produces fields of wind components, air temperature, relative humidity, mixing height and other micro-meteorological variables to produce the three-dimensional (3-D) meteorological fields that are used in the CALPUFF dispersion model. CALMET uses the meteorological inputs in combination with land use and geophysical information for the modelling domain to predict gridded meteorological fields for the region (**Scire *et al.*, 2000**).

CALPUFF is a multi-layer, multi species, non-steady-state puff dispersion model that can simulate the effects of time-varying and space-varying meteorological conditions on pollutant transport, transformation and removal. The model contains algorithms for near-source effects such as building downwash, partial plume penetration, sub-grid scale interactions as well as longer range effects such as pollutant removal, chemical transformation, vertical wind shear and coastal interaction effects. The model employs dispersion equations based on a Gaussian distribution of pollutants across released puffs and takes into account the complex arrangement of emissions from point, area, volume and line sources (**Scire *et al.*, 2000**).

A summary of the model set up and key inputs is presented in **Appendix A**.

3.2 Overview

The modelling system works as follows:

- TAPM is a prognostic meteorological model that generates gridded three-dimensional meteorological data for each hour of the model run period.
- CALMET, the meteorological pre-processor for the dispersion model CALPUFF, calculates fine resolution three-dimensional meteorological data based upon observed or prognostic ground and upper level meteorological data.
- CALPUFF then calculates the dispersion of plumes within this three-dimensional meteorological field.

An overview of the modelling system is presented in **Figure 3.1**. The modelling approach is in accordance with the *Generic Guidance and Optimum Model Settings for the CALPUFF Modelling System for Inclusion into the 'Approved Methods for the Modelling and Assessments of Air Pollutants in NSW, Australia'* (**TRC, 2010**).

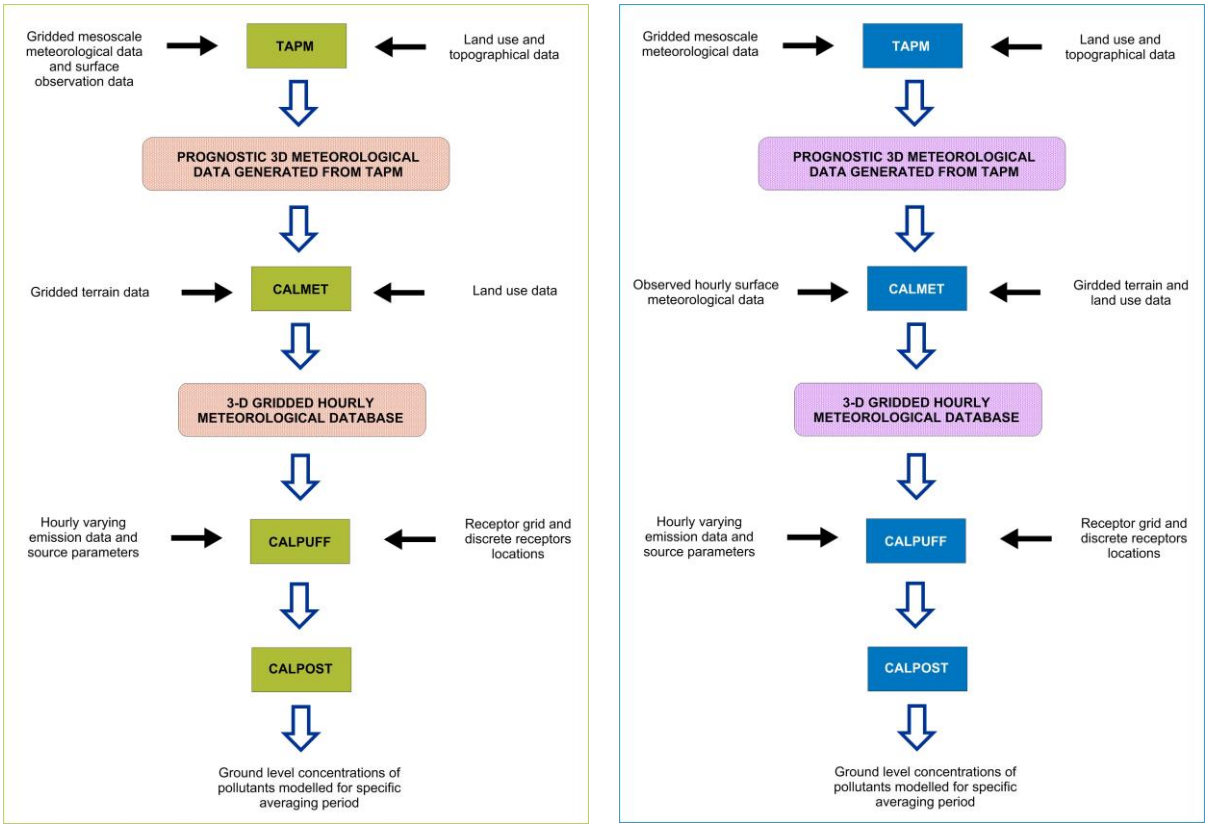
TAPM was chosen as the prognostic model for the study. The Weather Research and Forecasting Model (WRF) was also considered for the study but discounted due to the significantly greater computational requirements compared with TAPM.

TAPM has been extensively used as a prognostic modelling tool, both in Australia and internationally (**Borrego et al., 2012**; **Wang et al., 2008**; **Gallego et al., 2008**; **Soriano et al.; 2003**; **Mahmud, 2009**; **Mocioaca et al., 2009**; **Zoras et al., 2010**; **Garcia et al., 2013**).

While it is not possible to quantify the difference that an advanced model such as WRF would make to the study results and conclusion, the performance of the model used is evaluated in **Appendix B** and is shown to perform with an acceptable degree of accuracy. Limitations of TAPM in predicting light winds were investigated by comparing two different approaches to data assimilation and choosing the better method.

CALMET/CALPUFF is approved by the United States Environmental Protection Agency (US EPA) for long-range transport and in certain applications involving complex flow (**US EPA, 2005**). CALMET/CALPUFF is recommended by the NSW EPA for applications where steady-state conditions are not expected, such as complex terrain (**NSW DEC, 2005**). Experience to date suggests that CALPUFF performs reasonably well for ground-level, non-buoyant fugitive dust sources in the Hunter Valley, based on modelling for project approval of individual mines (**PAEHolmes, 2012**; **Pacific Environment, 2013**). Also given the regional scale of this assessment, the CALMET/CALPUFF modelling suite is considered appropriate (**Bennett et al., 2002**; **Levy et al., 2002**; **Zhou et al., 2003**).

Notwithstanding, a key outcome of this study will be demonstration of performance through robust model validation, principally via comparison with ambient monitoring data from the UHAQMN.



CALMET no-obs **CALMET hybrid**

Figure 3.1: Overview of modelling methodology

3.3 Surface meteorological data assimilation

Surface observation data from meteorological stations located in the modelling domain are included in the meteorological modelling. The inclusion of these data (referred to as data assimilation) provides real-world observations and improves the accuracy of the wind field. Two options for data assimilation were investigated:

- Option 1 - CALMET in no-obs mode: Data assimilation of observations in the prognostic model (inclusion of an observation file in TAPM).
- Option 2 - CALMET in hybrid mode: Data assimilation of observations in CALMET (inclusion of surface stations in CALMET model) with no observations in TAPM.

Option 1 was investigated due to the tendency for TAPM V4 to under predict wind speeds. The nudging of TAPM aims to avoid underestimated wind speeds in the generation of the prognostic 3D.dat file. The "nudged" 3D.dat is used as input into CALMET modelling in "no-obs" mode. CALMET in no-obs mode also aims to eliminate the occurrence of artificial regions of convergence and divergence which can occur when running CALMET in hybrid mode. The independent peer review noted that data assimilation in TAPM is not always recommended and Option 2 (CALMET in hybrid mode) was therefore also investigated. A comparison between Option 1 (CALMET no-obs) and Option 2 (CALMET hybrid) for key meteorological parameters is presented in **Appendix B**. Results from the dispersion model using both CALMET options are evaluated in **Appendix C**.

3.3.1 Assimilation and model evaluation sites

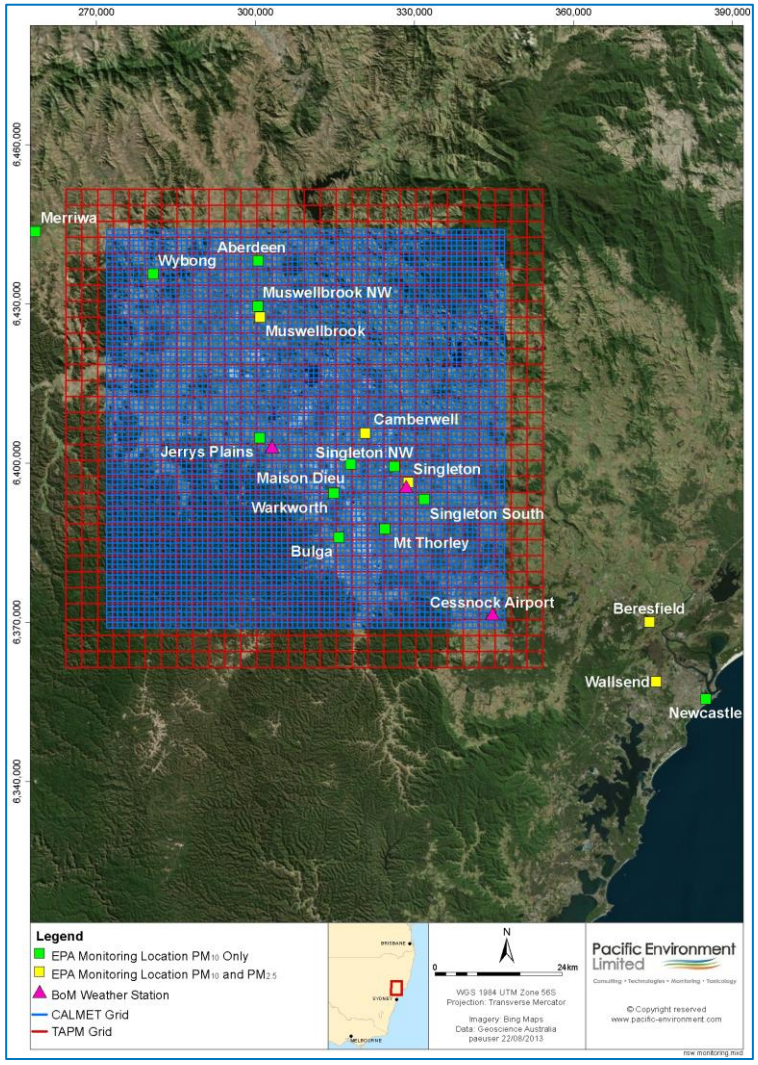
Of the 14 monitoring sites in the UHAQMN, 13 are located within the selected boundary of the dispersion model (the modelling domain). There is only one Bureau of Meteorology (BoM) site that records continuous data within the modelling domain (Cessnock Airport). All UHAQMN sites are presented in **Figure 3.2**, along with the TAPM and CALMET modelling domains. Observed hourly wind data from nine of the UHAQMN sites, as well as Cessnock Airport, are incorporated into the modelling. The four remaining sites are used as model evaluation sites, chosen as follows.

Of the three available sites in Singleton, all show similar wind patterns, and it was appropriate that at least of one of the Singleton sites was excluded and used for model evaluation. There are also two sites in Muswellbrook, and the Muswellbrook NW site shows some uncharacteristic winds from the northeast (not present at other sites). The Muswellbrook NW site was also excluded from the modelling and used for model evaluation, noting the uncharacteristic patterns in wind direction.

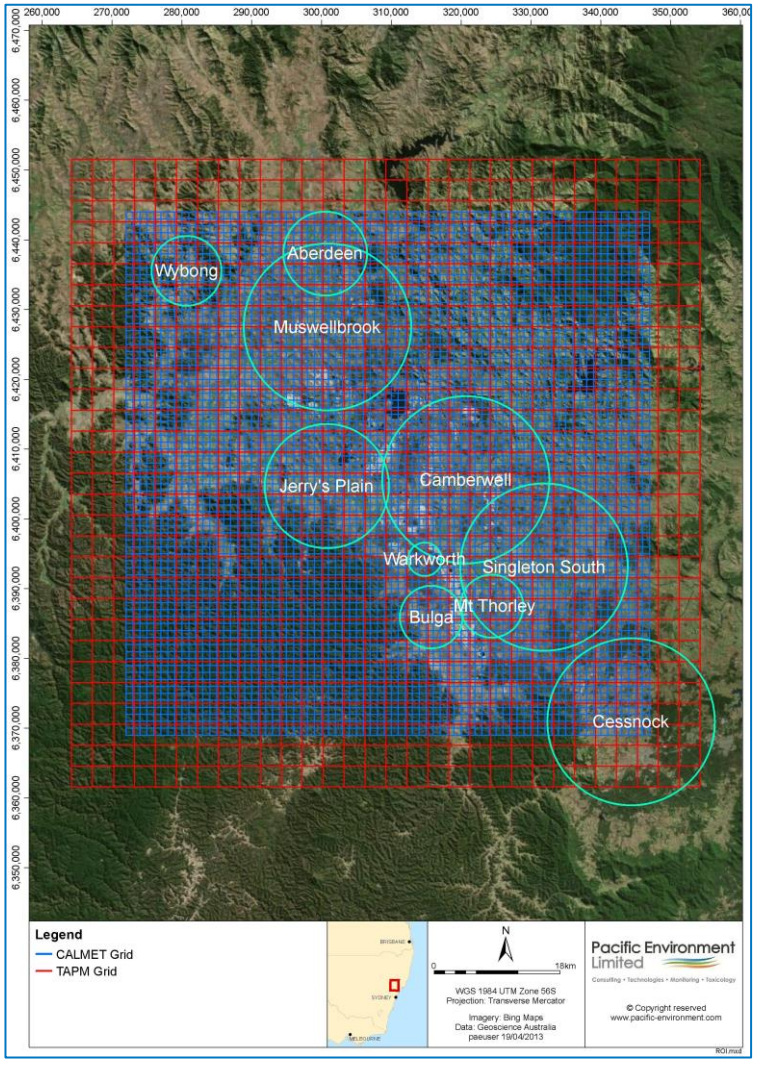
The influence of terrain on prevailing wind directions was analysed to inform an appropriate radius of influence (ROI) for each site included in the TAPM modelling for Option 1. Due to the tendency of TAPM to under predict wind speeds it is preferable to have as large a ROI as possible to achieve significant coverage of the modelling domain and to achieve consistency in the wind field. However, where wind patterns are influenced by local terrain, as opposed to regional scale topography, a smaller ROI is applied (for example at Wybong and Jerry's Plains). The TAPM ROI for each site are shown in **Figure 3.2**. No additional benefit is gained when an observational site ROI is wholly contained within another site's ROI, which was the case for Singleton NW and Maison Dieu. Therefore, these sites were also excluded and used for model evaluation. It is noted that Singleton NW and Maison Dieu also appear to have a smaller % occurrence of calm winds (less than 0.5 m/s) than most other sites, which is an important consideration in model evaluation (refer **Section 4**). The assimilation and evaluation sites are summarised in **Table 3.1**.

Table 3.1: Data assimilation and evaluation sites

Assimilation site	Evaluation site
Cessnock Airport	Maison Dieu
Mt Thorley	
Bulga	
Warkworth	Singleton
Singleton South	
Camberwell	Singleton NW
Jerry's Plains	
Muswellbrook	Muswellbrook NW
Aberdeen	
Wybong	



Upper and lower Hunter EPA and BoM monitoring sites with TAPM and CALMET modelling grids



Sites for data assimilation and TAPM ROI with TAPM and CALMET modelling grids

Figure 3.2: Monitoring network, TAPM and CALMET modelling domain & grids, data assimilation sites and radius of influence

3.4 Overview of prognostic modelling

TAPM is set up with three nested domains, composed of 30 grids along both the X and the Y axes, centred on -32˚27.704' latitude and 150˚ 58.222' longitude (309.240 km, 6406.569 km UTM Zone 56S), Each nested domain has a grid resolution of 30 km, 10 km, and 3 km respectively. The inner 3 km grid is used to generate gridded prognostic data (3D.dat) over an area of 90 km x 90 km. The prognostic modelling grids are chosen to ensure the inner nested grid provides 3-D prognostic data over the entire CALMET modelling domain of 75 km x 75 km. The justification for a CALMET modelling domain of 75 km x 75 km is discussed in **Section 3.5**.

Default TAPM terrain values are used. A summary of the TAPM set up and inputs is presented in **Appendix A**.

3.5 CALMET modelling

CALMET is run with a modelling domain covering a 75 x 75 km area with the origin (SW corner) at 272 km Easting and 6369 km Northing (UTM Zone 56S), consisting of 188 x 188 grid points with a 400 m resolution along both the X and Y axes. Model grid resolution is shown in **Figure 3.2**.

Model resolution is chosen based on a compromise between computational time and ability to resolve significant terrain features. The model domain is shown in **Figure 3.3**. The terrain resolution at the proposed grid spacing of 400 m is presented **Figure 3.4** (left panel) and compared with the ~90m resolution of the input data (right panel). This comparison shows that the model will resolve significant terrain features well and that the dominant features of the valley will be accounted for at 400 m grid spacing.

A modelling domain of 75 km x 75 km was chosen based on the following criteria:

- Incorporating the key population centres of Muswellbrook and Singleton.
- Incorporating all Hunter Valley mining operations, including some fringe mining operations such as Mangoola and Mt Pleasant.
- Incorporating significant valley terrain features for better diagnostic wind field generation.
- Capturing any significant land use variation and features that might influence wind fields.

Land-use is determined from Geographical Information System (GIS) data from the Australian Collaborative Land Use Mapping Programme (ACLUMP) and updated using aerial photography from Google Earth. Terrain data for the modelling is sourced from Shuttle Radar Topographic Mission (SRTM) data. SRTM data for Australia is sampled at three arc seconds, resulting in an approximate resolution of 90 m.

A summary of the model set up and inputs for both CALMET no-obs and CALMET hybrid is presented in **Appendix A**.

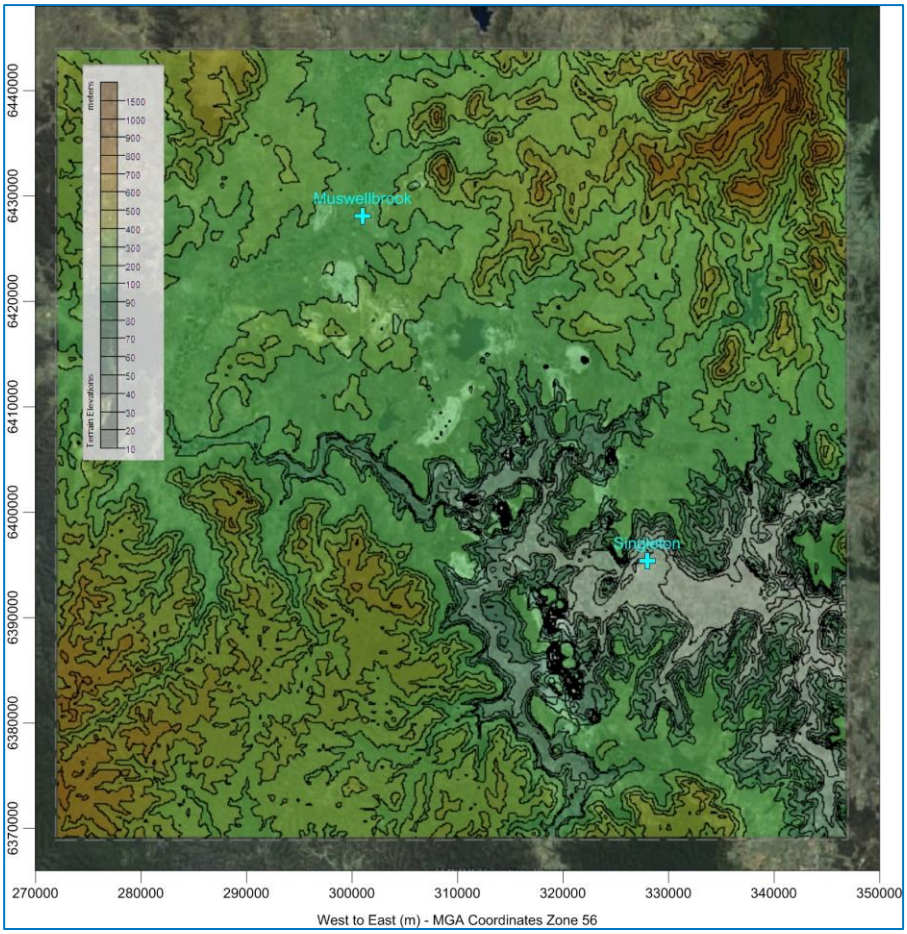


Figure 3.3: Modelling domain and terrain data

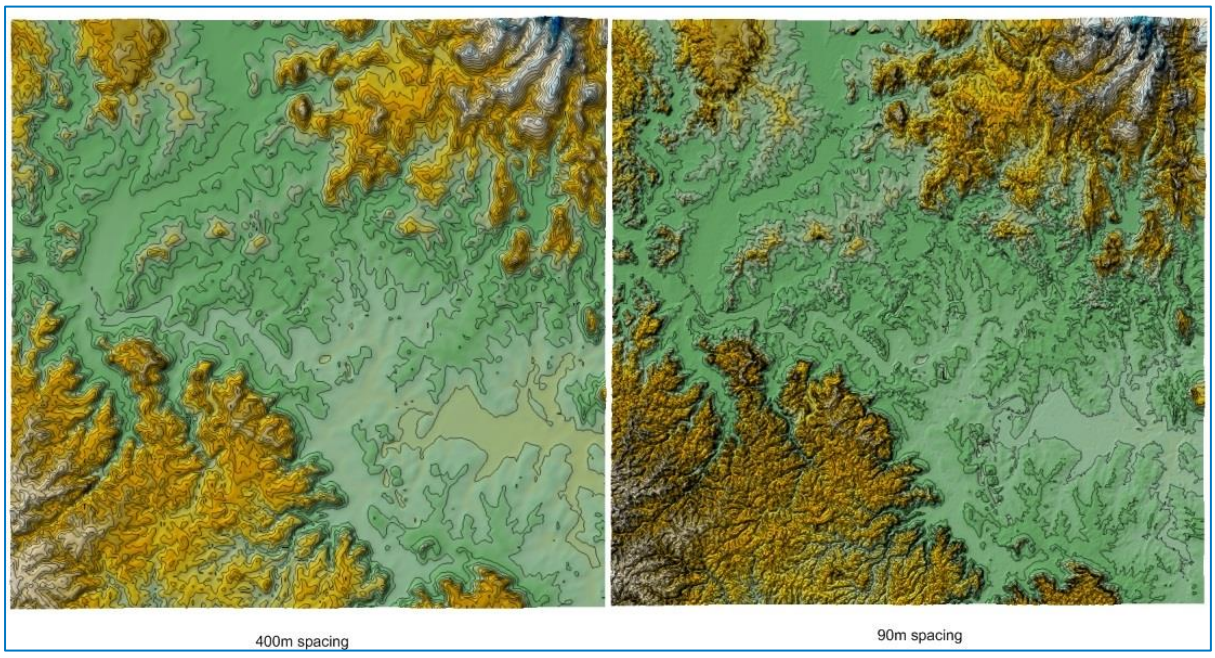


Figure 3.4: Terrain Resolution at 400 m (model grid spacing) compared to 90 m terrain from the SRTM data set

4 EVALUATION OF METEOROLOGICAL MODELLING

4.1 Introduction

Model evaluation was completed for both model options, as follows:

- CALMET Option 1 – no-obs: data assimilation of observations in the prognostic model (inclusion of an observation file in TAPM).
- CALMET Option 2 - hybrid mode: data assimilation of observations in CALMET (inclusion of surface stations in CALMET model).

The two options were evaluated to determine the effect of data assimilation at different stages in the modelling. One-hour data for wind speed, wind direction and temperature are evaluated visually as time series, frequency distributions and wind roses. Further analytical examination is presented using linear regression and percentile plots. The visual and analytical examination is presented in **Appendix B** and **Appendix D** and summarised in **Section 4.3**.

Model performance is also evaluated against statistical benchmarks (or ideal scores) for a variety of statistical tests. The results from the statistical evaluation are presented in **Appendix B** and summarised in **Section 4.3**.

4.2 Summary statistics

Summary statistics for the evaluation sites are presented in **Table 4.1** for both CALMET options. For both options, there is a tendency for the predicted annual average wind speeds to be lower than the observed at all sites except Singleton, where observed is lower than predicted. Further analysis of wind statistics for all sites (evaluation and assimilation) are shown in **Table 4.2.** For the CALMET no-obs option, the predicted annual average wind speeds are generally lower than the observed. For the CALMET hybrid option, the predicted annual average wind speeds generally correlate better with observed. Similarly, for the CALMET hybrid option the predicted calms generally correlate better with observed. This is expected as these sites were included directly in CALMET Option 2 (hybrid) which therefore gives weight to the observation in the generation of the wind field. The exception is at the Singleton site where the CALMET no-obs option is closer to the observed wind speeds and % calms. This may be a result of the multiple observation sites around Singleton which demonstrate variations in the observed data.

Where there are more than one observation site, the data show significant variability (Muswellbrook and Singleton). For example, on an annual basis the Singleton NW site (evaluation site) has 4% calms, the Singleton site (evaluation site) has 23% calms and the Singleton South site (data assimilation site) has 14.6%. The Muswellbrook site (data assimilation site) has 22% calms and the Muswellbrook NW site (evaluation site) has 9%. This suggests some localised influence on wind conditions. Where there are variations, there is a tendency for the predictions to correlate better with the sites that were included as assimilation sites, as expected.

Table 4.1shows that observed and predicted average temperatures correlate well across all evaluation sites for both model options.

Variations between observed and predicted wind directions are analysed visually, presented as windroses in **Appendix B**.

Table 4.1: Summary statistics – observed and predicted

Parameter	Measure	Singleton			Singleton NW			Muswellbrook NW			Maison Dieu		
		Observed	CALMET no-obs	CALMET hybrid	Observed	CALMET no-obs	CALMET hybrid	Observed	CALMET no-obs	CALMET hybrid	Observed	CALMET no-obs	CALMET hybrid
Wind Speed (m/s)	Mean	2.1	2.2	2.2	2.6	2.3	2.5	2.3	1.5	1.8	3.0	2.0	2.5
% Calms		22%	15%	6%	4%	13%	4%	9%	20%	15%	6%	17%	6%
Wind Direction (deg)		197	200	200	212	201	215	158	174	201	176	211	227
Temperature (°C)		17.3	17.4	17.4	17.5	17.3	17.4	16.4	17.2	17.1	17.0	17.3	17.5
Wind Speed (m/s)	Standard Deviation	1.8	1.8	1.8	1.6	1.8	1.6	1.7	1.3	1.4	2.2	1.6	1.6
Wind Direction (deg)		105	96	94	87	101	86	103	108	100	100	98	80
Temperature (°C)		6.7	5.8	5.8	6.0	5.9	5.7	7.4	6.2	6.2	7.0	5.9	5.9

Note: [a] Wind speed less than 0.5 m/s.

Table 4.2: Summary statistics for wind speed (WS) – observed and predicted - all sites

Site	Observed		Predicted - CALMET no-obs		Predicted - CALMET hybrid	
	Mean WS (m/s)	% Calms	Mean WS (m/s)	% Calms	Mean WS (m/s)	% Calms
Aberdeen	2.8	7%	2.2	9%	2.4	5%
Wybong	1.6	15%	1.9	7%	1.6	13%
Muswellbrook	1.9	22%	1.7	19%	1.9	20%
Muswellbrook NW	**2.3**	**9%**	**1.5**	**20%**	**1.8**	**15%**
Jerry's Plain	2.5	12%	2.3	8%	2.4	11%
Camberwell	2.5	14%	2.1	17%	2.5	13%
Bulga	1.9	22%	1.6	23%	1.9	21%
Warkwoth	1.9	23%	1.8	18%	1.9	22%
Maison Dieu	**3.0**	**6%**	**2.0**	**17%**	**2.5**	**6%**
Mount Thorley	2.5	9%	2.3	9%	2.4	9%
Singleton	**2.1**	**22%**	**2.2**	**15%**	**2.3**	**6%**
Singleton NW	**2.6**	**4%**	**2.3**	**13%**	**2.5**	**4%**
Singleton South	2.6	14%	1.9	15%	2.6	13%
BoM Cessnock Airport	2.7	12%	2.4	7%	2.9	7%

Note: sites in bold are evaluation sites

4.3 Statistical evaluation

For the CALMET no-obs model, regression analysis of wind speed (see **Appendix B**) showed a good agreement between predicted and observed, especially at the two singleton sites, as follows:

- Maison Dieu wind speed $R^2 = 0.78$
- Muswellbrook NW wind speed $R^2 = 0.71$
- Singleton wind speed $R^2 = 0.88$
- Singleton NW wind speed $R^2 = 0.81$

Percentile plots shown in **Appendix B** for CALMET no-obs demonstrate a slight under-prediction of low wind speeds at Singleton NW. At Maison Dieu and Muswellbrook NW there was a general underestimation of peak values, increasing with higher wind speeds. At Singleton and Singleton NW the percentile plots are close to unity.

For the CALMET hybrid model, regression analysis of wind speed (see **Appendix B**) shows reasonable agreement between predicted and observed at Muswellbrook NW and Singleton, but is not as strongly correlated as the CALMET no-obs model, as follows:

- Maison Dieu wind speed $R^2 = 0.54$
- Muswellbrook NW wind speed $R^2 = 0.68$
- Singleton wind speed $R^2 = 0.69$
- Singleton NW wind speed $R^2 = 0.59$

Percentile plots shown in **Appendix B** for CALMET hybrid demonstrate a slight under-prediction of at Maison Dieu and Muswellbrook NW. At Singleton and Singleton NW the percentile plots are close to unity.

Regression analysis of temperature shows excellent correlation ($R^2 > 0.8$) for all evaluation sites and for both CALMET options (refer **Appendix B**).

CALMET performance is also evaluated against statistical benchmarks (or ideal scores) for the following statistical tests:

- index of agreement
- gross error
- mean bias
- fractional bias
- skill_V and skill_r

The statistical measures used to quantify the differences between model predictions and observations are taken from the BOOT Statistical Model Evaluation Software Package (**Chang and Hanna, 2005**) and assessed against the performance benchmarks set for model evaluation (**Emery et. al, 2001)**. The evaluation of model performance against benchmarks is presented **Appendix B** and summarised as follows:

- For both CALMET options, the index of agreement (IOA) compares well against the benchmark for all sites and parameters with some approaching the ideal score of 1.
- The skill_v, skill_r and fractional bias test all fall within the acceptable range for both options.
- The mean gross error (MGE) compares favourably against benchmark for all parameters for the CALMET no-obs model. MGE falls outside the benchmark for wind direction for the CALMET hybrid model.
- For both CALMET options, model performance falls outside the benchmark for mean bias (MB) with the exception of temperature.

Overall, it was concluded that both CALMET options simulate the meteorology with an acceptable degree of accuracy.

5 ESTIMATING COAL MINE EMISSIONS

5.1 General approach to emission estimation

Publicly available emissions inventories are available for all existing mines that are used directly or indirectly to derive emissions for the study years. Few existing emissions inventories have data for the base year of the study (calendar year 2012), but some others are available for a year that is very close to the study base year. The following general approach is used in estimating emissions for the study years, in order of preference:

- All existing publicly available emission inventories were collated for all available years (taken from Environmental Assessments (EAs) and coal mine dust PRP responses) (see **Table 5.2**).
- All existing emissions inventories are updated to ensure consistency in the emissions estimation techniques[e] and available site-specific information for both PM_{10} and $PM_{2.5}$.
- For each available emission inventory, ratios of the PM emissions (kg/annum) to Run-of-Mine (ROM) coal (tonnes/annum) are calculated for each mine (PM_{10}/ROM and $PM_{2.5}$/ROM ratios). This gives the amount of PM generated for each tonne of ROM mined. By calculating site-specific ratios for each mine and each available inventory year, variations in stripping ratios are also accounted for. For example, where a particular mine removes large volumes of overburden, this mine will have a higher PM_{10}/ROM ratio than a mine where smaller volumes of overburden are removed to access the coal seam.
- ROM production for each study year is based on ROM estimates provided by the NSW Trade & Investment – Division of Resources & Energy (DRE).
- The PM/ROM ratios are then used to calculate the annual PM emissions for each study year at each mine[f], based on that ROM production for that year. Where more than one PM/ROM ratio exists for a mine (i.e. different inventory year) the most representative ratio was used to estimate emissions for the study year.
- Where no existing publicly available emission inventory or annual emission total is available for any year at a mine, a representative PM/ROM ratio has been used to derive emissions, for example based on a nearby mine or mine with similar production rates, exposed areas, stripping rates etc. This is mainly for BAU projections years where new mining operations are proposed.
- For mines that are proposed or approved but not yet commenced, the mine commencement year is taken from the DRE projections.

Activity data were not available for each study year. However, detailed bottom-up emissions inventories have been developed specific to each mine to derive the PM/ROM ratios. The use of a PM/ROM ratio has been used extensively for modelling cumulative assessments as part of EAs for coal mines in NSW, and the estimated emissions provide good agreement when compared with emissions developed using detailed activity data.

The derived PM_{10}/ROM ratio for this study ranges from 0.1 to 0.3. The derived $PM_{2.5}$/ROM ratio for this study ranges from 0.01 to 0.06. These ratios compare favourably with the 2008 NSW EPA Air Emission Inventory for the Greater Metropolitan Region in NSW (GMR Inventory) (Mining for Coal) which reports a PM_{10}/ROM ratio of 0.25 and $PM_{2.5}$/ROM ratio of 0.04.

The total estimated PM emissions for each mine are presented as kg PM_{10}/annum and kg $PM_{2.5}$/annum for each study year. For modelling purposes, the annual emissions are then split into wind-dependent and wind-independent sources and converted to hourly varying emissions (adjusted to the wind speed where appropriate). This is described further in **Section 5.3**.

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[e] The US EPA AP-42 emissions factors and equations used for dust generating activities at coal mines are presented in **Appendix E**.

[f] Activity data are not available to develop detailed bottom up emission inventories for each study year, however the PM/ROM ratios are based on detailed bottom up emission inventories specific to each mine (for a different year), and therefore estimates of total PM emissions are considered to have a good degree of accuracy.

5.2 Base year emissions (2012)

The ROM coal and estimated annual PM_{10} and $PM_{2.5}$ emissions for base year (2012) are presented in **Table 5.1**. Also shown are mines that are not included in the 2012 emissions inventory (completed or not yet approved). It is noted that once a mine ceases operations it is assumed to no longer emit dust. Depending on when the mine ceases and the progress of rehabilitation, there may be some wind blown dust from that facility, however the addition or exclusion of these emissions are expected to within the uncertainty bounds for emissions estimates and would not affect the outcomes of this study.

The detailed assumptions used in creating the coal mine emission inventories are provided in **Table 5.2**. Further detail on the annual production and estimated PM emissions for base year (2012) are presented in **Table 5.3**. Also shown is the original inventory year which was used as for the bottom-up emissions inventory development and the PM/ROM ratios adopted from these inventories. The estimated emissions presented in the far right columns are based on these ratios and the ROM amount assumed for 2012.

Table 5.1: Summary of estimated mining emissions for 2012

Mining operation	ROM coal (Mtpa)	PM_{10} (kg/year)	$PM_{2.5}$ (kg/year)
Ashton South East OC		3,297	415
Ashton UG	2.3		
Bengalla OC	8.4	980,712	139,027
Bulga OC	10.0	2,625,620	302,073
Beltana/Blakefield South UG	4.6		
Dellworth UG			
Drayton OC	5.6	854,823	131,913
Drayton South OC			
Ferndale OC			
Ferndale UG			
Hunter Valley Operations OC	15.9	3,006,438	382,832
Integra OC (Camberwell)	2.5	1,235,786	266,773
Integra UG (Glennies Creek)	2.1		
Liddell OC	6.9	1,335,393	151,365
Mangoola OC	10.5	841,434	122,257
Monash UG			
Mt Arthur Coal OC	22.9	2,187,569	404,954
Mt Owen OC (incl. Glendell & Rav East)	15.2	2,333,126	415,389
Mt Pleasant OC			
Mt Thorley Warkworth OC	16.8	3,743,013	567,691
Muswellbrook OC	1.1	161,097	20,745
Ravensworth West/Narama OC	2.8	916,364	121,237
Ravensworth North OC	3.0		
Ravensworth UG (Newpac)	2.3	3,297	415
Ridgelands UG			
Rix's Creek OC	2.7	618,933	125,636
Sandy Creek UG (& highwall)			
Spur Hill UG			
Wambo OC	4.2	2,405,896	314,562
Wambo UG	5.2		
West Muswellbrook			
TOTAL	**145**	**23,252,798**	**3,467,284**
TOTAL (tonnes/year)		**23,253**	**3,467**

Table 5.2: Key assumptions for 2012 estimated emissions

Mine	Key Assumptions	Emissions Inventory Source
Ashton Underground	• ROM coal provided by the DRE. • Emissions of PM_{10} and $PM_{2.5}$ were estimated by applying the PM:ROM ratios from the Ravensworth UG 2012 emissions inventory to the estimated ROM coal amount for Ashton Underground 2012. • Splits of WI/WS/WE based on Ravensworth UG emissions inventory.	*Air Quality Impact Assessment: Ashton South East Open Cut Mine (PAEHolmes, 2009)*
Bengalla	• ROM coal provided by the DRE. • Updated PAEHolmes 2011 emissions inventory with latest emission factors and controls from the PRP. • Splits of WI/WS/WE based on Bengalla 2011 emissions inventory.	*Air Quality Impact Assessment: Bengalla Mining Company Development Consent Modification (PAEHolmes, 2010)*
Bulga	• ROM coal provided by the DRE • PAEHolmes Bulga Modification (2014) emissions inventory updated for consistency in emission factors and controls from the PRP. PM emissions estimated by multiplying the PM:ROM ratios from the 2014 inventories to the DRE ROM. • Splits of WI/WS/WE based on Bulga Modification 2014 emissions inventory.	*Air Quality Impact Assessment: Bulga Coal Mine Modification Project (PAEHolmes, 2012)*
Drayton	• ROM coal provided by the DRE. PAEHolmes 2012 emissions inventory created as part of the Drayton South Project and updated for consistency in emission factors and controls from the PRP. PM emissions estimated by multiplying the PM:ROM ratios from the 2012 inventories to the DRE ROM coal. • Splits of WI/WS/WE based on Drayton 2012 emissions inventory.	*Final: Drayton South Air Quality and Greenhouse Gas Impact Assessment (PAEHolmes, 2012)*
Glendell	• ROM coal provided by the DRE for Mt. Owen OC. This was split for modelling Glendell/Ravensworth East based on ROM coal splits reported in the 2010/2011 PRP. • Holmes Air Sciences 2010 emissions inventory updated for consistency in emission factors and controls from the PRP. PM emissions estimated by multiplying the PM:ROM ratios from the 2010 inventories to the ROM coal estimated for 2012 as above. • Splits of WI/WS/WE based on Glendell 2010 emissions inventory.	*Air Quality Impact Assessment: Proposed Glendell Mine Modification to Development Consent (Holmes Air Sciences, 2007)*
HVO North	• ROM coal provided by the DRE. and split for HVO North/South using 2012 MOP splits given for the two mines in the AEMR. • PAEHolmes 2011 emissions inventory for the Carrington West Wing project updated for consistency in emission factors and controls from the PRP. PM emissions estimated by multiplying the PM:ROM ratios from the 2011 inventories to the ROM coal estimated for 2012 as above. • Splits of WI/WS/WE based on Carrington West Wing 2011 emissions inventory.	*Air Quality Impact Assessment: Carrington West Wing (PAEHolmes, 2010)*
HVO South	• ROM coal provided by the DRE. and split for HVO North/South using 2012 MOP splits given for the two mines in the AEMR. • Holmes Air Sciences 2010 emissions inventory updated for consistency in emission factors and controls from the PRP. PM emissions estimated by multiplying the PM:ROM ratios from the 2010 inventories to the ROM coal estimated for 2012 as above. • Splits of WI/WS/WE based on HVO South 2010 emissions inventory.	*Final Air Quality Assessment: Hunter Valley Operations South Coal Project (Holmes Air Sciences, 2008)*
Integra	• ROM coal provided by the DRE. . • Splits of WI/WS/WE based on Integra FY2011 emissions inventory	*Report: Integra Particulate Matter Control Best Practice Pollution reduction Program, Integra Mine Complex (PAEHolmes, 2012)*
Liddell	• ROM coal provided by the DRE. • Holmes Air Sciences 2011 emissions inventory updated for consistency in emission factors and controls from the PRP. PM emissions estimated by multiplying the PM:ROM ratios from the 2011	*Air Quality Assessment: Liddell Open Cut – Proposed*

	inventories to the ROM coal value for 2012 per the AEMR. • Splits of WI/WS/WE based on Liddell 2011 emissions inventory.	*Modifications (Holmes Air Sciences, 2006)*
Mangoola	• ROM coal provided by the DRE. Emissions inventory adapted from SKM 2011 emissions and updated for consistency in emission factors and controls from the PRP. PM emissions estimated by multiplying the PM:ROM ratios from the 2011 inventories to the ROM coal value for 2012 per the AEMR. • Splits of WI/WS/WE based on Mangoola 2011 emissions inventory.	*Mangoola Coal Proposed Mine Plan Modifications: Air Quality Impact Assessment (SKM, 2010)*
Mount Arthur	• ROM coal provided by the DRE. PAEHolmes PRP 2010/2011 emissions inventory updated with latest emission factors and controls from the PRP. PM emissions estimated by multiplying the PM:ROM ratios from the PRP 2010/2011 inventories to the ROM coal value for 2012 per the AEMR. • Splits of WI/WS/WE based on Mount Arthur 2010/2011 emissions inventory.	*Assessment of Coal Mine Particulate Matter Control Best Practice Pollution Reduction Program (PAEHolmes, 2011)*
Mount Owen	• ROM coal provided by the DRE. • Holmes Air Sciences 2013 emissions inventory updated with latest emission factors and controls from the PRP. • Splits of WI/WS/WE based on Mount Owen 2013 emissions inventory.	*Air Quality Assessment: Mt Owen Operations (Holmes Air Sciences, 2003)*
Mount Thorley	• ROM coal provided by the DRE combined for Mt Thorley Warkworth. This was split based on the maximum approved production listed for each in the AEMR. • Emissions estimated by multiplying the ROM as per above with the PM ratios from the 2012 emissions inventory developed for Warkworth. This was done as there is no recently available emissions inventory for Mt. Thorley. • Splits of WI/WS/WE based on Warkworth 2012 emissions inventory.	*Air Quality Impact Assessment: Warkworth Extension Project (PAEHolmes, 2010)*
Muswellbrook	• ROM coal provided by the DRE. • PAEHolmes 2012 emissions inventory for the Muswellbrook Coal Modification updated with latest emission factors and controls from the PRP. PM emissions estimated by multiplying the PM:ROM ratios from the 2012 inventories to the ROM coal value for FY2013 per the AEMR. • Splits of WI/WS/WE based on Muswellbrook Coal FY2013 emissions inventory.	*Muswellbrook Coal Mine Development Consent Modification – Air Quality and Greenhouse Gas Impact Assessment (PAEHolmes, 2010)*
Ravensworth East	• ROM coal provided by the DRE for Mt. Owen. This was split for Glendell/Ravensworth East using ROM coal data from the 2010/2011 PRP. • PAEHolmes 2016 emissions inventory from the Ravensworth East Resource Recovery Project updated for emission factor consistency and controls from the PRP. PM emissions estimated by multiplying the PM:ROM ratios from the 2016 inventories to the ROM coal estimated for 2012 as above. 2016 was the only inventory available for this Project. • Splits of WI/WS/WE based on Ravensworth East 2016 emissions inventory.	*Ravensworth East resource Recovery Project: Air Quality Impact Assessment (PAEHolmes, 2012)*
Ravensworth Operations	• ROM coal provided by the DRE. • PAEHolmes 2013 emissions inventory updated with latest emission factors and controls from the PRP. PM emissions estimated by multiplying the PM:ROM ratios from the 2013 inventories to the estimated ROM coal value for 2012 per the AEMR. • Splits of WI/WS/WE based on Ravensworth Operations 2013 emissions inventory.	*Air Quality Impact Assessment: Ravensworth Operations Project (PAEHolmes, 2010)*
Ravensworth Underground	• ROM coal provided by the DRE. • PAEHolmes 'future year' emissions inventory updated with latest emission factors and controls from the PRP. PM emissions estimated by multiplying the PM:ROM ratios from the 'future year' inventories to the 2012 ROM coal value per the Xstrata website. • It has been assumed that given it is an underground mine, activities and materials moved in the 'future year' would not change significantly over subsequent years. • Splits of WI/WS/WE based on Ravensworth Underground 'future year' emissions inventory.	*Report: Air Quality & Greenhouse Gas Assessment – Ravensworth Underground Mine – Final (PAEHolmes, 2010)*

Rix's Creek	• ROM coal provided by the DRE. • PM emissions were taken from the Rix's Creek 2012 PRP. • Splits of WI/WS/WE were based on the above emissions split by ratios from the Ravensworth East 2012 emissions inventory as this mine had a similar estimated TSP emissions value to Rix's Creek 2012.	*Rix's Creek Coal Mine Particular Matter – Best Management Practice Pollution Reduction Program (Todoroski Air Sciences, 2012)*
Wambo	• ROM coal provided by the DRE. • PAEHolmes 2013 emissions inventory updated for consistency in emission factors and controls from the PRP. PM emissions estimated by multiplying the PM:ROM ratios from the 2013 inventories to the estimated ROM coal value for FY2012 per the AEMR. • Splits of WI/WS/WE based on Wambo 2013 emissions inventory.	*Air Quality Impact Assessment: Wambo Development Project (Holmes Air Sciences, 2003)*
Warkworth	• ROM coal provided by the DRE combined for Mt Thorley Warkworth. This was split based on the maximum approved production listed for each in the AEMR. • PAEHolmes 2012 emissions inventory from the Warkworth Extension Project updated with latest emission factors and controls from the PRP. • Splits of WI/WS/WE based on Warkworth 2012 emissions inventory.	*Air Quality Impact Assessment: Warkworth Extension Project (PAEHolmes, 2010)*

WI = Wind insensitive sources
WS = Wind sensitive sources
WE = Wind erosion sources

Table 5.3: Detailed mining emissions for 2012

Mine	Original inventory year (updated for 2012)	Original inventory data						ROM (t) used for 2012	Estimated emissions (kg/y)	
		ROM (t/yr)	Waste (t/y)	PM_{10} (kg/yr)	$PM_{2.5}$ (kg/yr)	PM_{10}/ROM	$PM_{2.5}$/ROM		PM_{10}	$PM_{2.5}$
Ashton NEOC	-	MINING COMPLETED 2011.								
Ashton SEOC (incl. UG)	-	NOT YET OPERATING.								
Ashton UG		2,300,000	-	-	-	-	-	2,300,000	3,297	415
Bengalla	2011	10,700,000	96,587,180	1,249,240	177,093	0.1	0.02	8,400,000	980,712	139,027
Bulga (Incl. Blakefield South & Beltana Undergrounds)	2014	16,000,000	96,197,495	2,877,392	331,039	0.2	0.02	14,600,000	2,625,620	302,073
Bulga Optimisation Project	-	NOT YET OPERATING.								
Dartbrook	-	NOT YET OPERATING.								
Doyles Creek UG	-	NOT YET OPERATING.								
Drayton	2012	8,000,000	52,945,354	1,221,175	188,447	0.2	0.02	5,600,000	854,823	131,913
Drayton South	-	NOT YET OPERATING.								
Ferndale OC	-	NOT YET OPERATING.								
Ferndale UG	-	NOT YET OPERATING.								
Glendell	2010	1,853,003	24,776,559	329,933	53,720	0.2	0.03	3,819,208	680,022	110,722
HVO South	2010	10,600,000	243,205,283	1,930,665	257,119	0.2	0.02	8,480,000	1,544,532	205,695
HVO North	2011	11,807,907	163,079,093	2,326,422	281,889	0.2	0.02	7,420,000	1,461,906	177,137
Integra (incl. UG)	FY 2011	2,645,323	33,889,159	710,664	153,413	0.3	0.06	4,600,000	1,235,786	266,773
Liddell	2011	7,800,000	92,532,000	1,509,575	171,108	0.2	0.02	6,900,000	1,335,393	151,365
Mangoola	2011	8,500,000	40,063,700	681,161	98,970	0.1	0.01	10,500,000	841,434	122,257
Mt. Arthur	2010	17,204,107	173,992,099	1,643,458	304,230	0.1	0.02	22,900,000	2,187,569	404,954
Mt. Owen	2013	7,900,000	82,800,000	869,019	145,954	0.1	0.02	8,016,021	881,782	148,098
Mt. Pleasant	-	NOT YET OPERATING.								
Mt. Thorley	2012	No inventory available. Emissions estimated using Mt. Thorley ROM (AEMR) and Warkworth emission ratios.						6,000,000	1,336,790	202,747
Muswellbrook Coal	2012/2013	1,531,248	21,464,629	224,254	28,878	0.1465	0.0189	1,100,000	161,097	20,745
Ravensworth East	2016	1,300,000	23,040,000	298,005	60,492	0.2	0.05	3,364,771	771,322	156,569
Ravensworth Operations (West, Narama + Rav North)	2013	12,760,719	177,528,344	2,016,115	266,737	0.2	0.02	5,800,000	916,364	121,237
Ravensworth Underground	'Future Year'	7,000,000	No waste	10,034	1,262	0.0	0.00	2,300,000	3,297	415
Ridgelands UG	MINE NOT YET OPERATING									
Rix's Creek	No inventory. TAS emissions assumed to be 2011.	-	-	-	-	-	-	2,700,000	618,933	125,636
Spur Hill UG	MINE NOT YET OPERATING									
Wambo	2013	8,000,000	119,600,000	2,047,571	267,712	0.3	0.03	9,400,000	2,405,896	314,562
Warkworth Extension	2012	13,888,585	168,360,874	3,094,354	469,311	0.2	0.03	10,800,000	2,406,223	364,944
West Muswellbrook	MINE NOT YET OPERATING									

5.3 Hourly varying emissions

In developing hourly varying emissions, total annual emissions are split into three emission source categories, as follows:

- Wind-insensitive sources (where the emission rate is independent of the wind speed).
- Wind-sensitive sources (where there is a relationship between the emission rate and wind speed).
- Wind erosion sources (where the emission is dependent on the wind speed).

Splitting the total emissions into source categories allows an hourly varying emission rate to be adjusted according to the wind speed for the wind-sensitive and wind erosion sources. The annual emissions are assigned to each category based on the contribution of each category to the total mine emissions. This is calculated for each mine site based on the detailed bottom-up inventories, and is calculated by adding together emissions from each individual source type that falls into the categories above and dividing by the mines total emissions. These source category splits are calculated for each available inventory year.

As an example, the following scaling factors have been applied to numerous air quality impact assessments for coal mines in the Hunter Valley, based on a detailed analysis of mine dust inventories undertaken as part of the Mount Arthur North Environmental Impact Statement (EIS) (**URS, 2000**):

- 0.73 for emissions that are independent of wind speed.
- 0.14 for emissions that depend on wind speed (such as loading and dumping).
- 0.13 for wind erosion sources.

It is noted that these are not the scaling factors used in this study (site-specific scaling factors for each mine are developed). However, they are shown here to provide an indication of the relative contribution that each source activity contributes to total mines site emissions. It is clear that emissions sources that are independent of wind speed contribute most to total mine emissions. This is borne out in the recently completed coal mine dust PRPs which consistently identified hauling as the largest dust source[g].

The annual emissions for each source that is dependent on wind speed will be converted to hourly emissions for wind-sensitive sources are adjusted as follows (**US EPA, 1987**):

$$Emission_{adjusted} = Emission_{unadjusted} \times \left({Hourly\ Wind\ Speed}/{2.2}\right)^{1.3}$$

The annual emissions for each wind erosion source will be converted to hourly emissions for wind erosion sources are adjusted according to the cube of the wind speed (**Skidmore, 1998**):

$$Emission_{adjusted} = Emission_{unadjusted} \times Wind\ Speed^3$$

The hourly emissions are normalised to the annual average wind speed and annual emissions, to ensure the sum of the hourly emissions equals the annual total.

No adjustment is made for wind-independent sources, which are simply evenly split for each hour of the year.

[g] http://www.environment.nsw.gov.au/resources/ MinMedia/MinMedia13032201.pdf

5.4 BAU projected emissions (2016, 2021, 2026 and 2031)

The Division of Resources and Energy (DRE) have provided estimates of yearly ROM coal production for the Upper Hunter Valley out to 2030 and these estimates are used as the basis for estimating emissions. The estimates provided by the DRE include a "consent" scenario and a "likely" scenario. The difference in the ROM projections between the two scenarios is shown in **Figure 5.1**. The likely scenario shows steady growth between 2012 and 2016, compared with the consent scenario which grows rapidly between 2012 and 2016. The other major difference between the two scenarios occurs between 2021 and 2026, where the likely scenario continues steady growth but the consent scenario falls sharply, as existing mine consents lapse.

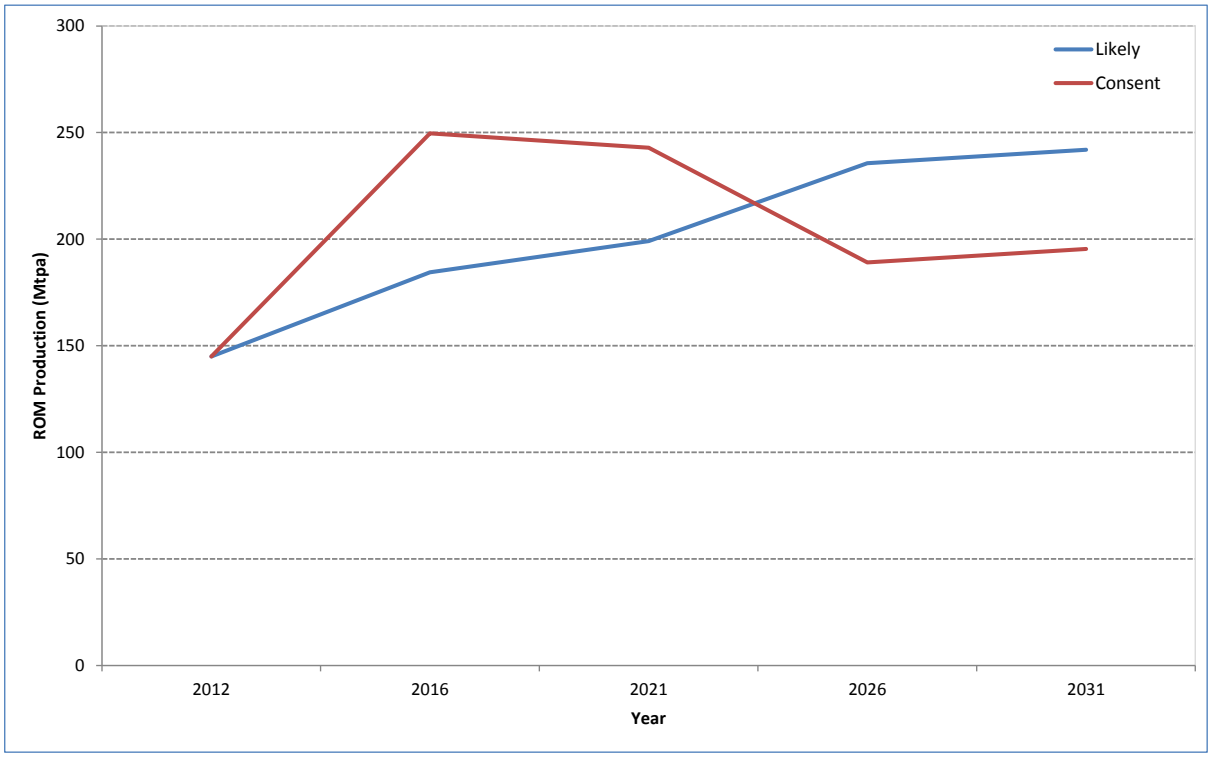
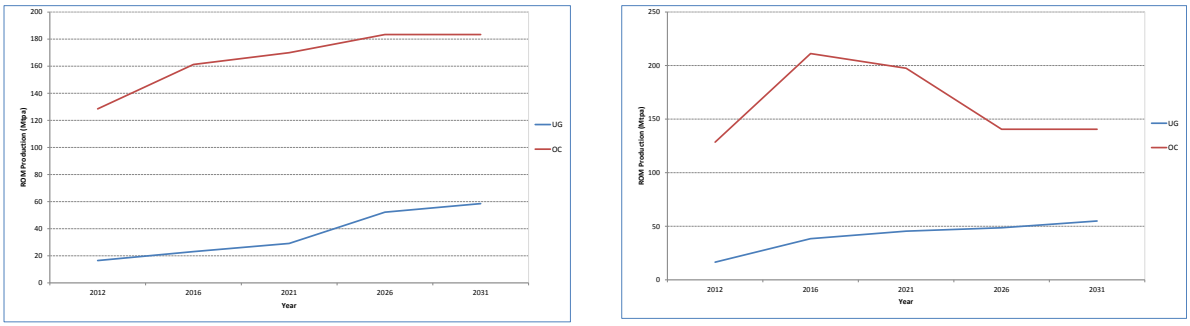


Figure 5.1: DRE forecast ROM production for Upper Hunter Valley

Figure 5.2 shows the split between open cut and underground mining into the future. The proportion of ROM coal from underground mining increases in 2026 and 2031, particularly for the "likely" scenario.



Likely Consent

Figure 5.2: DRE forecast ROM production for Open Cut and Underground

Estimates of PM emissions (kg/annum) for each BAU projection year are presented for the "likely" and "consent" scenario, based on the methodology described in **Section 5.1**. It is noted that the DRE estimates for 2030 are applied for 2031.

A summary of the estimated ROM coal production for all study years is presented in **Table 5.4**. The estimated annual PM_{10} and $PM_{2.5}$ emissions each year are presented in **Table 5.5.** The table shows all mines that are included in the future years (approved and not yet approved). The detailed assumptions used in creating the coal mine emission inventories are provided in **Appendix F**.

Table 5.4: Summary of DRE Projected ROM (Mtpa) for 2012, 2016, 2021, 2026 and 2031

Mining Operation	Likely Scenario					Consent Scenario				
	2012	2016	2021	2026	2031	2012	2016	2021	2026	2031
Ashton South East OC		1.7	3.4	3.4	3.4		3.6	3.6		
Ashton UG	2.3	3.6	3.6	3.6	3.6	2.3	5.2	5.2		
Beltana/Blakefield South UG	4.6	8.3	8.3	8.3	8.3	4.6	14.0	14.0	14.0	14.0
Bengalla OC	8.4	11.3	11.3	11.3	11.3	8.4	10.7			
Bulga OC	10.0	11.4	11.4	11.4	11.4	10.0	12.2	12.2	12.2	12.2
Dellworth UG				7.0	7.0				7.0	7.0
Drayton OC	5.6	3.5				5.6	3.5			
Drayton South OC		2.0	5.5	5.5	5.5		2.0	5.5	5.5	5.5
Ferndale OC				2.1	2.1				2.1	2.1
Ferndale UG				7.0	7.0				7.0	7.0
Hunter Valley Operations OC	15.9	23.0	28.0	28.0	28.0	15.9	38.0	38.0	16.0	16.0
Integra OC (Camberwell)	2.5	3.2	3.2	3.2	3.2	2.5	6.0	6.0		
Integra UG (Glennies Creek)	2.1	2.5	2.5	2.5	2.5	2.1	4.5	4.5	4.5	4.5
Liddell OC	6.9	7.7	7.7	7.7	7.7	6.9	8.0	8.0	8.0	8.0
Mangoola OC	10.5	12.6	12.6	12.6	12.6	10.5	10.5	10.5	10.5	10.5
Monash UG				7.0	7.0				7.0	7.0
Mt Arthur Coal OC	22.9	27.0	29.0	30.0	30.0	22.9	36.0	36.0	36.0	36.0
Mt Owen OC	15.2	17.0	17.0	17.0	17.0	15.2	10.0	10.0		
Mt Pleasant OC				11.5	11.5		10.5	10.5		
Mt Thorley Warkworth OC	16.8	20.3	20.3	20.3	20.3	16.8	28.0	28.0	28.0	28.0
Muswellbrook OC	1.1	1.2	1.2			1.1	1.2	1.2	1.2	1.2
Ravensworth North OC	3.0	10.5	10.5	10.5	10.5	3.0	16.0	16.0	16.0	16.0
Ravensworth UG (Newpac)	2.3	3.2	3.2	3.2	3.2	2.3	7.0	7.0		
Ravensworth West/Narama OC	2.8	2.0	2.0	2.0	2.0	2.8	5.0	5.0	5.0	5.0
Ridgelands				0.7	7.0				0.7	7.0
Rix's Creek OC	2.7	2.8	2.8	2.8	2.8	2.7	3.0			
Sandy Creek UG (& highwall)				1.4	1.4				1.4	1.4
Spur Hill UG			7.0	7.0	7.0			7.0	7.0	7.0
Wambo OC	4.2	4.1	4.1	4.1	4.1	4.2	7.0	7.0		
Wambo UG	5.2	5.5	4.5	4.5	4.5	5.2	7.7	7.7		
West Muswellbrook										
Total (Mtpa)	**145.0**	**184.4**	**199.1**	**235.6**	**241.9**	**145.0**	**249.6**	**242.9**	**189.1**	**195.4**

Table 5.5: Summary of estimated mining emissions for 2012, 2016, 2021, 2026 and 2031

	Likely		Consent		Likely		Consent		Likely		Consent		Likely		Consent	
Mining operation	PM_{10} (kg/yr)	$PM_{2.5}$ (kg/yr)	PM_{10} (kg/yr)	$PM_{2.5}$ (kg/yr)	PM_{10} (kg/yr)	$PM_{2.5}$ (kg/yr)	PM_{10} (kg/yr)	$PM_{2.5}$ (kg/yr)	PM_{10} (kg/yr)	$PM_{2.5}$ (kg/yr)	PM_{10} (kg/yr)	$PM_{2.5}$ (kg/yr)	PM_{10} (kg/yr)	$PM_{2.5}$ (kg/yr)	PM_{10} (kg/yr)	$PM_{2.5}$ (kg/yr)
	2016				**2021**				**2026**				**2031**			
Ashton South East OC	307,113	36,841	509,923	61,171	301,440	35,075	378,954	44,094	301,440	35,075			301,440	35,075		
Ashton UG																
Bengalla OC	1,431,790	208,846	1,355,766	197,757	1,431,790	208,846			1,431,790	208,846			1,431,790	208,846		
Bulga OC	3,542,789	407,592	4,711,729	542,077	3,542,789	407,592	4,711,729	542,077	3,542,789	407,592	4,711,729	542,077	3,542,789	407,592	4,711,729	542,077
Beltana/Blakefield South UG																
Dellworth UG									10,034	1,262	10,034	1,262	10,034	1,262	10,034	1,262
Drayton OC	784,710	145,624	784,710	145,624												
Drayton South OC	363,166	59,344	363,166	59,344	1,175,262	212,536	1,175,262	212,536	1,390,992	271,272	1,390,992	271,272	1,054,380	163,286	1,054,380	163,286
Ferndale OC									121,686	14,598	121,686	14,598	121,686	14,598	121,686	14,598
Ferndale UG									10,034	1,262	10,034	1,262	10,034	1,262	10,034	1,262
Hunter Valley Operations OC	3,963,951	519,039	6,549,136	857,542	4,738,439	616,820	6,430,738	837,113	4,738,439	616,820	2,707,679	352,469	4,738,439	616,820	2,707,679	352,469
Integra OC (Camberwell)	553,290	68,668	1,019,219	126,494	553,290	68,668	1,019,219	126,494	553,290	68,668	6,450	811	553,290	68,668	6,450	811
Integra UG (Glennies Creek)																
Liddell OC	1,490,222	168,915	1,548,282	175,496	1,490,222	168,915	1,548,282	175,496	1,490,222	168,915	1,548,282	175,496	1,490,222	168,915	1,548,282	175,496
Mangoola OC	1,009,721	146,709	841,434	122,257	1,009,721	146,709	841,434	122,257	1,009,721	146,709	841,434	122,257	1,009,721	146,709	841,434	122,257
Monash UG									10,034	1,262	10,034	1,262	10,034	1,262	10,034	1,262
Mt Arthur Coal OC	4,103,121	571,648	5,470,827	762,197	5,000,064	689,894	6,206,976	856,420	5,202,048	717,693	6,242,457	861,232	5,202,048	717,693	6,242,457	861,232
Mt Owen OC (incl. Glendell & Rav East)	2,185,525	375,886	1,285,603	221,110	2,123,008	373,661	1,248,828	219,801	2,123,008	373,661			2,123,008	373,661		
Mt Pleasant OC			841,434	122,257			841,434	122,257	921,571	133,901			921,571	133,901		
Mt Thorley Warkworth OC	3,832,752	584,317	5,286,554	805,955	3,832,752	584,317	5,286,552	805,955	3,832,752	584,317	5,286,554	805,955	4,009,000	604,165	5,529,655	833,331
Muswellbrook OC	175,742	22,631	175,742	22,631	175,742	22,631	175,742	22,631			175,742	22,631			175,742	22,631
Ravensworth West/Narama OC	1,441,526	187,584	2,421,764	315,142	1,906,360	255,012	3,202,684	428,421	1,839,461	245,287	3,090,295	412,083	1,920,685	254,206	3,226,750	427,066
Ravensworth North OC																
Ravensworth UG (Newpac)	4,587	577	10,034	1,262	4,587	577	10,034	1,262	4,587	577			4,587	577		
Ridgelands UG									1,003	126	1,003	126	10,034	1,262	10,034	1,262
Rix's Creek OC	641,857	130,289	687,703	139,596	641,857	130,289			641,857	130,289			641,857	130,289		
Sandy Creek UG (& highwall)									2,007	252	2,007	252	2,007	252	2,007	252
Spur Hill UG					10,034	1,262	10,034	1,262	10,034	1,262	10,034	1,262	10,034	1,262	10,034	1,262
Wambo OC	2,457,085	321,255	3,762,412	491,921	2,201,139	287,791	3,762,412	491,921	2,201,139	287,791			2,201,139	287,791		
Wambo UG																
West Muswellbrook																
TOTAL (tonnes/year)	**28,289**	**3,956**	**37,625**	**5,170**	**30,138**	**4,211**	**36,850**	**5,010**	**31,390**	**4,417**	**26,166**	**3,586**	**31,320**	**4,339**	**26,218**	**3,522**

6 ESTIMATING DIESEL EMISSIONS FROM COAL MINES

As part of an initiative to manage diesel emissions from non-road vehicles, the EPA surveyed 64 licenced coal mines in NSW to obtain to obtain detailed information about the composition and use of their diesel fleet, their maintenance and engine replacement schedules, fleet projections and fuel use (**NSW EPA, 2014**).

Based on this information, the EPA has estimated diesel emissions (PM_{10} and $PM_{2.5}$) for each mine in the Upper Hunter and made the data available for this study. The EPA estimated PM_{10} and $PM_{2.5}$ emissions from diesel combustion are presented in **Table 6.1**.

Table 6.1: Summary of EPA estimated coal mine diesel emissions - 2012

EPA Mine name	PM_{10} (kg/yr)	$PM_{2.5}$ (kg/yr)
ASHTON COAL MINE	1,157	1,122
BENGALLA MINE	53,008	51,418
SAXONVALE COLLIERY HOLDING (Bulga)	103,183	100,087
DRAYTON COAL MINE	65,184	63,228
HUNTER VALLEY OPERATIONS	134,861	130,816
INTEGRA COAL COMPLEX	28,960	28,091
LIDDELL COAL OPERATIONS	49,240	47,763
XSTRATA MANGOOLA	27,195	26,379
MT ARTHUR COAL	177,971	172,632
MT OWEN COAL MINE	45,273	43,915
MOUNT THORLEY OPERATIONS	59,124	57,350
WARKWORTH COAL MINE	96,247	93,360
MUSWELLBROOK COLLIERY HOLDING	17,592	17,064
RAVENSWORTH EAST MINE/GLENDELL MINE	29,397	28,515
RAVENSWORTH MINING COMPLEX	23,719	23,007
RIX'S CREEK COLLIERY	26,156	25,371
WAMBO COAL PTY LTD	80,513	78,098
TOTAL (tonnes/year)	**1,019**	**988**

6.1 BAU projected emissions (2016, 2021, 2026 and 2031)

The EPA has also provided information on diesel consumption and ROM production for 2012. Using this information a site specific diesel intensity factor (kL diesel per tonne ROM) has been derived for each mine. The diesel intensity factor varies from 0.0003 to 0.008 kL/tonne of ROM, depending on whether a mine operation is open cut, underground or a combination of both.

Using the DRE projected ROM production rates for BAU years, future diesel consumption is projected using the site specific diesel intensity factors. The annual PM_{10} and $PM_{2.5}$ emissions are then estimated based on mine specific emissions factors (kg/kL.year), also provided by the EPA based on their survey data, as follows:

$$Emissions_{\,(kg/year)} = ROM_{(Mtpa)} \times 10^6 \times Diesel\ intensity_{(kL/t\ ROM)} \times Emission\ Factor_{\,(kg/kL.year)}$$

The estimated diesel emissions for 2016, 2021, 2026 and 2031 are presented in **Table 6.2** to **Table 6.5**, for both the "likely" and "consent" scenario.

Table 6.2: Summary of estimated diesel emissions for BAU - 2016

Mining Operation	Likely		Consent	
	PM_{10} (kg/yr)	$PM_{2.5}$ (kg/yr)	PM_{10} (kg/yr)	$PM_{2.5}$ (kg/yr)
Ashton South East OC	15,197	14,741	32,181	31,216
Ashton UG	1,806	1,752	2,609	2,531
Bengalla OC	71,676	69,526	67,870	65,834
Bulga OC	117,629	114,100	125,883	122,107
Beltana/Blakefield South UG	2,082	2,020	3,512	3,407
Drayton OC	41,815	40,561	41,815	40,561
Drayton South OC	23,894	23,177	23,894	23,177
Ferndale OC				
Ferndale UG				
Hunter Valley Operations OC	194,069	188,247	320,636	311,017
Integra OC (Camberwell)	36,152	35,068	66,596	64,598
Integra UG (Glennies Creek)				
Liddell OC	55,203	53,547	57,353	55,633
Mangoola OC	32,637	31,658	27,197	26,382
Mt Arthur Coal OC	223,592	216,884	298,123	289,179
Mt Owen OC (includes Glendell and Ravensworth East)	95,018	92,167	55,893	54,216
Ravensworth North OC	38,470	37,316	61,983	60,123
Ravensworth West/Narama OC	7,328	7,108	19,370	18,789
Ravensworth UG (Newpac)	803	779	1,756	1,703
Mt Pleasant OC			89,819	87,124
Mt Thorley Warkworth OC	191,581	185,834	264,250	256,322
Muswellbrook OC	20,062	19,460	20,062	19,460
Rix's Creek OC	27,236	26,419	29,181	28,306
Wambo OC	82,657	80,177	142,988	138,699
Wambo UG				
West Muswellbrook				
Dellworth UG				
Monash UG				
Ridgelands UG				
Sandy Creek UG (& highwall)				
Spur Hill UG				
Total (kg/year)	**1,289,713**	**1,251,021**	**1,669,511**	**1,619,426**
Total (tonnes/year)	**1,290**	**1,251**	**1,670**	**1,619**

Table 6.3: Summary of estimated diesel emissions for BAU - 2021

Mining Operation	Likely		Consent	
	PM_{10} (kg/yr)	$PM_{2.5}$ (kg/yr)	PM_{10} (kg/yr)	$PM_{2.5}$ (kg/yr)
Ashton South East OC	30,393	29,481	32,181	31,216
Ashton UG	1,806	1,752	2,609	2,531
Bengalla OC	71,676	69,526		
Bulga OC	117,629	114,100	125,883	122,107
Beltana/Blakefield South UG	2,082	2,020	3,512	3,407
Drayton OC				
Drayton South OC	65,709	63,738	65,709	63,738
Ferndale OC				
Ferndale UG				
Hunter Valley Operations OC	236,258	229,171	320,636	311,017
Integra OC (Camberwell)	36,152	35,068	66,596	64,598
Integra UG (Glennies Creek)				
Liddell OC	55,203	53,547	57,353	55,633
Mangoola OC	32,637	31,658	27,197	26,382
Mt Arthur Coal OC	240,154	232,950	298,123	289,179
Mt Owen OC (includes Glendell and Ravensworth East)	95,018	92,167	55,893	54,216
Ravensworth North OC	38,470	37,316	61,983	60,123
Ravensworth West/Narama OC	7,328	7,108	19,370	18,789
Ravensworth UG (Newpac)	803	779	1,756	1,703
Mt Pleasant OC			89,819	87,124
Mt Thorley Warkworth OC	191,581	185,834	264,250	256,322
Muswellbrook OC	20,062	19,460	20,062	19,460
Rix's Creek OC	27,236	26,419		
Wambo OC	74,047	71,825	142,988	138,699
Wambo UG				
West Muswellbrook				
Dellworth UG				
Monash UG				
Ridgelands UG				
Sandy Creek UG (& highwall)				
Spur Hill UG	1,756	1,703	1,756	1,703
Total (kg/year)	**1,356,807**	**1,316,103**	**1,574,216**	**1,526,989**
Total (tonnes/year)	**1,357**	**1,316**	**1,574**	**1,527**

Table 6.4: Summary of estimated diesel emissions for BAU - 2026

Mining Operation	Likely		Consent	
	PM_{10} (kg/yr)	$PM_{2.5}$ (kg/yr)	PM_{10} (kg/yr)	$PM_{2.5}$ (kg/yr)
Ashton South East OC	30,393	29,481		
Ashton UG	1,806	1,752		
Bengalla OC	71,676	69,526		
Bulga OC	117,629	114,100	125,883	122,107
Beltana/Blakefield South UG	2,082	2,020	3,512	3,407
Drayton OC				
Drayton South OC	65,709	63,738	65,709	63,738
Ferndale OC	17,964	22,799	17,964	22,799
Ferndale UG	1,756	1,703	1,756	1,703
Hunter Valley Operations OC	236,258	229,171	135,005	130,955
Integra OC (Camberwell)	36,152	35,068	28,541	27,685
Integra UG (Glennies Creek)				
Liddell OC	55,203	53,547	57,353	55,633
Mangoola OC	32,637	31,658	27,197	26,382
Mt Arthur Coal OC	248,436	240,983	298,123	289,179
Mt Owen OC (includes Glendell and Ravensworth East)	95,018	92,167		
Ravensworth North OC	38,470	37,316	47,491	46,066
Ravensworth West/Narama OC	7,328	7,108	14,841	14,396
Ravensworth UG (Newpac)	803	779		
Mt Pleasant OC	98,373	95,422		
Mt Thorley Warkworth OC	191,581	185,834	264,250	256,322
Muswellbrook OC			20,062	19,460
Rix's Creek OC	27,236	26,419		
Wambo OC	74,047	71,825		
Wambo UG				
West Muswellbrok				
Dellworth UG	1,756	1,703	1,756	1,703
Monash UG	1,756	1,703	1,756	1,703
Ridgelands UG	176	170	176	170
Sandy Creek UG (& highwall)	351	341	351	341
Spur Hill UG	1,756	1,703	1,756	1,703
Total (kg/year)	**1,447,438**	**1,404,015**	**1,093,764**	**1,060,951**
Total (tonnes/year)	**1,447**	**1,404**	**1,094**	**1,061**

Table 6.5: Summary of the diesel emissions for BAU 2031

Mining Operation	Likely		Consent	
	PM_{10} (kg/yr)	$PM_{2.5}$ (kg/yr)	PM_{10} (kg/yr)	$PM_{2.5}$ (kg/yr)
Ashton South East OC	30,393	29,481		
Ashton UG	1,806	1,752		
Bengalla OC	71,676	69,526		
Bulga OC	117,629	114,100	125,883	122,107
Beltana/Blakefield South UG	2,082	2,020	3,512	3,407
Drayton OC				
Drayton South OC	65,709	63,738	65,709	63,738
Ferndale OC	117,629	114,100	125,883	122,107
Ferndale UG	2,082	2,020	3,512	3,407
Hunter Valley Operations OC	236,258	229,171	135,005	130,955
Integra OC (Camberwell)	36,152	35,068	28,541	27,685
Integra UG (Glennies Creek)				
Liddell OC	55,203	53,547	57,353	55,633
Mangoola OC	32,637	31,658	27,197	26,382
Mt Arthur Coal OC	248,436	240,983	298,123	289,179
Mt Owen OC (includes Glendell and Ravensworth East)	95,018	92,167		
Ravensworth North OC	38,470	37,316	47,491	46,066
Ravensworth West/Narama OC	7,328	7,108	14,841	14,396
Ravensworth UG (Newpac)	803	779		
Mt Pleasant OC	98,373	95,422		
Mt Thorley Warkworth OC	191,581	185,834	264,250	256,322
Muswellbrook OC			20,062	19,460
Rix's Creek OC	27,236	26,419		
Wambo OC	74,047	71,825		
Wambo UG				
West Muswellbrook				
Dellworth UG	1,756	1,703	1,756	1,703
Monash UG	1,756	1,703	1,756	1,703
Ridgelands UG	1,756	1,703	1,756	1,703
Sandy Creek UG (& highwall)	351	341	351	341
Spur Hill UG	1,756	1,703	1,756	1,703
Total (kg/year)	1,449,019	1,405,548	1,095,344	1,062,484
Total (tonnes/year)	**1,449**	**1,406**	**1,095**	**1,062**

Emissions from non-road diesel are also included in the GMR inventory data for industrial and commercial fugitive and off-road mobile files (ASE). For modelling, the annual total (for each grid cell) has been scaled according to ASE daily, weekly and monthly profiles (also provided by the EPA). The profiles are used to create temporally varying (hourly) emissions files required for modelling.

It is noted that the US EPA AP-42 emission factors used in the coal mine emissions inventories may include PM emissions from both the mechanical processes (i.e. crustal material) and the diesel exhaust (combustion). Therefore, there is an element of double counting when the emissions from diesel exhaust from coal mine vehicles are estimated separately. However, discussions with Chatten Cowherrd of MRI Global, who was involved in the derivation of AP-42 emission factors, indicated that sampling mostly captured the crustal component of the dust and diesel exhaust would generally have been a minor component.

7 ESTIMATING EMISSIONS FROM OTHER SOURCES

Emissions data for sources other than coal mines and non-road diesel have been provided by the NSW EPA, extracted from the Air Emission Inventory for the Greater Metropolitan Region (GMR) in NSW (**NSW EPA 2012a, 2012b, 2012c and 2012d**) (hereafter referred to as the GMR inventory). The emissions file and types are described in **Table 7.1**. Emissions for 2012 are based on GMR inventory for 2008 and scaled to take into account any changes between 2008 and 2012, as follows:

- Uptake of "AS/NZS 4013:1999 *Domestic solid fuel burning appliances - Method for determination of flue gas emission*".
- PM controls for commercial and industrial sources based on Clean Air Regulation Regulatory Impact Statement (**NSW DECCW, 2010**).
- PM controls for on-road mobile sources from **NSW EPA** (**2012e**).

Table 7.1: Summary of the GMR inventory files

File Type	Description	File format
PSE	Industrial and commercial point sources	Monthly weekend and weekday files. PSE includes coal fired power stations emissions
ASE	Industrial & commercial fugitive and off-road mobile area	Monthly weekend and weekday files. ASE includes non-road diesel emissions (modelled separately)
DSE	Domestic-commercial area sources	Monthly weekend and weekday files. DSE includes domestic wood heaters emissions. These are the largest emission source in the DSE file
BSE	Biogenic-geogenic area sources	Monthly weekend and weekday files.
MVSE	On-road mobile area sources	Monthly weekend and weekday files.
WHE	Wood heater sources only	Annual emissions with monthly, weekly and daily profiles

The emissions files were provided for the entire GMR, and the first step was to extract emissions corresponding to the modelling area for this study. A summary of the annual emission totals for sources within the modelling area are presented in **Table 7.2**. Further details on the specific treatment of emissions sources are provided in the following sections.

Table 7.2: Summary of the annual emissions for each source (tonnes/yr)

Source Group	Annual PM_{10} Emissions tonnes/yr	Annual $PM_{2.5}$ Emissions tonnes/yr
Wood heater sources only	59	56
Power stations only	2,564	1,432
Other Industrial and commercial point sources	1.0	0.3
Biogenic-geogenic area sources	517	74
Domestic-commercial area sources	61	57
On-road mobile area sources	28	20

7.1 Wood heater emissions

Emissions from wood heaters are included in the domestic-commercial area source files (DSE) and were also provided separately as an annual total for each grid cell. For modelling, the annual total (for each grid cell) has been scaled according to daily, weekly and monthly profiles (also provided by the EPA). The profiles are used to create temporally varying (hourly) emissions files required for modelling.

Further consideration was given to better resolving wood heater emission profiles, for example by adjusting for probability of usage and usage intensity. For probability of usage, adjustments for Heating Degree Days (HDD) were investigated. HDD are determined from the difference between the average daily temperature and the adopted comfort level temperature. The adjustment methodology for HDD is outlined in **US EPA (2001)**. A scaling factor for HDD was determined based on the difference between the inventory year (2008) and the modelled year (2012); however, the scaling factor derived (close to 1) was considered inconsequential to the modelling predictions (especially in the context of the sensitivity of modelling results to chosen model parameters (see **Section 9.2**).

Furthermore, as modelling results for 2012 are scaled for BAU projections in future years, the adjustments for HDD for 2012 would flow to all other years.

The daily profiles provided by the EPA resolve intensity of usage. An example of the hourly varying wood heater $PM_{2.5}$ emissions (g/s) for July at a location in Muswellbrook is shown in **Figure 7.1**. Also presented in the plot is the corresponding hourly average ambient temperature (°C) and measured $PM_{2.5}$ concentration (µg/m^3) (at the Muswellbrook EPA site).

The plots show a marked increase in emissions from 4 pm (red line), followed by a drop after 11pm when intensity of usage would be expected to drop. The point at which wood heater emissions increase correlates with a temperature decrease (blue line).

As expected, the increase in measured $PM_{2.5}$ concentration at the Muswellbrook monitoring site (green line) increases in line with the increase in wood heater emissions.

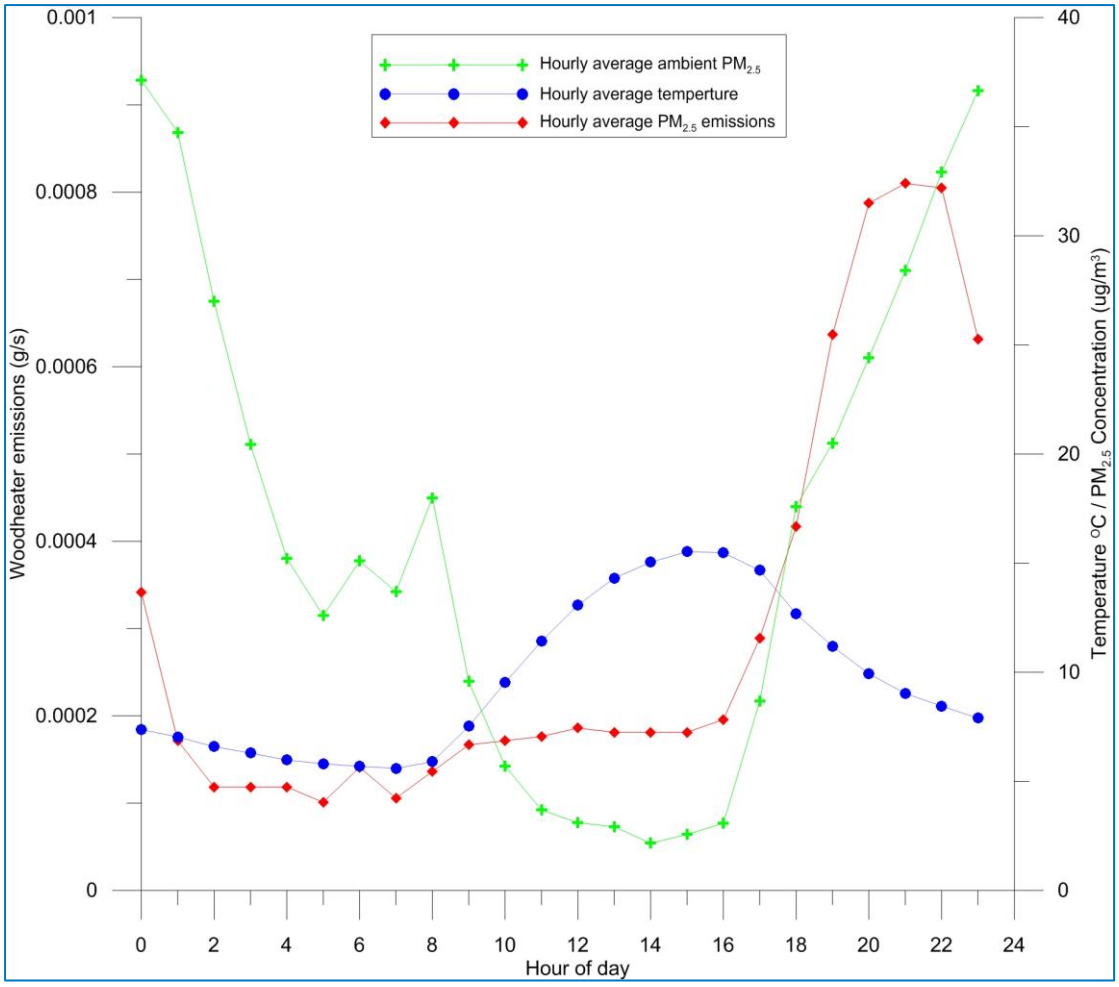


Figure 7.1: Hourly wood heater emissions for July with temperature and $PM_{2.5}$ concentration

7.2 Coal-fired electrical power generation

Emission data for coal-fired electrical power generation are included in the industrial point source files (PSE). The emissions (and point source parameters) for coal fired electrical power generation are extracted from the PSE emissions file. The power stations modelled are Redbank, Bayswater and Liddell power stations. Monthly files for weekdays and weekends were collated into an annual hourly varying emissions file.

7.3 Other sources

GMR inventory data for the ASE, DSE, BSE and MVSE files are provided as 1 km x 1 km gridded area emissions files. These emissions were aggregated into 3 km x 3 km emissions files to generate emissions files for modelling (further discussion provided in **Section 9**). Monthly files for weekday and weekends were collated into an annual hourly varying emissions file.

7.4 BAU projected emissions (2016, 2021, 2026 and 2031)

GMR inventory annual emissions to area files for 2016, 2021, 2026 and 2031 are provided by the NSW EPA for all sectors (Biogenic-Geogenic, Commercial, Domestic-Commercial, Industrial, Off-Road Mobile and On-Road Mobile).

The projections assume growth as detailed in (**NSW EPA 2012a, 2012b, 2012c and 2012d**) plus uptake of mandated emission standards outlined in **Section 6**.

The emissions to area files are used to derive scaling factors to apply to BAU projected PM_{10} and $PM_{2.5}$ concentrations. The scaling factors derived from the annual emissions to area files are summarised in **Table 7.3**.

Table 7.3: Summary of the scaling factors

Module	PM_{10}				$PM_{2.5}$			
	2012 - 2016	2012-2021	2012-2026	2012-2031	2012 - 2016	2012-2021	2012-2026	2012-2031
Biogenic	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00
Commercial	0.95	0.86	0.93	1.00	0.93	0.82	0.86	0.91
Domestic-Commercial	0.95	0.96	0.96	0.96	0.95	0.96	0.96	0.96
Industrial	1.07	1.17	1.27	1.36	1.05	1.12	1.18	1.25
Off-Road Mobile	1.05	1.11	1.17	1.23	1.05	1.11	1.17	1.23
On-Road Mobile	0.93	0.88	0.88	0.90	0.88	0.79	0.77	0.76

8 MODEL SENSITIVITY

A number of sensitivity tests were completed for various model inputs. The following sections summarise these sensitivity tests, with further detail is presented in **Appendix G**.

8.1 Sensitivity of chosen value for initial plume spread

The sensitivity of modelled initial plume spread to predicted concentrations in Singleton and Muswellbrook was assessed. The preferred modelling approach was to 'smear' the coal mine emissions across the nominated number of volume sources for all activities. A horizontal plume spread (initial sigma y) was calculated based on the distance between the allocated volume source locations (divided by 4.3). This was compared to fixed sigma y of 10m (based on a nominal plume dimension for various mining activities).

The results of this sensitivity test showed that changing the horizontal spread had little effect on the predicted annual average ground-level $PM_{2.5}$ concentrations in Singleton and Muswellbrook, as shown in **Table 8.1**. Results for all locations and for PM_{10} are presented in **Appendix G**.

Final modelling results are presented using a varying sigma y based on source separation.

Table 8.1: Sensitivity test results for initial plume spread

EPA Monitoring Station	Predicted annual average $PM_{2.5}$ concentration ($\mu g/m^3$)	
	Sigma Y based on source seperation	Sigma Y at 10m
Muswellbrook	1.9	1.9
Muswellbrook NW	1.5	1.5
Singleton	1.3	1.3
Singleton NW	3.8	3.8
Singleton South	0.9	0.9

8.2 Wet deposition

The sensitivity of the model results to wet deposition was tested and found to lower the predicted annual average ground level concentrations, as expected. The results for $PM_{2.5}$ at Singleton and Muswellbrook are shown in **Table 8.2**. Modelling of wet deposition relies on the model accurately predicting the precipitation rate. Analysis of the CALMET output indicates that the predicted precipitation was significantly higher than observed (refer **Appendix G**).

Including this option would overestimate the effect of wet deposition. Further uncertainty would be introduced for estimating BAU projections if wet deposition was included. For these reasons, the option of wet deposition was not modelled for the final results presented in this report. Further results are presented in **Appendix G**.

It is noted that rainfall observations were not assimilated in the modelling, which may help explain the poor agreement. There is a scarcity of hourly rainfall data for the modelling domain (the UHAQMN site do not measure rainfall and the BoM sites at Singleton and Muswellbrook only report daily rainfall).

Table 8.2: Sensitivity test results for wet deposition

EPA Monitoring Station	Predicted annual average $PM_{2.5}$ concentration ($\mu g/m^3$)	
	Without Wet Deposition	With Wet Deposition
Muswellbrook	1.9	1.4
Muswellbrook NW	1.5	1.0
Singleton	1.3	1.0
Singleton NW	3.8	3.4
Singleton South	0.9	0.7

8.3 Sensitivity tests for wood heater source configuration

Preliminary modelling indicted wood heater modelling was very sensitive to the chosen value for initial vertical plume spread (sigma z). Predicted ground level concentrations (GLCs) were doubled by decreasing sigma z by a factor of four.

The value for sigma z chosen for modelling was based on the estimated final plume rise height determined for ambient conditions of zero degrees Celsius. Final plume rise height was determined using the Briggs plume rise equation for stable conditions (**Hanna et al., 1982**) and assumed a plume exit velocity of 2 m/s and a plume temperature of 50 degrees Celsius (**Stone, 1969**). The calculated final plume rise was 45.6 m with a derived sigma z of 10.6 m.

Using this approach, a sensitivity test was completed for Muswellbrook wood heater emissions. The predicted ground level concentration of $PM_{2.5}$, at the Muswellbrook monitoring site, was compared with the measured average hourly $PM_{2.5}$ concentration, as shown in **Figure 8.1**. The plot shows daily profiles of 1 hour averages, grouped by month of the year (i.e. daily and monthly profile of ground level concentrations).

The plots show that the modelling predictions for wood heater emissions at Muswellbrook track well to the monitoring data in terms of seasonal and diurnal patterns.

The profile in the measured data shows a clear seasonal pattern, with $PM_{2.5}$ concentrations significantly increasing in winter. This seasonal pattern is explained by either a change in prevailing wind (from southeast to northwest in winter), wood heaters emissions or a combination of both. The diurnal pattern (peaks in the evening/night and drops during the day) suggests a strong wood heater influence. Assuming therefore that the profile seen in the monitoring data (red line in **Figure 8.1**) is a result of wood heater emissions, it is concluded that the model is predicting this source to a reasonable level of accuracy.

Results for Singleton are also presented in **Appendix G**. The modelling predictions at Singleton also track well for most heating months. However, there is an over prediction in June and July.

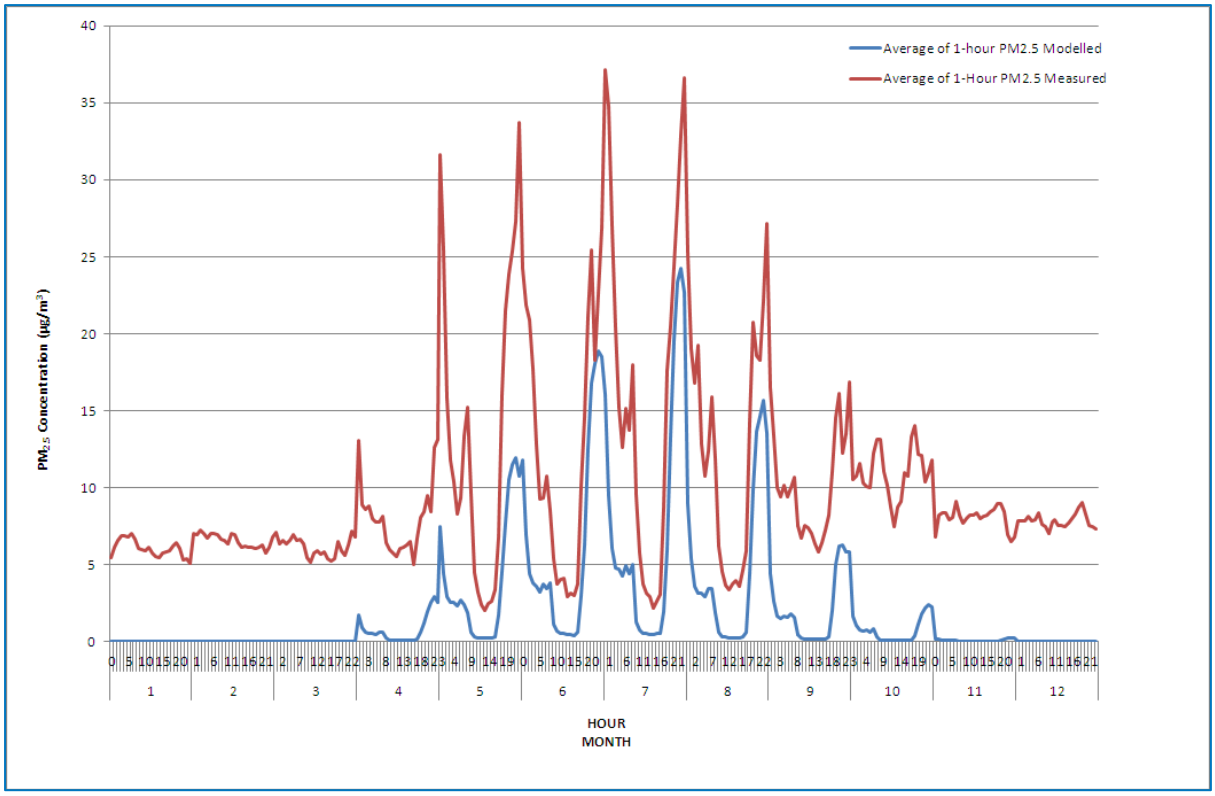


Figure 8.1: Wood heater $PM_{2.5}$ modelling predictions - Muswellbrook (compared to measured)

8.4 Sensitivity test for GMR inventory source configuration

Two options were tested for modelling gridded GMR inventory emissions data with sources represented as area source configuration and as volume sources configuration. For all emission sources, volume source configuration results in higher ground level concentrations, as follows:

- Ground level concentrations for ASE, DSE and MVSE emissions (as described in **Table 7.1**) are on average 2 times higher for volume source configuration, for both PM_{10} and $PM_{2.5}$.
- Ground level concentrations for BSE emissions (as described in **Table 7.1**) are on average 1.4 times higher for volume source configuration, for both PM_{10} and $PM_{2.5}$.

The results are presented in **Appendix F**. The decision was made to proceed with the volume source configuration for presentation of final results. This is based on improved model evaluation (when compared to monitoring data) using the volume source configuration. Furthermore, wood heaters and non-road diesel were modelled separately using volume source configurations.

Non-road diesel is modelled in the same way as coal mine emissions (as the majority is consumed at coal mines) and approvals modelling in the Hunter Valley has consistently used volume source configurations to model coal mine emissions.

Wood heaters were also considered to be better represented as volume sources due to the sensitivity of results in initial vertical spread (as outlined in **Section 8.3**). It was therefore more appropriate for ASE (which are mostly non-road diesel) and DSE (which are mostly wood heaters) to be modelled in the same way.

8.5 Sensitivity of model predictions at exact locations

Modelling predictions (both PM_{10} and $PM_{2.5}$) are made at each UHAQMN site and used for model evaluation. A sensitivity run was completed to test whether an ensemble average of predictions at various points around each monitoring location would provide a different result to the prediction at the monitoring site. Eight discrete receptor points were placed at 400 m intervals around each monitoring site. The average "vicinity" prediction was compared with the actual prediction at the monitoring site. For almost all source groups and locations, very little difference was seen between the actual and the vicinity prediction. The results are presented in **Appendix G**. It was therefore concluded that the model predictions at the UHAQMN site locations are suitable for model evaluation and the vicinity predictions were not considered further.

9 OVERVIEW OF SOURCE APPORTIONMENT MODELLING

Source apportionment modelling is used to quantify the contribution of primary anthropogenic PM emissions to annual average ambient PM_{10} and $PM_{2.5}$ concentrations for the source groups below:

- Coal mines (mechanically generated dust from mining)
- Domestic wood heaters
- Coal fired electrical power generation
- Non-road diesel exhaust

Although the focus of this study is on the source groups above and specifically their contribution to annual average ambient PM_{10} and $PM_{2.5}$ concentrations in Singleton and Muswellbrook, a key component of the study is to evaluate the performance of the model for base year (2012) emissions. The performance of the model is assessed by comparing annual average model predictions to the monitoring data for 2012, collected from UHAQMN sites. Of the 13 monitoring sites located in the modelling domain, all measure PM_{10} and only Singleton, Muswellbrook and Camberwell measure $PM_{2.5}$.

For model evaluation, all emissions sources are modelled and the following sources included as source groups:

- Domestic commercial sources (other than wood heaters)
- Industrial and commercial fugitive sources (other than coal mines and non-road diesel)
- Other industrial and commercial point sources (other than power stations)
- On-road mobile sources
- Biogenic and geogenic sources

Source apportionment modelling using CALPUFF was completed for each of the source groups. Model evaluation (base year 2012) compares modelling for all sources with monitoring data[h].

A number of model sensitivity runs were completed before final modelling for each source group was completed. The following sections provide technical detail on how each source group was modelled and also describes the sensitivity tests completed.

9.1 Coal mines

Activities at each individual mine are represented as a series of volume sources with the number of volume sources chosen based on the size of the mine, the extent of exposed areas and the haul road lengths.

The approach of using volume sources for various mining activity aims to "smear" the total emissions across the nominated number of volume sources (according to the emission categories described in **Section 5.3**). This approach was also due to the practical limitations of assigning individual activities to specific source types for this number of mines. The approach is appropriate for the regional scale modelling for this study.

For each volume source, estimates of horizontal spread (initial sigma y (σy)) and vertical spread (initial sigma z (σz)) need to be assigned. Values of σz are typically assigned based on the plume height at source divided by 2.15 and values of σy assigned based on the plume width at source divided by 4.3. Values of σy and σz are therefore dependent on the source type.

[h] The focus of this study is primary anthropogenic PM. There is also a significant component of PM that is secondary and is included in the monitoring data. Therefore, secondary (and some natural PM) needs to be added for model evaluation. Further details provided in Section 9.8.

For this study it was not practical to assign values of σy and σz for individual mining activities due to the number of activities included in each volume source and the amount of coal mines included in the study. Instead, the initial plume spread is chosen based on the distance between allocated volume source locations. Using this approach, the assumption is made that emissions from various types of mining equipment are released from each volume source location. For example, a volume source located in the pit may include emissions from a dozer, an excavator loading trucks, hauling and wind erosion.

The vertical spread (initial sigma z (σz)) was chosen based on recommendations made in the US EPA Haul Road Workgroup (**US EPA, 2012**) as follows.

- Vertical spread calculated as plume height divided by 2.15.
- Plume height was determined based on vehicle height times 1.7.

Vertical spread was calculated to be 4.7 based on a vehicle height of 6 m, which is reasonable assumption for mining equipment.

Modelling was completed for two size fractions, fine and coarse. Fine particles were modelled using $PM_{2.5}$ emissions rates with a particle geometric mean diameter of 1.5 µm. The coarse fraction was modeled using $PM_{2.5\text{-}10}$ emission rates (PM_{10} emissions minus $PM_{2.5}$ emissions) with a particle geometric mean diameter of 5.94 µm. The particle mass mean diameters were determined from particle size distribution data for various coal mining activities (presented in **SPCC (1986)**).

Figure 9.1 shows the mine lease boundaries and the volume source locations modelled (dots) for the base year scenario (2012). Other years are shown in **Appendix H.**

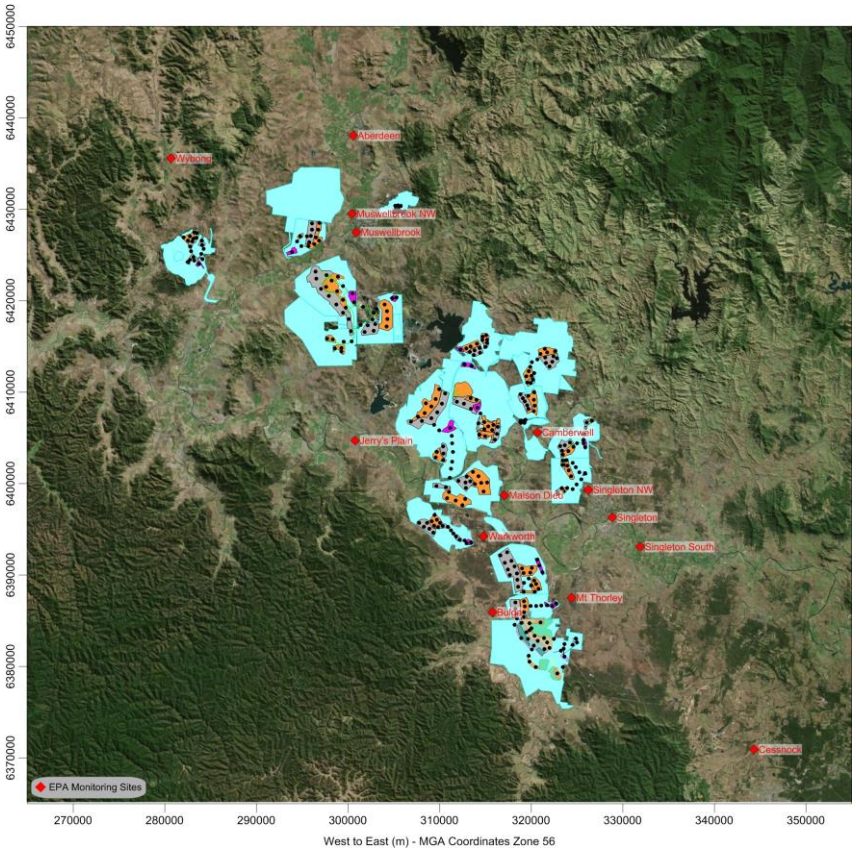


Figure 9.1: Mine sources modelled for base year (2012)

9.2 Wood heaters

Wood heater emissions are represented in CALPUFF as volume sources. It is not practical to model a volume source for each grid point in the modelling domain as over 2,000 wood heater volume sources would be required. This would have led to computational times that would be unworkable given the project timeline. We have therefore modelled wood heater emissions in separate groups, with finer resolution in areas with higher emissions (the population centres of Singleton and Muswellbrook) and coarser resolution in areas with low emissions.

In Singleton and Muswellbrook, we have modelled volume sources at a 1 km x 1 km resolution (corresponding to the resolution at which emissions are provided in the GMR inventory). At all other locations where wood heater emissions are a lot lower, the emissions were spread over a larger area for modelling. A graphical representation of the emissions is presented in **Appendix I**.

The initial plume horizontal spread (σy) is assigned a value based on resolution (source spacing). For Singleton and Muswellbrook wood heater emissions, volume sources are set at a separation distance of 1 km and σy is assigned as 233 m (1km divided by 4.3). This essentially spreads the wood heater emissions for each 1 km x 1 km grid cell across a Gaussian distribution with initial spread defined by 233 m in the horizontal. The values of sigma z are discussed in **Section 8.3**.

A particle geometric mean diameter of 1 µm is chosen for both PM_{10} and $PM_{2.5}$ from this source. The US EPA AP-42 chapter for Residential Wood Stoves (**US EPA (1996)**) notes that 95% of the particles emitted from a wood stove are less than 0.4 microns in size, although the background documentation for this chapter notes that the size distribution of wood smoke aerosol are dependent on burning conditions, fuel type and stove type. For cool burning stoves, for example, up to 50% of measured particles were in the range 0.6 – 1.2 microns (**Rau, 1989**). In the absence of size distribution data for Australian wood heaters, a value of 1 µm is chosen for modeling.

9.3 Non-road diesel

The estimated coal mine diesel emissions are represented as volume sources and spatially distributed across the same source locations used to represent the coal mine emissions and modelled in the same way (described in **Section 9.1**).

The non-road diesel emissions that are not 'mining for coal, are represented as a volume source assigned to a 1 km x 1 km dimension (corresponding to the resolution at which emissions are provided in the GMR inventory) with an initial plume spread is assigned as 233 m (1 km divided by 4.3).

A particle geometric mean diameter of 1 µm is chosen for both PM_{10} and $PM_{2.5}$ (based on the US EPA AP-42 for Industrial Diesel Engines which indicates all PM is sub 2.5 µm).

9.4 Electric power generation

Power stations are represented as point sources, according to the source characteristics (release height, temperature, exist velocity) provided in the GMR inventory point source emissions file.

Modelling was completed for two size fractions, $PM_{2.5}$ and PM_{10}. $PM_{2.5}$ is represented with a particle geometric mean diameter of 1 µm and PM_{10} is represented with a particle geometric mean diameter of 3 µm (based on the US EPA AP-42 for Coal Combustion).

9.5 Other emissions sources

All other emissions sources (gridded ASE, DSE, MVSE, BSE emissions) have been aggregated from 1 km x 1 km resolution to a 3 km x 3 km resolution for modelling, due to limitations within CALPUFF for the number of sources that can be included. Better resolution can be achieved for future work by recompiling the code in CALPUFF to deal with more sources. Increasing the resolution for these sources will have the greatest effect on modelling results for locations where there is a higher concentration of

emissions, for example domestic commercial sources in Singleton and Muswellbrook. It is noted that by modelling wood heaters separately (which comprise the majority of DSE emissions) we have essentially improved the resolution for DSE emissions at the population centres of Singleton and Muswellbrook. Similarly, by modelling non-road diesel across coal mine source locations we have also significantly improved the resolution for ASE emissions. Therefore the only gridded emission sources that would benefit from improved resolution are the biogenic (BSE) and on-road mobile (MVSE).

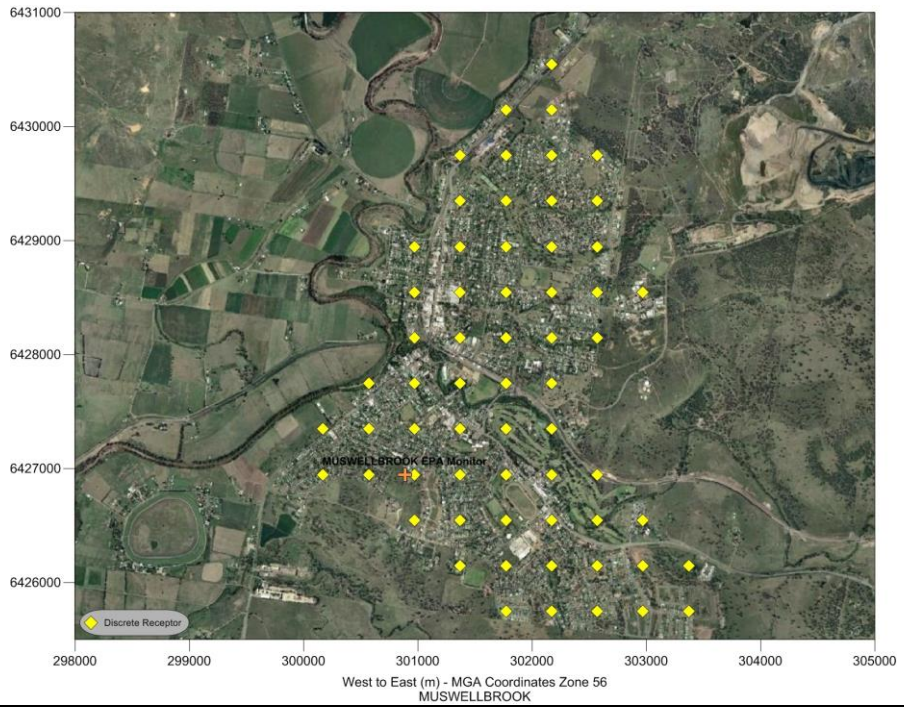
Each volume source is assigned a 3 km x 3 km dimension with the initial horizontal spread of the plume assigned as 698 m. The initial vertical spread for DSE was set to the same as wood heaters and ASE was set to the same as non-road diesel. BSE and MVSE sources were given an initial vertical spread of 1 m.

9.6 Receptors for source contribution

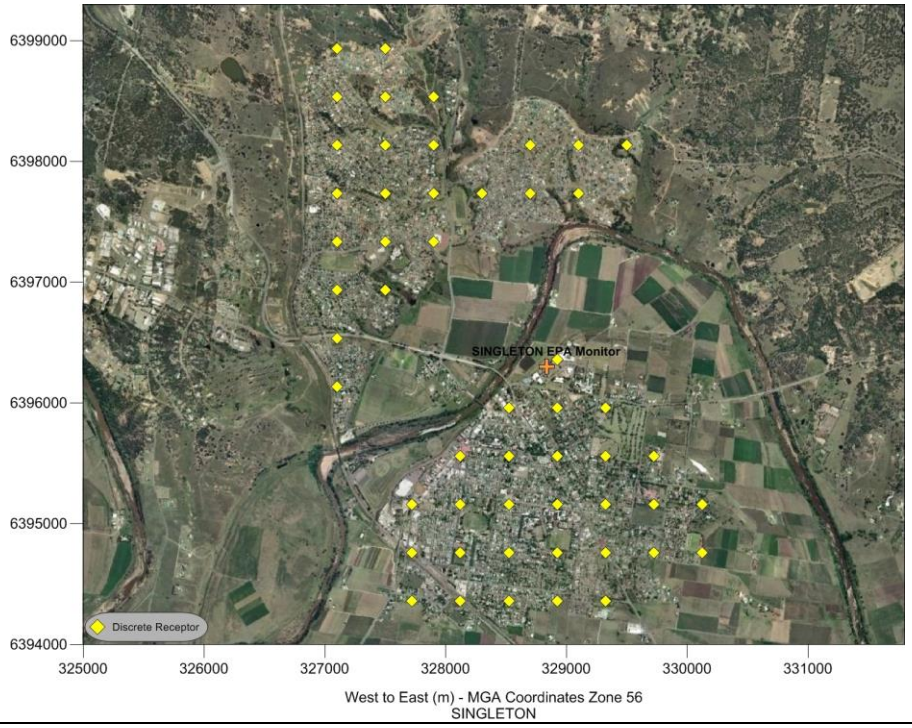
The contributions of different source groups to PM_{10} and $PM_{2.5}$ concentrations in Singleton and Muswellbrook are determined by setting discrete locations within the townships of Singleton and Muswellbrook. To represent Singleton, 52 discrete locations are chosen in the township, again at a 400 m spacing. To represent Muswellbrook, 62 discrete locations are chosen in the township at 400 m spacing. The locations are shown in **Figure 9.2.** These locations are also used in the emission-reduction scenario analysis.

9.7 Modelling scenarios

Modelling predictions of annual average PM_{10} and $PM_{2.5}$ are presented for a base year 2012 and business as usual (BAU) projections for years 2016, 2021, 2026 and 2031. Separate modelling runs are completed for coal mines and coal mine diesel to capture spatial variation in emissions sources as mining changes. For all other sources the predicted GLCs for the base case model scenario are scaled according the changes in annual emissions. The approach of scaling the base year 2012 results is appropriate for sources where no significant spatial change is expected (for example roadways) or where temporal profiles are not likely to change (for example wood heaters). Scaling is also an appropriate approach where it is not possible to predict future spatial and temporal changes (for example in biogenic emissions).



Muswellbrook



Singleton

Figure 9.2: Discrete receptor locations – Muswellbrook and Singleton

9.8 Treatment of other non-modelled sources of PM

PM_{10} is measured at all UHAQMN sites using TEOMs and $PM_{2.5}$ is measured at Singleton, Muswellbrook and Camberwell using BAMs. The monitoring data, depending on the instrument, include the following components of PM:

- Primary natural PM
- Secondary natural PM
- Primary anthropogenic PM
- Secondary anthropogenic PM

Primary natural PM is emitted directly into the atmosphere as a result of processes such as wind erosion (*e.g.* mineral dust) and the production of marine aerosols (*e.g.* sea salt). Primary anthropogenic particles result from processes involving either combustion (*e.g.* industrial activity, domestic wood heaters, vehicle exhaust) or abrasion (*e.g.* road vehicle tyre wear). Secondary PM is not emitted directly, but is formed by chemical reactions involving gas-phase components of the atmosphere. The main gaseous precursors are oxides of nitrogen (NO_X), ammonia (NH_3), sulfur oxides (SO_X) and volatile organic compounds (VOCs). Again, the origin of these precursors may be natural or anthropogenic. Various studies have shown that secondary particles contribute significantly to $PM_{2.5}$ concentrations and, to a lesser extent, PM_{10} (see, for example, the extensive review by the United States Environmental Protection Agency **(USEPA, 2009)**).

Modelled PM included in this study relates only to primary anthropogenic sources. Therefore, to enable a like-with-like comparison between the modelled and measured PM it is necessary to: (i) account for non-modelled PM components where these have been measured and, to a lesser extent, (ii) remove modelled PM components which have not been measured.

The treatment of non-modelled (secondary and natural) PM in this study draws heavily on the Upper Hunter Fine Particle Characterisation Study (UHPCS), which summarises the major components and sources of $PM_{2.5}$ in Singleton and Muswellbrook (**Hibberd et al, 2013**). The study provides chemical composition of $PM_{2.5}$ mass and identified a number of "factors" using positive matrix factorisation techniques (PMF). The factors relevant to this study, which relate to secondary and natural PM, are secondary sulphate, secondary nitrate, sea salt and industry aged sea salt[i]. The other components of $PM_{2.5}$ that are used are black carbon (BC) (as a surrogate for elemental carbon (EC) (**Hibberd et al, 2013**)) and organic carbon (OC). EC is emitted directly, mainly from incomplete combustion while OC is emitted directly from fossil fuel and biomass burning and also formed through atmospheric reactions as secondary organic carbon. Both OC and EC are used in the estimation of secondary organic aerosol, as described below and further in **Appendix J**.

The following steps outline the approach used for the treatment of non-modelled (secondary and natural) PM:

Step 1: Extraordinary natural events are reviewed and, where required, these periods are excluded from the PM monitoring data as they are not modelled. However, no known widespread bushfires, dust storms or other unusual events were identified in the BoM monthly weather extreme weather reviews, nor observed in satellite observation images (Terra-MODIS[j]).

Step 2: The components of PM that are included in (and excluded from) the monitoring data and the modelling results are identified (see **Table 9.1** and **Table 9.2**). The shaded cells show where an additional treatment is required. Note, due to the different monitoring methods for PM_{10} and $PM_{2.5}$ the components of PM that are assumed to be included in the monitoring data differ for each size fraction,

[i] Industry aged sea salt is sea salt which has, over time, displaced the chloride ion molecule with SO_4 from industry sources

[j] MODIS = Moderate Resolution Imaging Spectroradiometer (http:// http://earthobservatory.nasa.gov)

mainly due to heated inlet in the TEOM removing some components from the PM_{10} measurements (**AQEG, 2005**).

Step 3: **$PM_{2.5}$ adjustment** - using $PM_{2.5}$ characterisation data from the Upper Hunter Fine Particle Characterisation Study, determine the absolute value (concentration) of each component of $PM_{2.5}$ that is not modelled but is measured by the BAM (this includes marine aerosol (salt) and secondary particles). Add the absolute values for the 'missing' components to the $PM_{2.5}$ modelling results. Note, for sites outside Singleton and Muswellbrook, it is assumed that the $PM_{2.5}$ characterisation would be taken as the average of the Singleton and Muswellbrook data.

Step 4: **PM_{10} adjustment** - determine, using the literature (i.e. **Chan et al., 2008**) the PM_{10}:$PM_{2.5}$ ratio for each component of PM_{10} that is not modelled but is measured by the TEOM (this includes marine aerosol and ammonium sulphate). Use this ratio to estimate the absolute value (concentration) of each component of PM_{10} that is not modelled but measured in the Upper Hunter Fine Particle Characterisation Study. Add these absolute values (marine aerosol and sulphate) to the PM_{10} modelling results. One slight complication is that primary anthropogenic organic carbon is included in the modelling but not all organic carbon is included in the TEOM PM_{10} data. We have assumed that when operated at 50 °C. the TEOM fails to measure approximately 40% of the organic PM (**Tortajada-Genaro and Borrás, 2011**) and this is subtracted from the analysis.

The components of PM that are included in (and excluded from) the monitoring data and the modelling results are identified in **Table 9.1** and **Table 9.2**. The results of this analysis are presented in **Table 9.3** to **Table 9.6,** showing the monthly totals for 24-hour average $PM_{2.5}$ and PM_{10} that is added (or removed) to the modeling predictions to account for secondary and natural PM.

On an annual basis, the estimated secondary and natural PM added for PM_{10} is 7.6 µg/m^3 in Muswellbrook and 9.3 µg/m^3 in Singleton. The estimated secondary and natural PM added for $PM_{2.5}$ is 4.3 µg/m^3 in Muswellbrook and 4.2 µg/m^3 in Singleton. Further discussion on the approach, as well as a worked example of the calculation is provided in **Appendix J**.

Table 9.1: Treatment of $PM_{2.5}$ measurements (BAM)

Natural/ anthropogenic	Primary/ secondary	Organic/ inorganic	Component	Measured	Modelled	Treatment in analysis
Natural	Primary	Inorganic	Marine aerosol	Yes	No	Added to modelled concentrations based on UHPCS data ('salt' and industry aged salt)
			Wind-blown mineral dust	Yes	Yes	Sources included in the inventory and modelled
		Organic	Vegetal material	Yes	Yes	Sources included in the inventory and modelled
	Secondary	Organic	Biogenic aerosol	Yes	No	Estimated using EC tracer method based on UHPCS data
Anthropogenic	Primary	Inorganic	Mineral dust (*e.g.* mining)	Yes	Yes	Sources included in the inventory and modelled
			Abrasion products (*e.g.* tyre and brake wear)	Yes	Yes	Sources included in the inventory and modelled
			Elemental carbon (*e.g.* diesel exhaust)	Yes	Yes	Sources included in the inventory and modelled
		Organic	Organic carbon (*e.g.* diesel exhaust)	Yes	Yes	Sources included in the inventory and modelled
	Secondary	Inorganic	Ammonium nitrate (some sodium nitrate)	Yes	No	Added to modelled concentrations based on UHPCS data (secondary nitrate)
			Ammonium sulfate	Yes	No	Added to modelled concentrations based on UHPCS data (secondary sulfate)
		Organic	Organic carbon	Yes	No	Added to modelled concentrations based on UHPCS data (EC tracer method)
Water vapour				No	No	No action required – assumed not measured.

Table 9.2: Treatment of PM_{10} measurements (TEOM)

Natural/ anthropogenic	Primary/ secondary	Organic/ inorganic	Component	Measured	Modelled	Treatment in analysis
Natural	Primary	Inorganic	Marine aerosol	Yes	No	Estimated and added to modelling results based on Chan et al (2008) and UHPCS data ('salt' and industry aged salt)
			Wind-blown mineral dust	Yes	Yes	Sources included in the inventory and modelled
		Organic	Vegetal material	Yes	Yes	Sources included in the inventory and modelled
	Secondary	Organic	Biogenic aerosol	No[(a)]	No	No action required – not measured by TEOM
Anthropogenic	Primary	Inorganic	Mineral dust (*e.g.* mining)	Yes	Yes	Sources included in the inventory and modelled
			Abrasion products (*e.g.* tyre and brake wear)	Yes	Yes	Sources included in the inventory and modelled
			Elemental carbon (*e.g.* diesel exhaust)	Yes	Yes	Sources included in the inventory and modelled
		Organic	Organic carbon	No[(a)]	Yes	Removed from model results based on $PM_{2.5}$ data[(b)].
	Secondary	Inorganic	Ammonium nitrate (some sodium nitrate)	No	No	No action required – not measured by TEOM.
			Ammonium sulfate	Yes	No	Estimated and added to modelling results based on Chan *et al.* (2008) and UHPCS data (secondary sulfate)
		Organic	Organic carbon	No[(a)]	No	No action required – not measured by TEOM.
Water vapour				No	No	No action required – not measured by TEOM.

(a) We have assumed that 40% of the organic carbon is removed by the TEOM.

(b) The $PM_{2.5}$ data contain three organic carbon (OC) components: natural secondary, anthropogenic primary and anthropogenic secondary. The secondary organic aerosol (SOA) component of $PM_{2.5}$ can be derived using the EC tracer method (**Duan *et al.*, 2005**). Primary anthropogenic OC is then the difference between the total OC reported in UHPSC and the estimated SOA. This primary anthropogenic OC value is subtracted from the model prediction. It is also assumed that all SOA is in the $PM_{2.5}$ fraction.

Table 9.3: Secondary and natural $PM_{2.5}$ added to modelling for Muswellbrook

	Mass concentration (ug/m³) based on 24-hour average					
	Natural Primary Inorganic	Natural Secondary Organic	Anthropogenic Secondary Organic	Anthropogenic Secondary Inorganic	Anthropogenic Secondary Inorganic	TOTAL (ug/m³, 24-hour average)
	Sea salt	Combined SOA		Nitrate	Sulphate	
Jan	2.4	1.1		0.3	1.2	**5.0**
Feb	1.2	0.7		0.1	3.0	**5.0**
Mar	1.3	0.7		0.1	1.6	**3.8**
Apr	0.8	0.8		0.4	2.1	**4.2**
May	0.4	1.1		0.6	1.2	**3.4**
Jun	0.3	1.8		0.7	1.1	**4.0**
Jul	0.3	1.0		0.8	0.6	**2.7**
Aug	0.8	2.2		0.8	0.5	**4.2**
Sep	1.3	0.9		0.5	0.9	**3.6**
Oct	2.2	0.5		0.6	1.3	**4.6**
Nov	2.0	1.3		0.5	1.7	**5.5**
Dec	2.5	1.6		0.3	1.6	**5.9**
Average						**4.3**

Table 9.4: Secondary and natural PM_{10} added (or removed) to modelling for Muswellbrook

	Mass concentration (ug/m³) based on 24-hour average			
	Natural Primary Inorganic	Anthropogenic Secondary Inorganic	Anthropogenic Primary Organic	TOTAL (ug/m³, 24-hour average)
	Sea salt	Sulphate	Inc. in model	
Jan	9.6	2.7	-0.22	**12.1**
Feb	5.1	6.8	-0.24	**11.6**
Mar	5.4	3.6	-0.34	**8.7**
Apr	3.2	4.9	-0.55	**7.5**
May	1.8	2.7	-1.53	**3.0**
Jun	1.2	2.6	-0.87	**2.9**
Jul	1.1	1.4	-1.85	**0.6**
Aug	3.1	1.0	-1.34	**2.8**
Sep	5.2	2.1	-1.16	**6.1**
Oct	8.9	3.0	-0.89	**11.0**
Nov	8.2	3.8	-0.47	**11.6**
Dec	10.2	3.7	-0.31	**13.6**
Average				**7.6**

Table 9.5: Secondary and natural $PM_{2.5}$ added to modelling for Singleton

	Mass concentration (ug/m³) based on 24-hour average					
	Natural Primary Inorganic	Natural Secondary Organic	Anthropogenic Secondary Organic	Anthropogenic Secondary Inorganic	Anthropogenic Secondary Inorganic	TOTAL (ug/m³, 24-hour average)
	Sea salt	Combined SOA		Nitrate	Sulphate	
Jan	3.4	0.9		0.2	1.4	**5.8**
Feb	1.7	0.6		0.1	2.8	**5.1**
Mar	2.0	0.9		0.2	1.3	**4.4**
Apr	1.0	0.5		0.2	2.1	**3.9**
May	0.4	0.7		0.2	1.5	**2.8**
Jun	0.3	0.9		0.2	0.8	**2.2**
Jul	0.4	0.8		0.2	0.3	**1.7**
Aug	0.7	1.0		0.2	0.4	**2.4**
Sep	1.6	1.6		0.3	1.1	**4.6**
Oct	2.6	1.2		0.2	1.2	**5.1**
Nov	2.5	1.2		0.2	1.8	**5.8**
Dec	3.1	1.6		0.2	1.4	**6.3**
Average						**4.2**

Table 9.6: Secondary and natural PM_{10} added (or removed) to modelling for Singleton

	Mass concentration (ug/m³) based on 24-hour average			
	Natural Primary Inorganic	Anthropogenic Secondary Inorganic	Anthropogenic Primary Organic	TOTAL (ug/m³, 24-hour average)
	Sea salt	Sulphate	Inc. in model	
Jan	13.6	3.1	-0.23	**16.5**
Feb	6.8	6.3	-0.22	**12.9**
Mar	8.1	3.1	-0.17	**11.0**
Apr	4.3	4.8	-0.38	**8.6**
May	1.6	3.4	-0.77	**4.2**
Jun	1.1	1.9	-0.50	**2.5**
Jul	1.6	0.8	-0.67	**1.7**
Aug	3.0	0.8	-0.86	**3.0**
Sep	6.7	2.4	-0.82	**8.3**
Oct	10.4	2.6	-0.44	**12.6**
Nov	10.3	4.2	-0.27	**14.2**
Dec	12.6	3.3	-0.09	**15.7**
Average				**9.3**

9.8.1 Addition of boundary flux from sources outside the model domain

Consideration needs to be given to PM that may flow into the modelling domain to account for a 'regional background' boundary flux. Unfortunately, there were insufficient data available to include a boundary flux in the modelling (by selecting the boundary concentration (BCON) module within CALPUFF). This methodology requires characterisation of the air mass (in terms of concentrations and depth) flowing into the model domain along each boundary. There were insufficient monitoring data along each boundary too allow this approach.

Instead, an additional post processing step was completed whereby a wind direction dependent and hourly varying background file was created for each of the UHAQMN sites located closest to the model domain boundary. In this way, only monitoring data is included as boundary flux when winds are blowing from outside the model domain. The wind direction dependent hourly data are added to the hourly modelling predictions at the model evaluation sites located in a prevailing downwind direction from the boundary flux site.

The following sites are used showing the corresponding wind directions when the hourly data are for added as boundary flux:

- Aberdeen PM_{10} monitoring data when wind is blowing into the model domain from the north (between 337.5 and 22.5 degrees).
- Merriwa PM_{10} monitoring data when wind is blowing into the model domain from the northwest (between 292.5 and 337.5 degrees).
- Jerry's Plains PM_{10} monitoring data when wind is blowing into the model domain from the west (between 247.5 and 292.5 degrees).
- Bulga PM_{10} monitoring data when wind is blowing into the model domain from the southwest (between 202.5 and 247.5 degrees).
- Warkworth PM_{10} monitoring data when wind is blowing into the model domain from the southwest (between 202.5 and 247.5 degrees).
- Singleton South PM_{10} monitoring data when wind is blowing into the model domain from the southeast (between 112.5 and 157.5 degrees).

As an example, Muswellbrook and Muswellbrook NW are downwind of northerly winds blowing from Aberdeen, which is located close to the northern boundary of the domain. Hourly data from Aberdeen are added to the modelling predictions at Muswellbrook for those hours when the wind direction is from the north.

The hourly data that are added as boundary flux are shown graphically in **Figure 9.3**. A summary of the annum average PM_{10} concentrations added as boundary flux are presented in **Table 9.7**.

None of the sites above measure $PM_{2.5}$, and therefore an alternative approach is used. Ratios of $PM_{2.5}/PM_{10}$ are derived for the three sites which have co-located PM monitors for these size fractions. A temperature-based adjustment is made to the PM_{10} data, prior to calculating the ratio, to account for loss of semi-volatiles in the TEOM data (based on the CSIRO-derived temperature adjustment factor for TEOM data (**NEPM Peer Review Committee, 2001**)). The annual average $PM_{2.5}/PM_{10}$ ratios are:

- Muswellbrook – 0.5
- Singleton – 0.4
- Camberwell – 0.3

Using these ratios, the wind direction dependent hourly PM_{10} data are scaled to derive $PM_{2.5}$ boundary flux.

It is noted that is approach has limitations and introduces another source of uncertainty for the final modelling results. The main limitations in this approach are summarised as follows:

- Very few monitoring sites used in the analysis are outside or close to the model domain boundary (refer **Figure 3.2**). Monitoring data collected at sites within the model domain will include some contribution from emissions sources located between the site and the model domain boundary (when winds are blowing from outside the domain). There would therefore be an element of double counting where these emissions sources have been modelled. This was a consideration when choosing the monitoring sites for boundary flux and where possible only sites with minimal emissions sources between the site and the boundary where chosen. The most notable exception is Singleton south, which is located inside the modelling domain and has emissions sources located between it and the southeast boundary (refer to **Appendix I** to see the spatial distribution of the emissions sources).
- Diurnal recirculation of winds is common in the Hunter valley, particularly in Autumn and Spring. As a result there may be an element of double counting when PM within the model domain are transported, as an example, to the southeast in the morning and the same PM is transported back to the northwest in the afternoon when the wind patterns shift.
- The cut-off point chosen for wind directions that are considered to be blowing into the domain is rather arbitrary.

Recommendations are made in **Section 15** for addressing these limitations in future work.

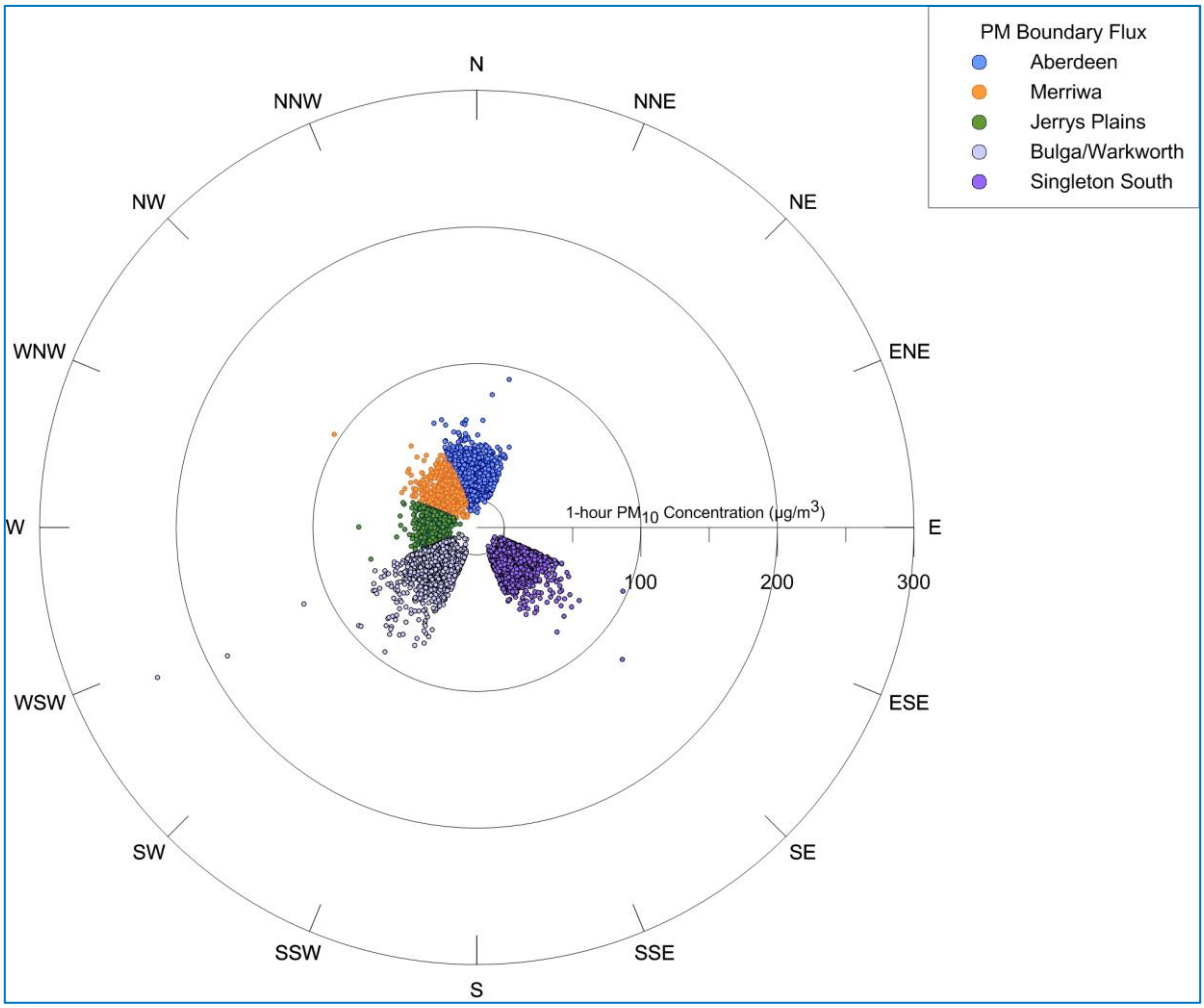


Figure 9.3: Hourly data added as boundary flux

Table 9.7: Summary of annual average PM_{10} (µg/m³) added as boundary flux

UHAQMN site	Aberdeen	Merriwa	Jerrys Plains	Bulga	Warkworth	Singleton Sth
Added for winds from:	north >337.5 < 22.5	northwest >292.5 < 337.5	north >337.5 <22.5	southwest >202.5 <247.5	southwest >202.5 <247.5	southeast >112.5 <157.5
Muswellbrook	4 µg/m³	-	-	-	-	-
Singleton	-	-	-	-	-	4 µg/m³
Camberwell	-	-	2 µg/m³	-	-	-
Singleton NW	-	-	-	-	3 µg/m³	-
Singleton South	-	-	-	-	-	4 µg/m³
Muswellbrook NW	4 µg/m³	-	-	-	-	-
Maison Dieu	-	-	2 µg/m³	-	-	-
Mount Thorley	-	-	-	1 µg/m³	-	-
Bulga	-	-	2 µg/m³	-	-	-
Warkworth	-	-	-	1 µg/m³	-	-
Jerrys Plains	-	2 µg/m³	-	-	-	-
Wybong	-	2 µg/m³	-	-	-	-
Aberdeen	-	2 µg/m³	-	-	-	-

10 BASE YEAR 2012 MODEL EVALUATION

Model evaluation is used to determine if the air quality model is acceptable as a means to inform the BAU emission projections and emission-reduction scenarios. Model predictions at each of the UHAQMN sites are compared to monitoring data for annual average PM_{10} and $PM_{2.5}$.

Final results in this section are presented for the CALMET hybrid option. Preliminary modelling compared the performance of both CALMET options (no-obs and hybrid) in predicting ground level concentrations of PM_{10} and $PM_{2.5}$ (**Appendix C**). In comparing the performance of each option, it is important to understand that studies such as this have inherent uncertainty, which is often difficult to quantify (either in terms of an absolute value or percentage error) (described further in **Section 10.1**). The difference in observed and predicted between each CALMET option is relatively small and likely to be within study uncertainty (see **Appendix C**). While a definitive statement cannot therefore be made on which option performs better, results from this point forward are presented for the CALMET hybrid option. It is considered that the CALMET hybrid is the better option given the extensive observations available in the study domain (**Hu et al., 2010**).

The modelling results presented are for all emission sources in the model domain, with the addition of an estimated secondary / natural PM component plus boundary flux from sources outside the model domain. The predicted annual average $PM_{2.5}$ concentrations are presented in **Table 10.1**.

The model predictions compare favourably with the observed $PM_{2.5}$ concentrations at Singleton and Muswellbrook. The model prediction compares favourably to observed at Muswellbrook (112%) and Singleton (109%). At Camberwell, the predicted $PM_{2.5}$ concentrations are significantly higher than observed (158%).

Table 10.1: Observed and predicted annual average $PM_{2.5}$ at UHAQMN sites

UHAQMN Site	Annual average $PM_{2.5}$ concentration (µg/m³)		
	Observed	Predicted	Predicted as % of observed
Muswellbrook	10.0	11.2	112%
Singleton	8.0	8.7	109%
Camberwell	7.5	11.9	158%

The predicted annual average PM_{10} concentrations are presented in **Table 10.2**. The model predictions compare favourably with the observed PM_{10} concentrations at most sites. There is a tendency for over prediction at Muswellbrook (107%) and at Camberwell (122%), while Singleton compares well (99%).

Generally, the model over predicts close to mining and under predicts further from mining. The most significant model over prediction occurs at Warkworth, followed by Mount Thorley and Bulga. The over predictions at these sites are attributable to coal mine modelling. The locations that are most susceptible to over prediction are those that are aligned between coal mine sources and the prevailing northwest and southeast wind directions. Conversely, Maison Dieu, which is also located close to mining, does not experience the same over prediction. Being located outside of the predominant wind axes, this site is less susceptible to impact from modelled source locations, including potential for recirculation events.

Under predictions are seen at locations on the periphery of the model domain (Wybong, Aberdeen). While attempts have been made to incorporate the PM contribution from sources outside the domain, there is a degree of uncertainty due to on limited monitoring data outside the domain.

Table 10.2: Observed and predicted annual average PM_{10} at UHAQMN sites (CALMET hybrid Option 2)

UHAQMN Site	Annual average PM_{10} concentration (µg/m³)		
	Observed	Predicted	Predicted as % of observed
Muswellbrook	21.8	23.2	107%
Singleton	22.3	22.0	99%
Camberwell	26.5	32.4	122%
Singleton NW	25.9	36.0	139%
Singleton South	19.0	19.8	104%
Muswellbrook NW	19.1	19.1	100%
Maison Dieu	25.7	27.4	107%
Mount Thorley	24.7	35.0	142%
Bulga	18.6	27.1	146%
Warkworth	21.1	50.4	239%
Jerry's Plains	10.8	13.8	128%
Wybong	15.4	11.9	78%
Aberdeen	17.0	12.0	71%

10.1 Quantifying uncertainty

In evaluating model performance of each option, it is important to understand that studies such as this have inherent uncertainty, in both the modelled and non-modelled components (secondary PM and boundary flux).

10.1.1 Model uncertainty

It is difficult to quantify model uncertainty, which can result from:

- Uncertainty in emission estimates.
- Uncertainty in measured meteorological inputs.
- Uncertainty in source characterisation.
- Uncertainty in measured ambient data and any adjustments applied.
- Uncertainty in model physics.

It is noted that uncertainty described above increases for future year (BAU) predictions, mostly from the assumptions made in estimating emissions in future years. For example in compiling ROM production estimates out to 2030, the DRE need to make assumptions on export demand and coal price, as well as taking into account recent Government approvals and increasing community opposition, all of which influences mine expansion and new projects.

Leaving aside data input errors, the uncertainties listed above have been reported to result in up to 50% error in predicted GLC in flat terrain (**US EPA, 2005**; **Pasquill, 1974**). Furthermore, uncertainty in the measured wind direction of 5 to 10 degrees can result in predicted ground-level concentration errors of 20% to 70% for a particular time and location (**US EPA, 2005**; **Pasquill, 1974**). It is generally recommended that an air quality model is acceptable at a screening level if more than half of the short-term model predictions lie within a factor of two of the observations (**DEFRA, 2010**).

Efforts to reduce model uncertainty for this study include:

- Developing bottom-up emission inventories for coal mines using the best available emission estimation techniques.

- Incorporating extensive meteorological input data from the UHAQMN and undertaking an extensive evaluation of model performance.
- Incorporating observation data into the prognostic modelling to reduce error associated with the tendency of TAPM V4 to under predict wind speeds.
- Comparing two different meteorological assimilation options for CALMET modelling.
- Performing model sensitivity tests for all major sources and for different source characterisation.
- Performing model sensitivity tests for space and time predictions.

It is noted that dispersion models are typically more accurate at predicting concentrations over longer time periods (e.g. annual averages) than shorter ones (e.g. 24-hour averages). They are also better at estimating the magnitude of the highest concentration across both time and space (i.e. the highest concentration occurring sometime, somewhere within the model domain). It is generally beyond the capabilities of current dispersion models to accurately predict a given concentration at a given point in time. In other words, pairing short-term dispersion model predictions with observations in both time and space typically results in poor correlation (**US EPA, 2005**).

The objective of this assessment is to compare annual average PM_{10} and $PM_{2.5}$ in Singleton and Muswellbrook (presented as town averages). By examining long term predictions averaged across multiple receptors, model uncertainty is likely to be less than described above.

10.1.2 Uncertainty in non-modelled PM

There are limitations in the treatment approach for both non-modelled PM and modelled PM that is not measured by monitoring instrumentation.

In characterising the components of $PM_{2.5}$, we have assumed that the data for Singleton is valid for all monitoring sites south of Singleton. For all other sites north of Singleton, the Muswellbrook $PM_{2.5}$ characteristation data is applied. While this is recognised as a limitation, it is noted that the monitoring data indicates that $PM_{2.5}$ characterisation displays similar patterns between Singleton and Muswellbrook and the annual estimated secondary and natural $PM_{2.5}$ is largely the same. This is likely to be due to the longer atmospheric residence time for fine particles.

Another limitation is the use of PM_{10}:$PM_{2.5}$ ratios for each component of PM_{10}, in the absence of PM_{10} data from the UHPCS. The ratios are based on monitoring data collected in major Australian cities (**Chan et al., 2008**) and the application to less urbanised areas for this study domain is a limitation for estimated annual secondary and natural PM_{10}, which varies more between Singleton and Muswellbrook than for $PM_{2.5}$.

The factor analysis presented in the UHPCS provides well resolved mass concentration data for secondary sulphate, secondary nitrate and sea salt. However, the estimation of secondary organic aerosol is derived. A recent report on $PM_{2.5}$ in the UK the Air Quality Expert Group (**AQEG, 2012**) concluded that whilst many of the processes determining $PM_{2.5}$ concentrations are understood and can be represented reasonably well in models, there remain some processes where there is incomplete understanding and/or knowledge, including secondary organic aerosol and the treatment of particle-bound water (PBW).

Due to the different monitoring methods for PM_{10} and $PM_{2.5}$ the components of PM that are assumed to be included in the monitoring data differ for each size fraction, mainly due to heated inlet in the TEOM removing some components from the PM_{10} measurements (**AQEG, 2005**). Further complications in the measurement of water vapour are not limited to the heating of sample inlets, with the filters themselves susceptible to changes in mass due to absorption of water. Some filter materials, and the sampled PM itself, exhibit hysteresis effects (i.e. water vapour is absorbed from the atmosphere, but is then hard to remove during filter conditioning). It is difficult to correct for these effects as they can vary between different filter types and batches in ways that are not fully understood. In summary, the $PM_{2.5}$ metric does not correspond to definite physical or chemical components of the air, but is in effect defined by the measurement method (**AQEG, 2012**).

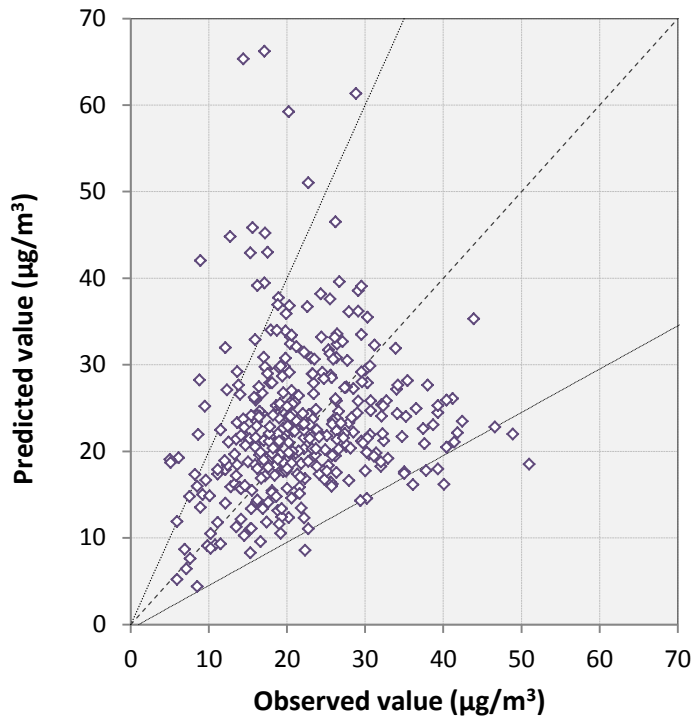
10.2 Statistical evaluation

Scatter plots of the paired observed and predicted 24-hour PM_{10} and $PM_{2.5}$ concentrations provide a useful evaluation of model performance and are presented in **Figure 10.1**, **Figure 10.2** and **Figure 10.3** for Muswellbrook, Singleton and Camberwell. The 'factor of 2' acceptability described in Section 10.1 is represented on the scatter plots as the 1:2 and 1:0.5 data fits (dashed lines).

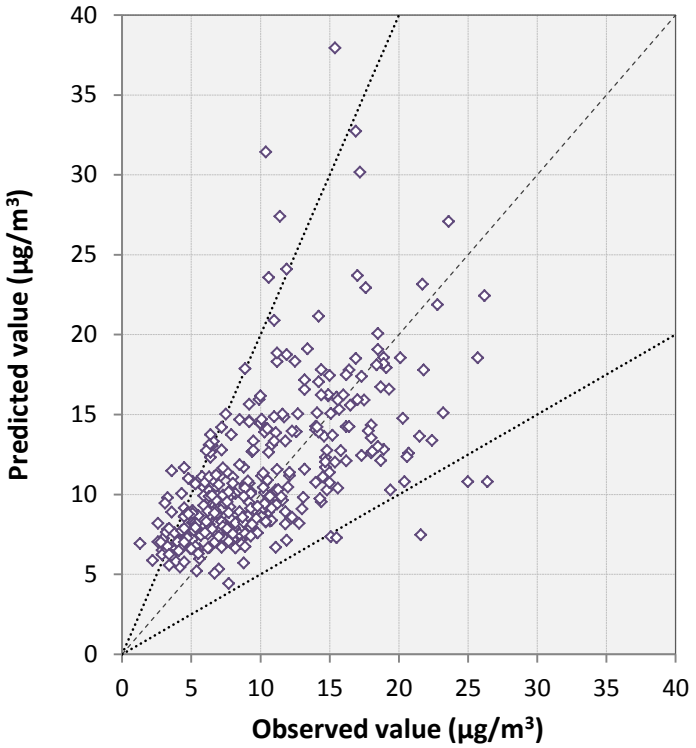
The scatter plots presented in **Figure 10.1**, **Figure 10.2** and **Figure 10.3** indicate that the majority of model predictions fall within a factor of 2 of the observations at all sites for PM_{10} and $PM_{2.5}$.

The time component is removed and the data presented as percentile plots in **Figure 10.4**, **Figure 10.5** and **Figure 10.6**. The percentile plots for Muswellbrook show an excellent correlation. At Singleton there is a tendency for under-prediction at higher concentrations and at Camberwell there is a general tendency for over-prediction.

Additional statistical analyses, used to quantify the differences between model predictions and observations, are presented in **Appendix K**. This analysis shows good agreement for fractional bias and normalised mean bias at both Singleton and Muswellbrook.

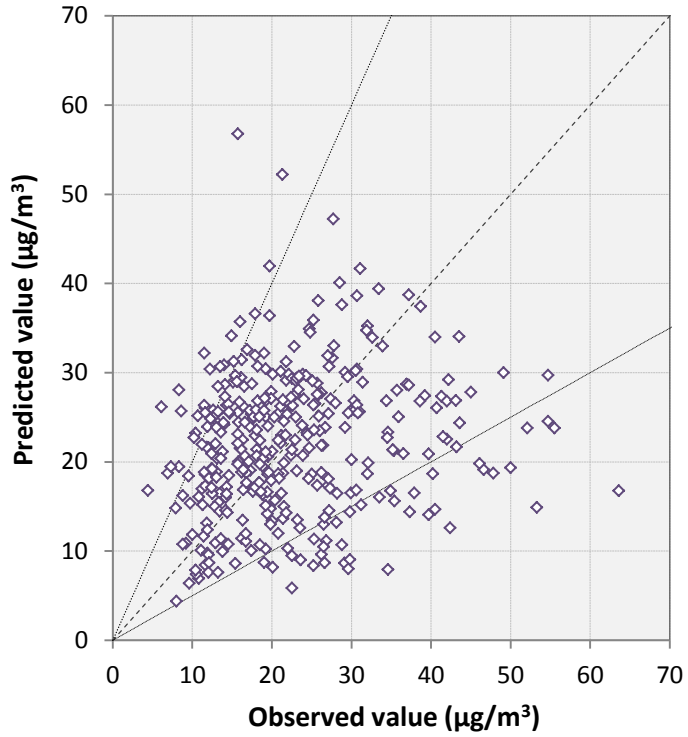


Muswellbrook PM_{10}

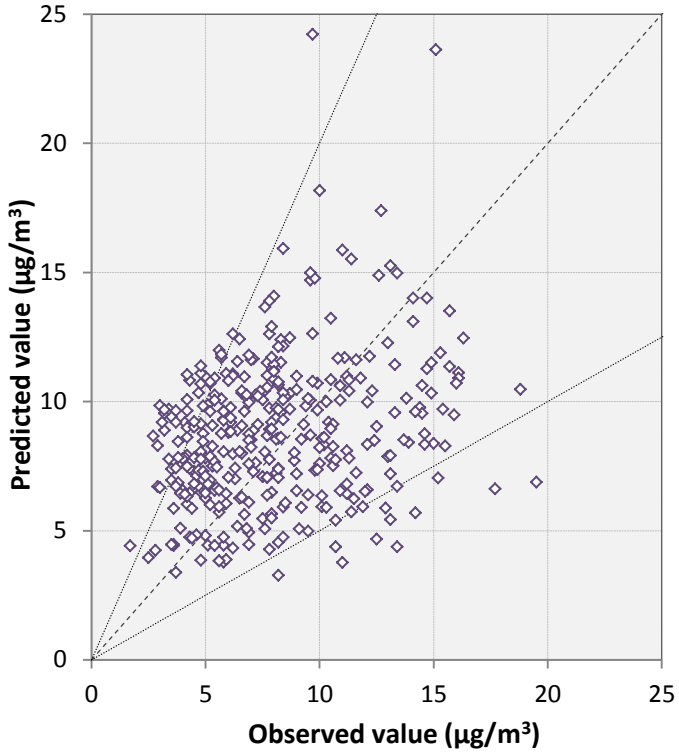


Muswellbrook $PM_{2.5}$

Figure 10.1: Scatter plots of Muswellbrook observed and predicted 24-hour PM_{10} and $PM_{2.5}$ concentrations paired in time

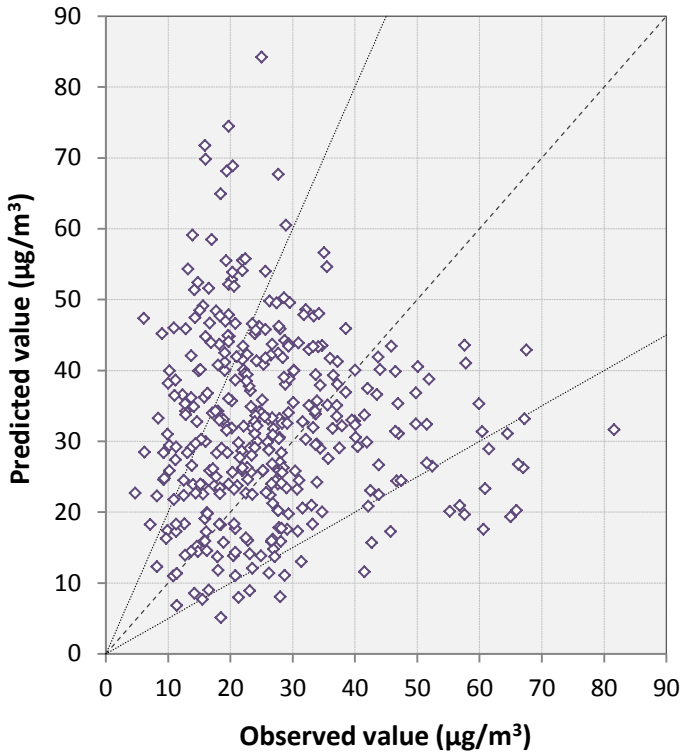


Singleton PM_{10}

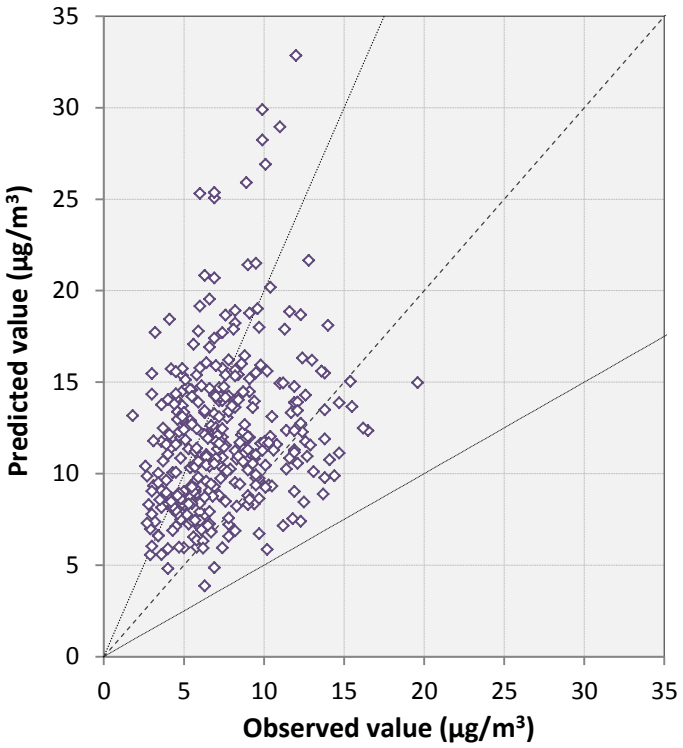


Singleton $PM_{2.5}$

Figure 10.2: Scatter plots of Singleton observed and predicted 24-hour PM_{10} and $PM_{2.5}$ concentrations paired in time

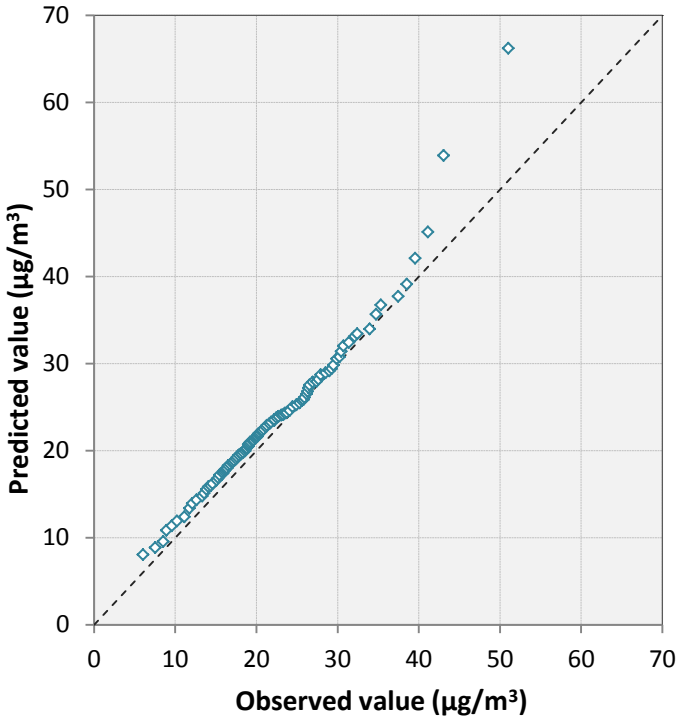


Camberwell PM_{10}

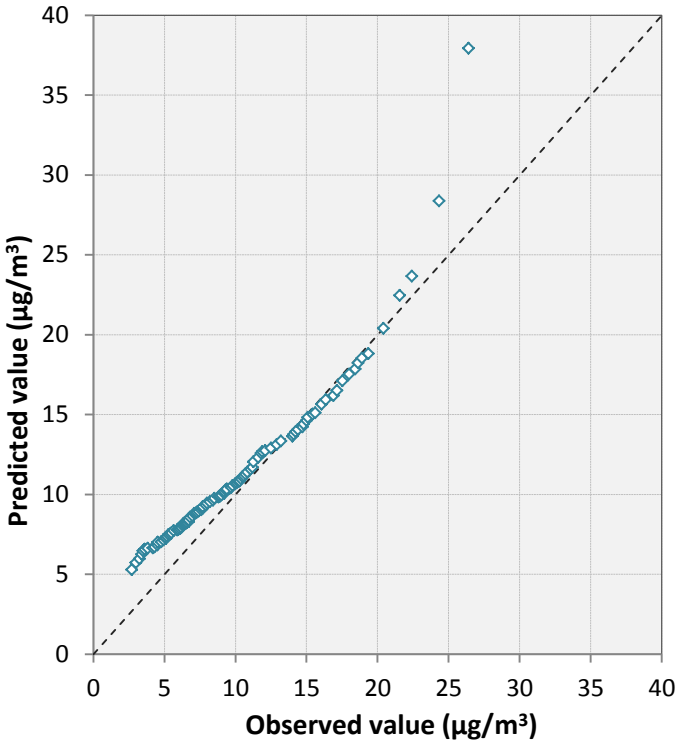


Camberwell $PM_{2.5}$

Figure 10.3: Scatter plots of Camberwell observed and predicted 24-hour PM_{10} and $PM_{2.5}$ concentrations paired in time

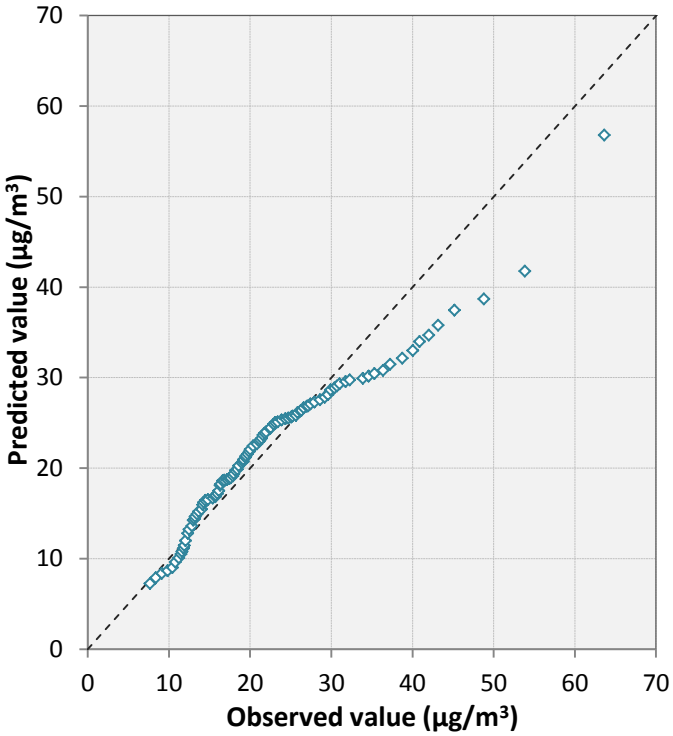


Muswellbrook PM_{10}

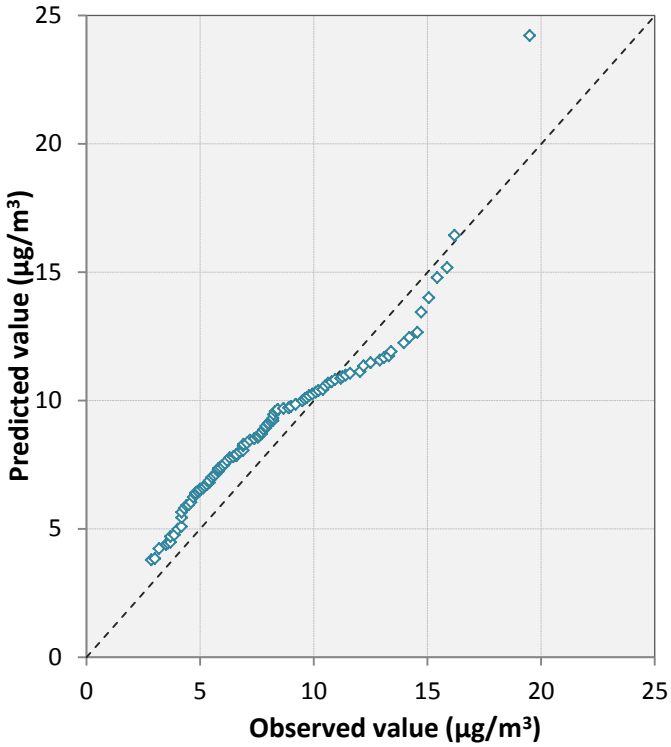


Muswellbrook $PM_{2.5}$

Figure 10.4: Q-Q plots of Muswellbrook observed and predicted 24-hour PM_{10} and $PM_{2.5}$ concentrations

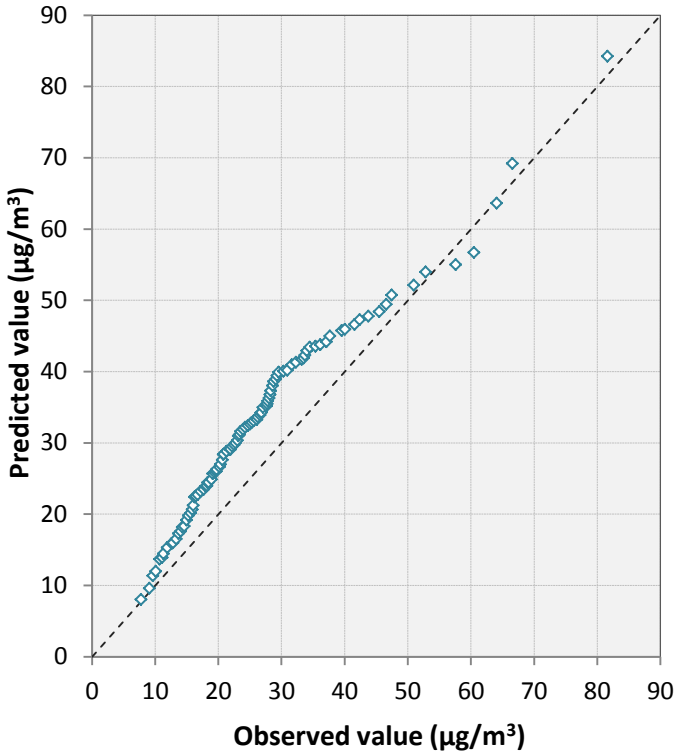


Singleton PM_{10}

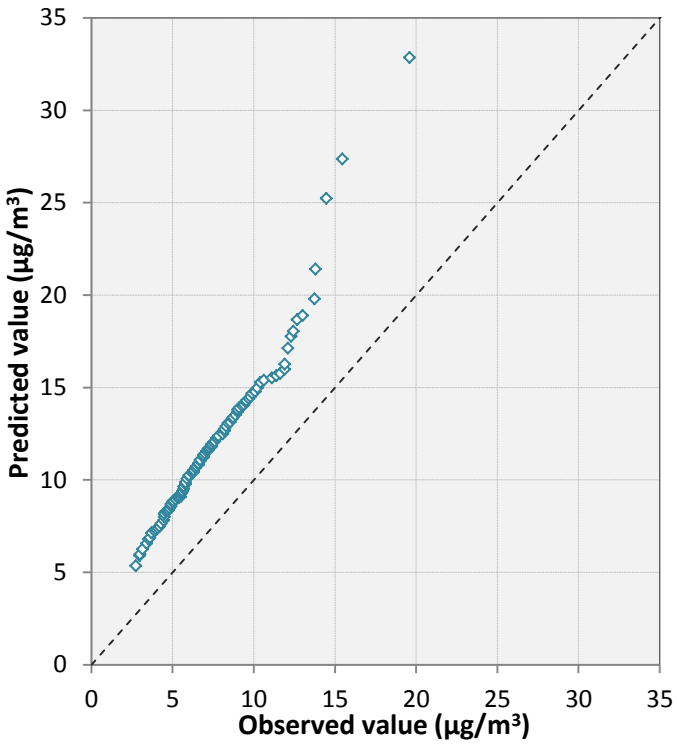


Singleton $PM_{2.5}$

Figure 10.5: Q-Q plots of Singleton observed and predicted 24-hour PM_{10} and $PM_{2.5}$ concentrations



Camberwell PM_{10}



Camberwell $PM_{2.5}$

Figure 10.6: Q-Q plots of Camberwell observed and predicted 24-hour PM_{10} and $PM_{2.5}$ concentrations

10.3 Seasonal variation

The seasonal variability in the observed and predicted $PM_{2.5}$ concentration is presented in **Table 10.3**. Modelling predictions in Muswellbrook show good correlation with the observed data for each season. The highest observed and predicted $PM_{2.5}$ concentrations in Muswellbrook occur in winter, which can be attributed to wood heaters.

At Singleton, a similar conclusion can be drawn with good correlation between predicted and observed for each season, although small under predictions are noted. The highest observed $PM_{2.5}$ concentrations occur in spring and winter and the highest predicted occur in spring and summer.

At Camberwell, an over prediction is seen in all seasons. The highest observed $PM_{2.5}$ concentrations occur in summer and the highest predicted occurs in autumn.

Table 10.3: Seasonal variation in $PM_{2.5}$ concentration

Average $PM_{2.5}$ Concentrations (µg/m³)						
Season	Muswellbrook		Singleton		Camberwell	
	Predicted	Observed	Predicted	Observed	Predicted	Observed
Spring	10	10	10	9	11	8
Summer	9	7	10	7	12	9
Autumn	10	9	8	8	13	8
Winter	15	14	8	9	11	7

The seasonal variability in the observed and predicted PM_{10} concentration is presented in **Table 10.4**. Modelling predictions in Muswellbrook show good correlation with the observed data in summer and autumn but correlate less favourably in spring and winter. The highest observed PM_{10} concentrations occur in spring and the highest predicted occur in winter.

At Singleton, a good correlation is seen in Autumn but the model under predicts in winter and spring and over predicts in summer. The highest observed PM_{10} concentrations occur in spring and the highest predicted occur in spring and summer.

At Camberwell, the model over predicts in summer and autumn and correlates better in spring and winter. The highest observed PM_{10} concentrations occur in spring and the highest predicted occurs in autumn.

Table 10.4: Seasonal variation in PM_{10} concentration

Average PM_{10} Concentrations (µg/m³)						
Season	Muswellbrook		Singleton		Camberwell	
	Predicted	Observed	Predicted	Observed	Predicted	Observed
Spring	24	27	25	28	32	36
Summer	22	22	26	18	34	22
Autumn	22	20	21	22	36	24
Winter	24	18	16	21	26	23

Seasonal variation is also presented graphically in **Figure 10.7** and **Figure 10.8**.

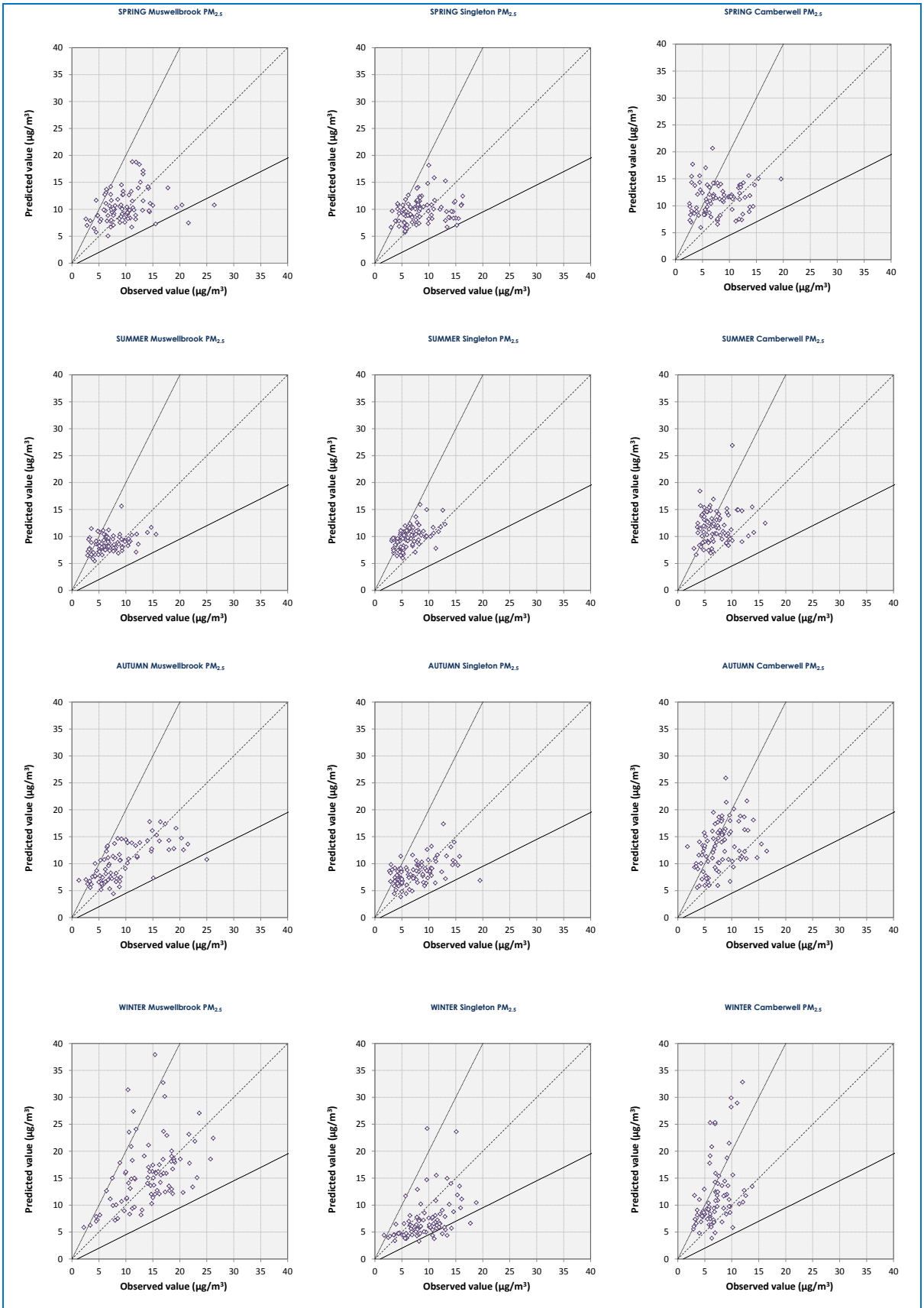


Figure 10.7: Scatter plots of observed and predicted 24-hour $PM_{2.5}$ concentrations

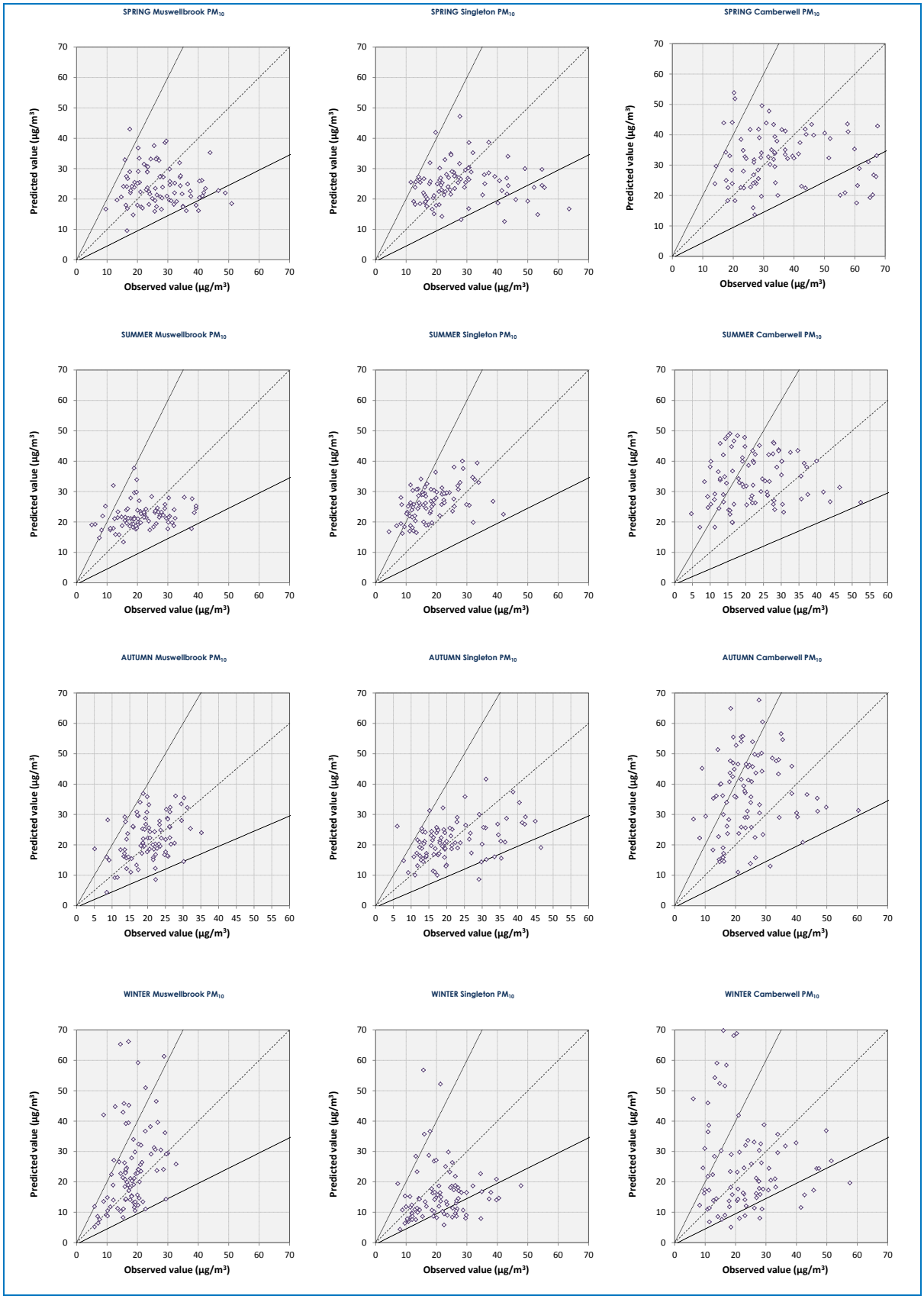


Figure 10.8: Scatter plots of observed and predicted 24-hour PM_{10} concentrations

11 SOURCE APPORTIONMENT

The estimated percentage source contributions to annual average PM_{10} and $PM_{2.5}$ concentrations are summarised in **Table 11.1**. The contributions from the four key anthropogenic PM emissions sources are shown as a percentage of total modelled ground level concentrations, at Singleton and Muswellbrook (presented as an ensemble town averages based on the receptor locations shown in **Figure 9.2**).

The data are also presented as pie charts in **Figure 11.1** and **Figure 11.2** and showing all sources of PM emissions, including estimated contribution from secondary PM and boundary from outside the modelling domain. The pie charts show modelled source contributions to annual average PM_{10} and $PM_{2.5}$ concentration as ensemble town average.

The modelled contributions of these sources to annual average PM_{10} and $PM_{2.5}$ ground-level concentrations in Muswellbrook and Singleton are shown in **Table 11.2**.

Table 11.1: Predicted source contribution as % at Muswellbrook and Singleton, base year 2012

	Muswellbrook		Singleton	
	PM_{10}	**$PM_{2.5}$**	**PM_{10}**	**$PM_{2.5}$**
Coal Mines	28%	12%	29%	15%
Wood heaters	8%	17%	6%	14%
Non-road diesel	3%	5%	2%	4%
Power stations	0.5%	0.6%	0.3%	0.5%

Table 11.2 presents the annual average PM_{10} and $PM_{2.5}$ concentrations for each of the four key anthropogenic PM emissions sources modelled

Table 11.2: Predicted ground level concentration by source at Muswellbrook and Singleton, base year 2012

	Muswellbrook		Singleton	
	PM_{10} ($\mu g/m^3$)	**$PM_{2.5}$($\mu g/m^3$)**	**PM_{10}($\mu g/m^3$)**	**$PM_{2.5}$($\mu g/m^3$)**
Coal Mines	5.9	1.2	6.9	1.4
Wood heaters	1.7	1.7	1.4	1.4
Non-road diesel	0.5	0.5	0.4	0.4
Power stations	0.1	0.1	0.1	0.05

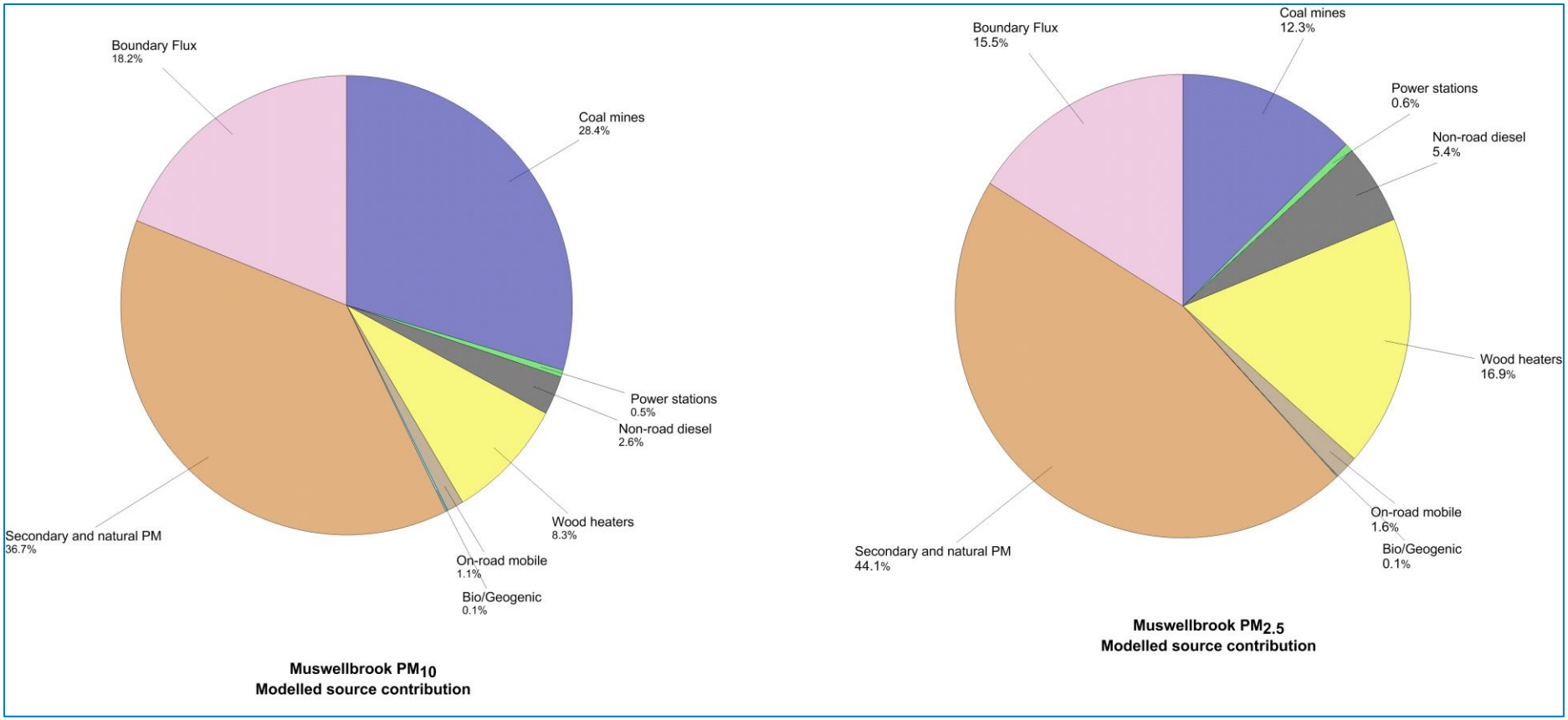


Figure 11.1: Modelled source apportionment- Muswellbrook town average, base year 2012 – PM_{10} and $PM_{2.5}$

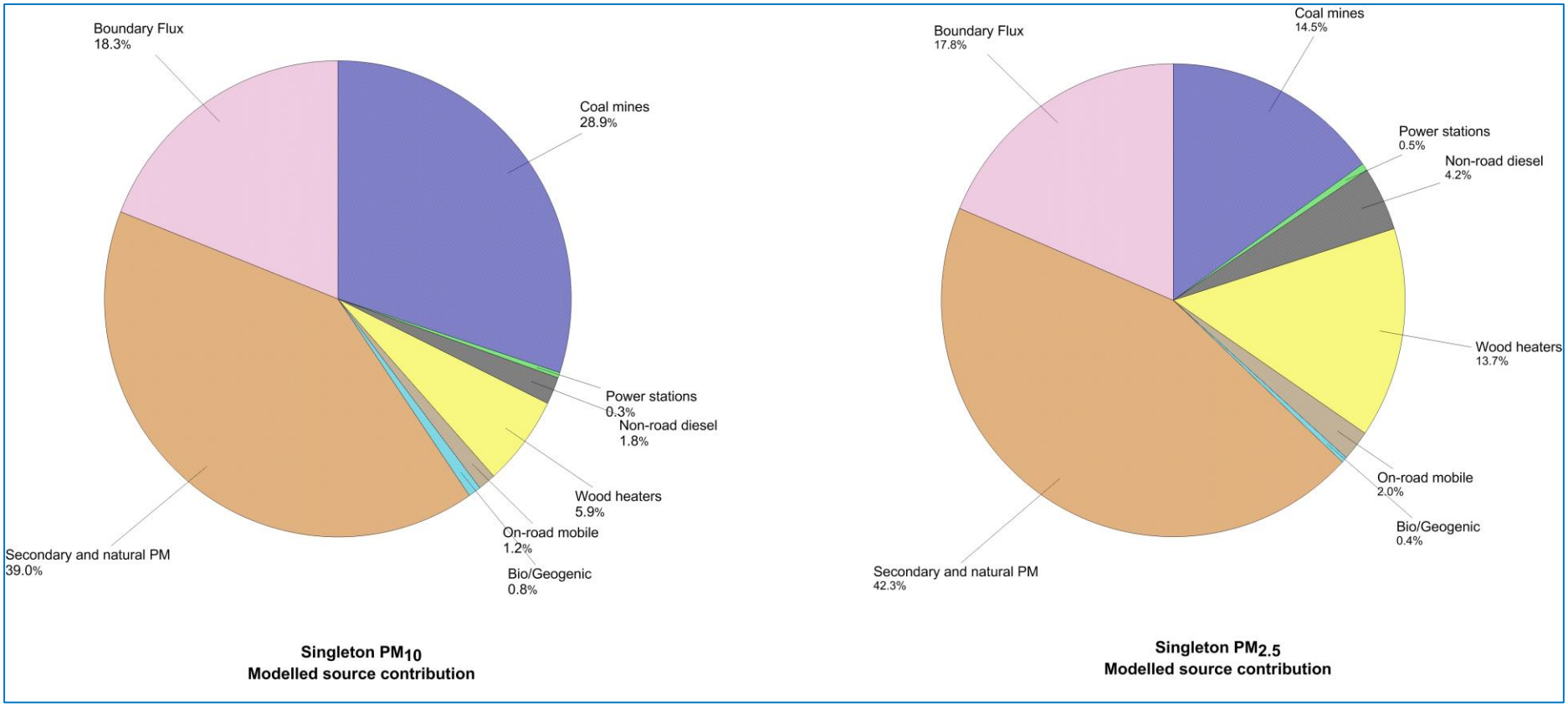


Figure 11.2: Modelled source apportionment - Singleton town average, base year 2012 – PM_{10} and $PM_{2.5}$

11.1 Seasonal variation

The seasonal variation in source contribution is presented in **Figure 11.3** and **Figure 11.4** and summarised in **Table 11.3** to **Table 11.6**. In winter, wood heater emissions are the largest source of primary anthropogenic $PM_{2.5}$ concentrations in both Muswellbrook and Singleton. In autumn the largest source of primary anthropogenic $PM_{2.5}$ in Singleton is coal mining and in Muswellbrook the largest sources are coal mining and wood heaters. In summer coal mining is the largest source of primary anthropogenic $PM_{2.5}$ in both Singleton and Muswellbrook. In spring the largest source of primary anthropogenic $PM_{2.5}$ in Singleton and Muswellbrook is coal mining, followed by wood heaters.

Table 11.3: Predicted seasonal source contribution to $PM_{2.5}$ - Muswellbrook

Source	Muswellbrook Spring $PM_{2.5}$	Muswellbrook Summer $PM_{2.5}$	Muswellbrook Autumn $PM_{2.5}$	Muswellbrook Winter $PM_{2.5}$
Coal mines	10%	12%	15%	16%
Power stations	0.5%	0.8%	0.7%	0.3%
Non-road diesel	4%	4%	7%	6%
Wood heaters	8%	0%	13%	36%
On-road mobile	1%	2%	2%	1%
Bio/Geogenic	0.1%	0.1%	0.1%	0.01%
Secondary and natural PM	49%	68%	41%	28%
Boundary Flux	24%	9%	16%	13%

Table 11.4: Predicted seasonal source contribution to $PM_{2.5}$ - Singleton

Source	Singleton Spring $PM_{2.5}$	Singleton Summer $PM_{2.5}$	Singleton Autumn $PM_{2.5}$	Singleton Winter $PM_{2.5}$
Coal mines	12%	7%	18%	21%
Power stations	0.6%	0.4%	0.5%	0.4%
Non-road diesel	3%	2%	5%	6%
Wood heaters	7%	0%	12%	37%
On-road mobile	1.6%	1.8%	2.6%	2.0%
Bio/Geogenic	0.5%	0.2%	0.5%	0.1%
Secondary and natural PM	49%	58%	39%	22%
Boundary Flux	22%	27%	16%	5%

Coal mine emissions are the largest source of primary anthropogenic PM_{10} concentrations in both Muswellbrook and Singleton for all seasons. In winter, wood heaters are also a significant source.

Table 11.5: Predicted seasonal source contribution to PM_{10} - Muswellbrook

Source	Muswellbrook Spring PM_{10}	Muswellbrook Summer PM_{10}	Muswellbrook Autumn PM_{10}	Muswellbrook Winter PM_{10}
Coal mines	23%	24%	34%	40%
Power stations	0.4%	0.5%	0.6%	0.4%
Non-road diesel	2%	2%	3%	4%
Wood heaters	4%	0%	6%	27%
On-road mobile	1%	1%	1%	2%
Bio/Geogenic	0.2%	0.2%	0.1%	0.04%
Secondary and natural PM	44%	61%	33%	12%
Boundary Flux	25%	9%	19%	23%

Table 11.6: Predicted seasonal source contribution to PM_{10} - Singleton

Source	Singleton Spring PM_{10}	Singleton Summer PM_{10}	Singleton Autumn PM_{10}	Singleton Winter PM_{10}
Coal mines	24%	13%	35%	55%
Power stations	0.4%	0.3%	0.4%	0.4%
Non-road diesel	1%	1%	2%	3%
Wood heaters	3%	0%	5%	21%
On-road mobile	0.9%	0.9%	1.6%	1.6%
Bio/Geogenic	1.4%	1.1%	0.4%	0.3%
Secondary and natural PM	45%	56%	35%	13.6%
Boundary Flux	22%	25%	17%	7%

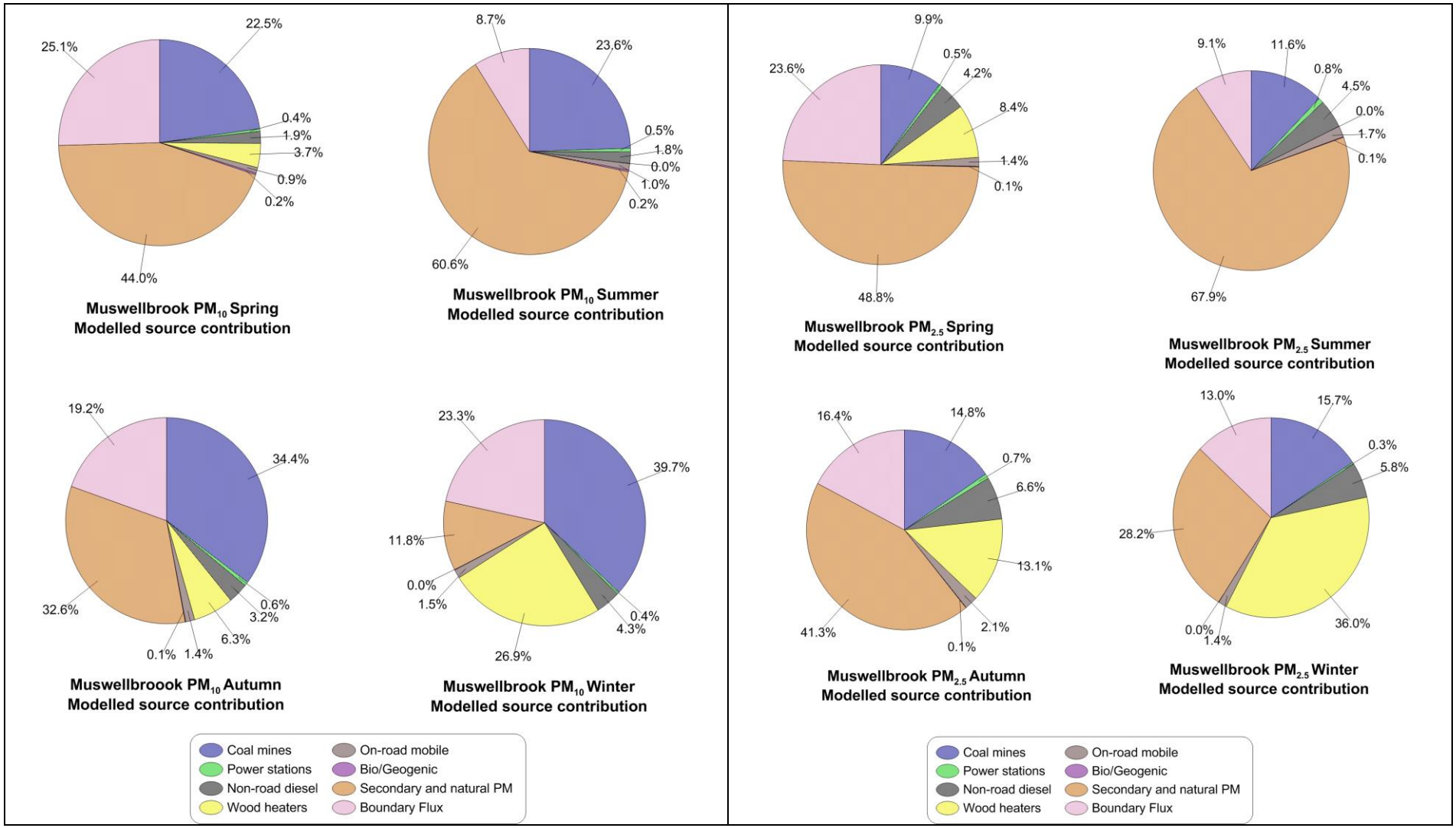


Figure 11.3: Seasonal modelled source apportionment- Muswellbrook town average PM_{10} and $PM_{2.5}$

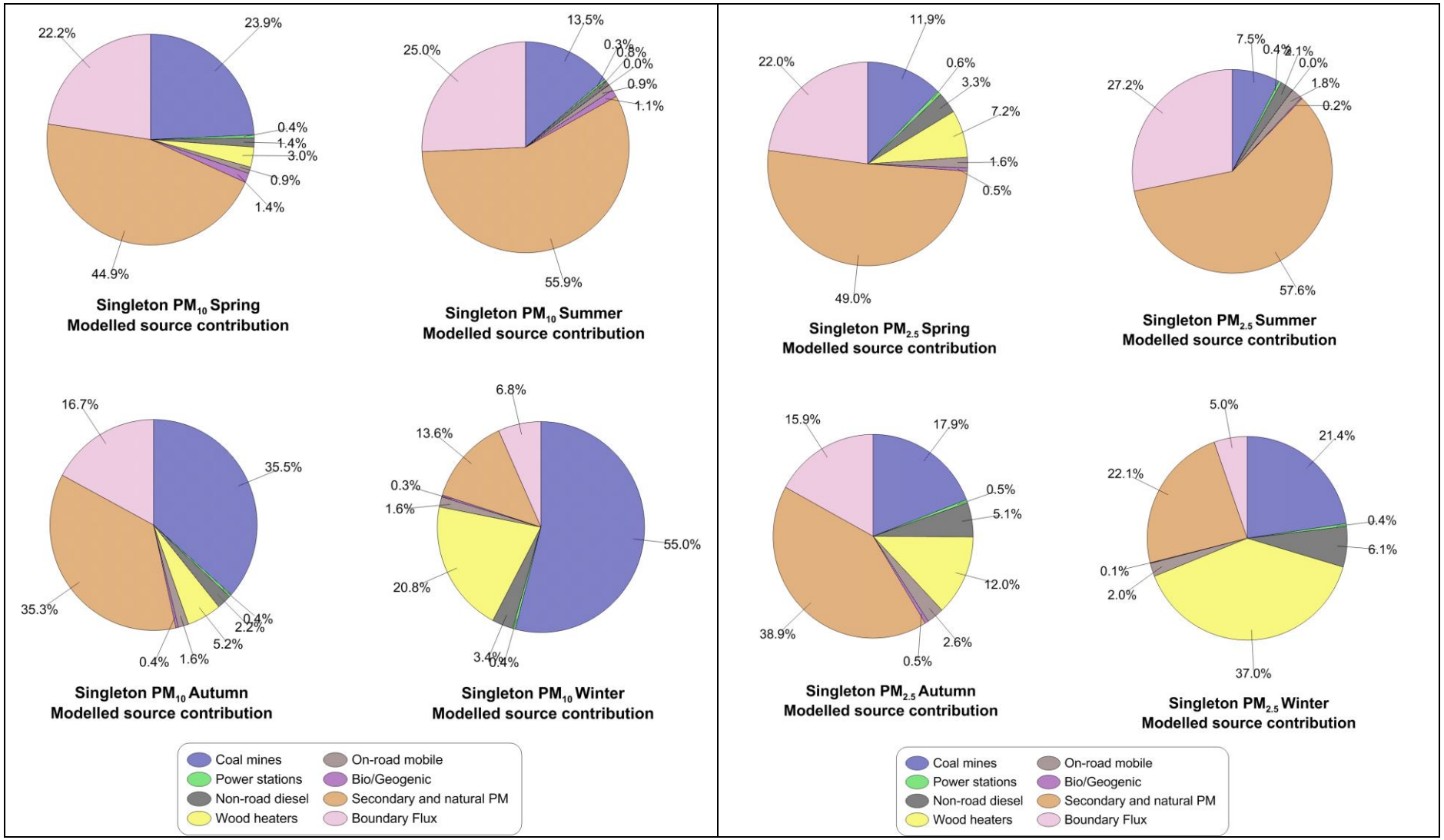


Figure 11.4: Seasonal modelled source apportionment- Singleton town average PM_{10} and $PM_{2.5}$

12 BAU PROJECTIONS

BAU projections are presented for a "consent" scenario and a "likely" scenario, based on the BAU projections for coal production discussed **Section 5.4**. The "consent" scenario projections are based on existing mine approvals whereas the "likely" scenario takes into account forecast growth, from modifications to existing approvals and planned new projects.

The increase in emissions from non-road diesel is scaled in line with increased coal production, based on the methodology described in **Section 6.1.** The BAU increase from other sources is based on scaling factors derived from the GMR inventory, as described in **Section 7.4**. It is assumed that other sources, including background and secondary PM remain constant.

12.1 Muswellbrook – $PM_{2.5}$

The $PM_{2.5}$ concentrations for the BAU "likely" scenario in 2016, 2021, 2026 and 2031 are shown in **Figure 12.1** (presented as a Muswellbrook town average).

Under the BAU "likely" scenario, the annual average $PM_{2.5}$ concentrations in Muswellbrook increase in 2016 but drop in 2021. This is a result of certain mining activity moving away from Muswellbrook, for example Drayton mine finishing and being replaced by Drayton South. The annual average $PM_{2.5}$ concentrations in Muswellbrook increase again in 2026, as new mines are established, before dropping slightly in 2031.

As discussed in **Section 5.4** the proportion of ROM coal from underground mining increases into future years, meaning that despite an increase in ROM coal production, the estimated emissions and resultant ground level concentrations level off in later years.

The source contributions to total predicted $PM_{2.5}$ concentration in Muswellbrook for the "likely scenario" are summarised in **Table 12.1** (absolute values) and **Table 12.2** (percentages).

The $PM_{2.5}$ concentrations for the BAU "consent" scenario in 2016, 2021, 2026 and 2031 are shown in **Figure 12.2** (presented as a Muswellbrook town average).

Under the BAU "consent" scenario, the annual average $PM_{2.5}$ concentrations in Muswellbrook increase in 2016, drop in 2021 and 2016 and level off in 2031. As discussed in **Section 5.4** under the consent scenario ROM coal production grows rapidly between 2012 and 2016 but falls sharply, as existing mine consents lapse.

The source contributions to total predicted $PM_{2.5}$ concentration in Muswellbrook for the "consent" scenario are summarised in **Table 12.3** (absolute values) and **Table 12.4** (percentages).

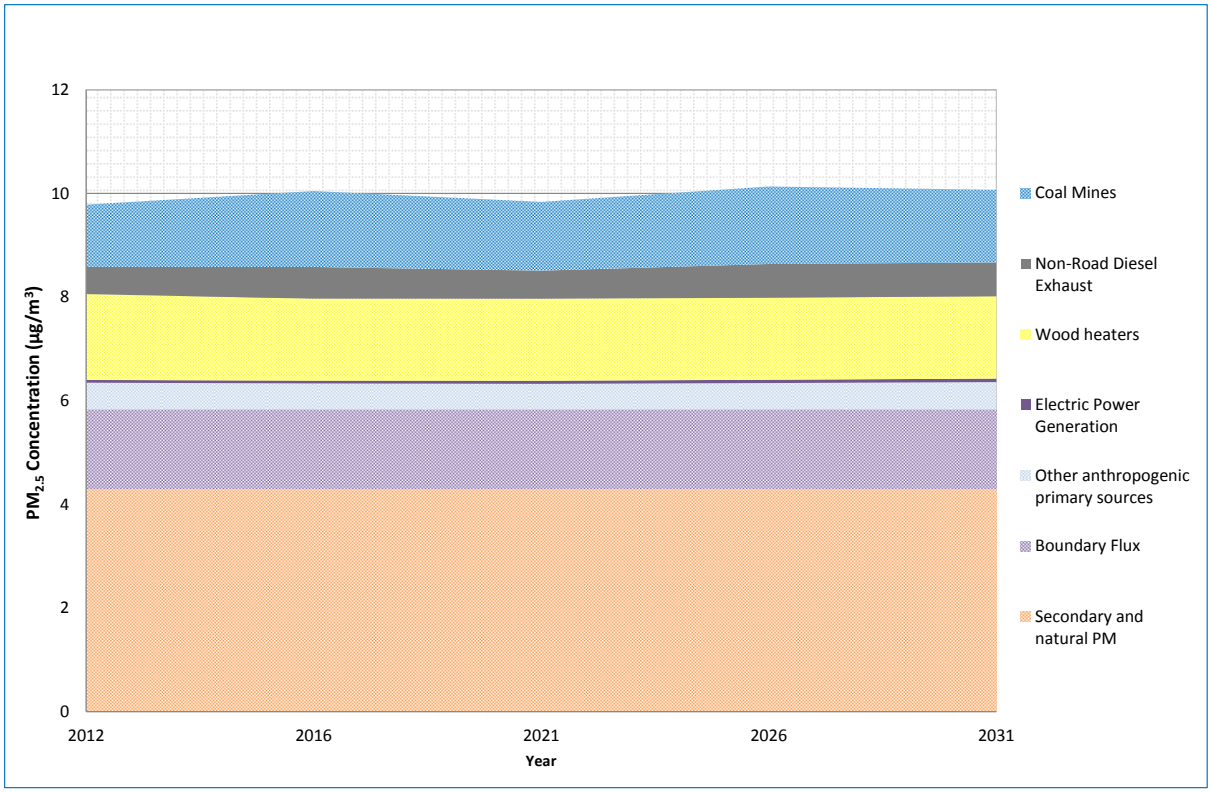


Figure 12.1: BAU "likely" scenario annual average $PM_{2.5}$ concentration in Muswellbrook

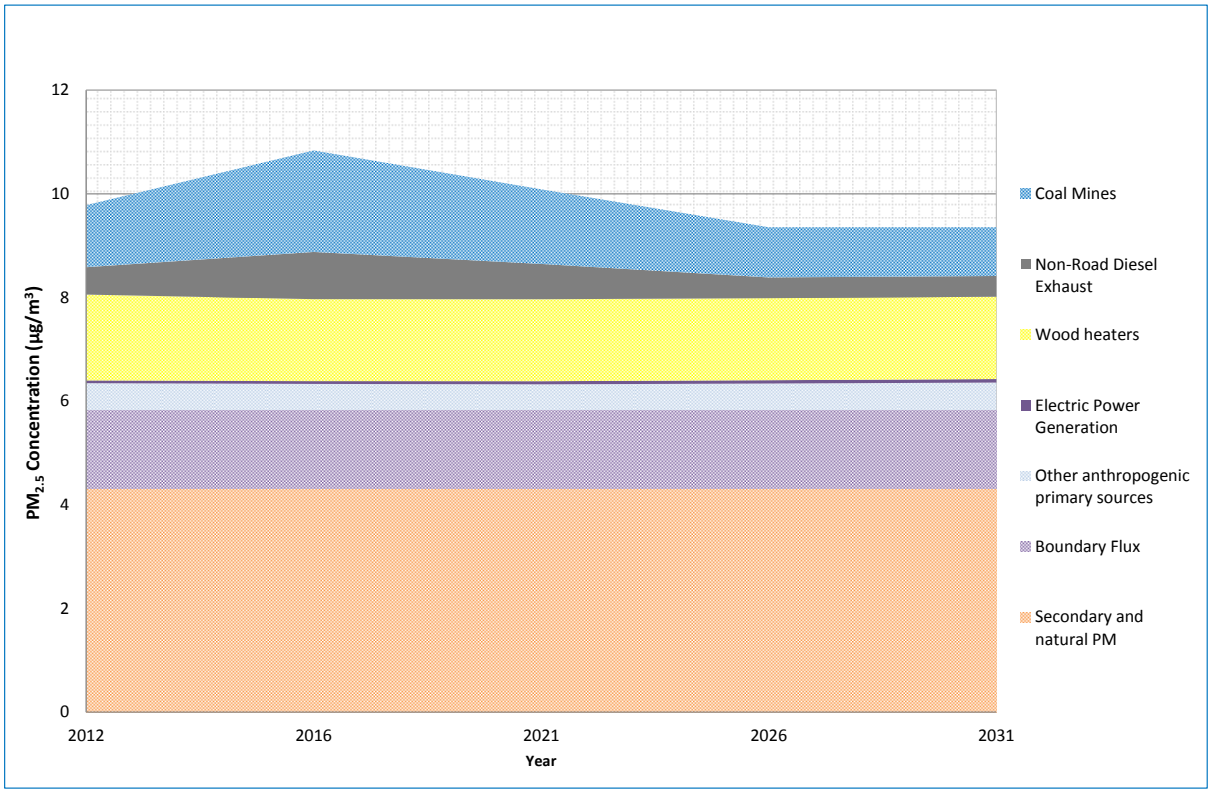


Figure 12.2: BAU "consent" scenario annual average $PM_{2.5}$ concentration in Muswellbrook

Table 12.1: BAU "likely" scenario ($PM_{2.5}$ concentration (µg/m³)) – Muswellbrook

Source	Annual average $PM_{2.5}$ concentration (µg/m³)				
	2012	2016	2021	2026	2031
Coal Mines	1.2	1.5	1.3	1.5	1.4
Power Stations	0.05	0.06	0.06	0.06	0.07
Non-Road Diesel Exhaust	0.5	0.6	0.5	0.7	0.7
Wood heaters	1.7	1.6	1.6	1.6	1.6
Sub-total (4 sources)	**3.4**	**3.7**	**3.5**	**3.8**	**3.7**
Other anthropogenic primary sources	0.5	0.5	0.5	0.5	0.5
Secondary and natural PM	4.3	4.3	4.3	4.3	4.3
Boundary Flux	1.5	1.5	1.5	1.5	1.5
Total concentration	**9.8**	**10.0**	**9.8**	**10.1**	**10.1**

Table 12.2: BAU "likely" scenario (% contribution to $PM_{2.5}$ concentration (µg/m³)) – Muswellbrook

Source	% contribution to $PM_{2.5}$ concentration (µg/m³)				
	2012	2016	2021	2026	2031
Coal Mines	12%	15%	14%	15%	14%
Power Stations	0.6%	0.6%	0.6%	0.6%	0.7%
Non-Road Diesel Exhaust	5%	6%	6%	6%	6%
Wood heaters	17%	16%	16%	16%	16%
Sub-total (4 sources)	**35%**	**37%**	**36%**	**37%**	**37%**
Other anthropogenic primary sources	5%	5%	5%	5%	5%
Secondary and natural PM	44%	43%	44%	43%	43%
Boundary Flux	16%	15%	15%	15%	15%

Table 12.3: BAU "consent" scenario ($PM_{2.5}$ concentration (µg/m³)) – Muswellbrook

Source	Annual average $PM_{2.5}$ concentration (µg/m³)				
	2012	2016	2021	2026	2031
Coal Mines	1.2	2.0	1.4	1.0	0.9
Power Stations	0.05	0.06	0.06	0.06	0.07
Non-Road Diesel Exhaust	0.5	0.9	0.7	0.4	0.4
Wood heaters	1.7	1.6	1.6	1.6	1.6
Sub-total (4 sources)	**3.4**	**4.5**	**3.8**	**3.0**	**3.0**
Other anthropogenic primary sources	0.5	0.5	0.5	0.5	0.5
Secondary and natural PM	4.3	4.3	4.3	4.3	4.3
Boundary Flux	1.5	1.5	1.5	1.5	1.5
Total concentration	**9.8**	**10.8**	**10.1**	**9.4**	**9.4**

Table 12.4: BAU "consent" scenario (% contribution to $PM_{2.5}$ concentration (µg/m³)) – Muswellbrook

Source	% contribution to $PM_{2.5}$ concentration (µg/m³)				
	2012	2016	2021	2026	2031
Coal Mines	12%	18%	14%	10%	10%
Power Stations	0.6%	0.5%	0.6%	0.7%	0.7%
Non-Road Diesel Exhaust	5%	8%	7%	4%	4%
Wood heaters	17%	15%	16%	17%	17%
Sub-total (4 sources)	**35%**	**42%**	**37%**	**32%**	**32%**
Other anthropogenic primary sources	5%	5%	5%	5%	6%
Secondary and natural PM	44%	40%	43%	46%	46%
Boundary Flux	16%	14%	15%	16%	16%

12.2 Singleton – $PM_{2.5}$

The $PM_{2.5}$ concentrations for the BAU "likely" scenario in 2016, 2021, 2026 and 2031 are shown in **Figure 12.3** (presented as a Singleton town average).

Under the BAU "likely" scenario, the annual average $PM_{2.5}$ concentrations in Singleton increase very slightly each year (~0.1 µg/m^3), from a combination of all sources. The percentage contribution of individual sources to annual average $PM_{2.5}$ concentrations in Singleton remains relatively consistent for the BAU "likely" scenario.

The source contributions to total predicted $PM_{2.5}$ concentration in Singleton for the "likely" scenario are presented in **Table 12.5** (absolute values) and (percentages) **Table 12.6**.

The $PM_{2.5}$ concentrations for the BAU "consent" scenario in 2016, 2021, 2026 and 2031 are shown in **Figure 12.4** (presented as a Singleton town average).

Under the BAU "consent" scenario, the annual average $PM_{2.5}$ concentrations in Singleton increase in 2016, drop in 2021 and 2016 and level off in 2031.

The source contributions to total predicted $PM_{2.5}$ concentration in Singleton for the "consent" scenario are presented in **Table 12.7** (absolute values) and **Table 12.8** (percentages).

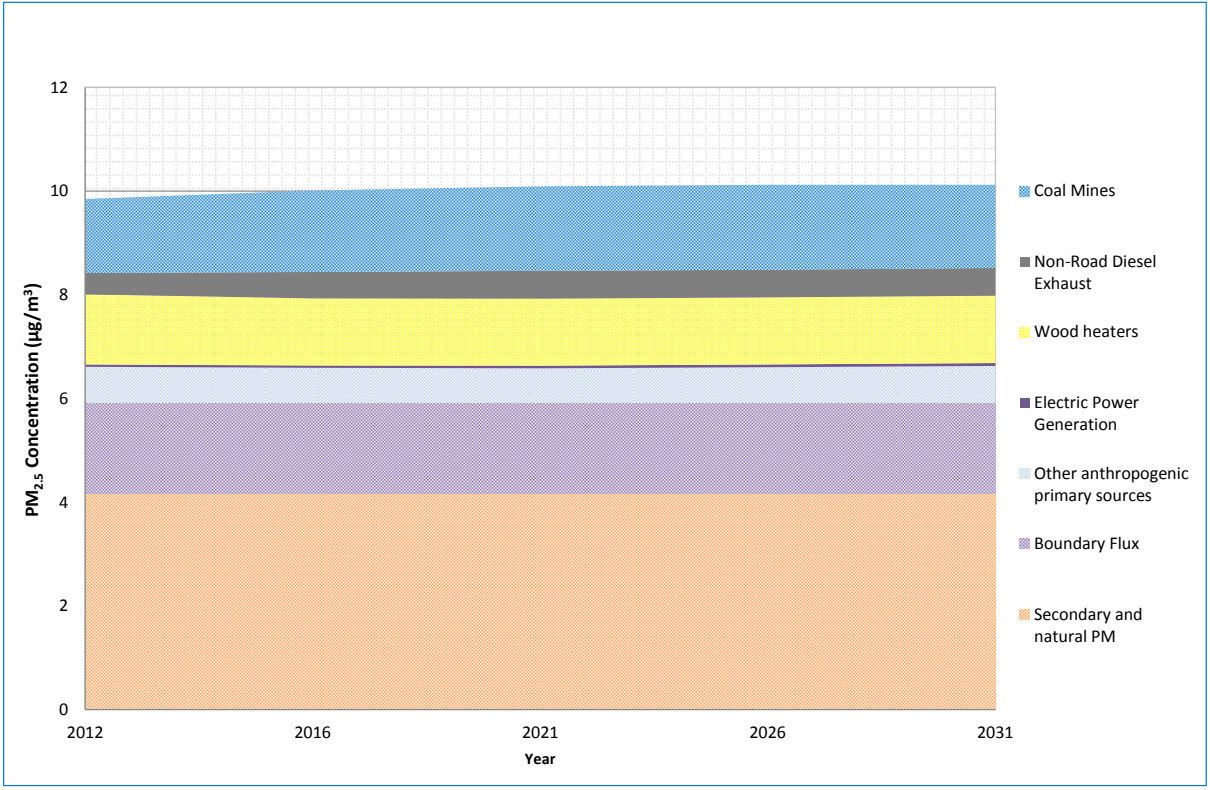


Figure 12.3: BAU "likely" scenario annual average $PM_{2.5}$ concentration in Singleton

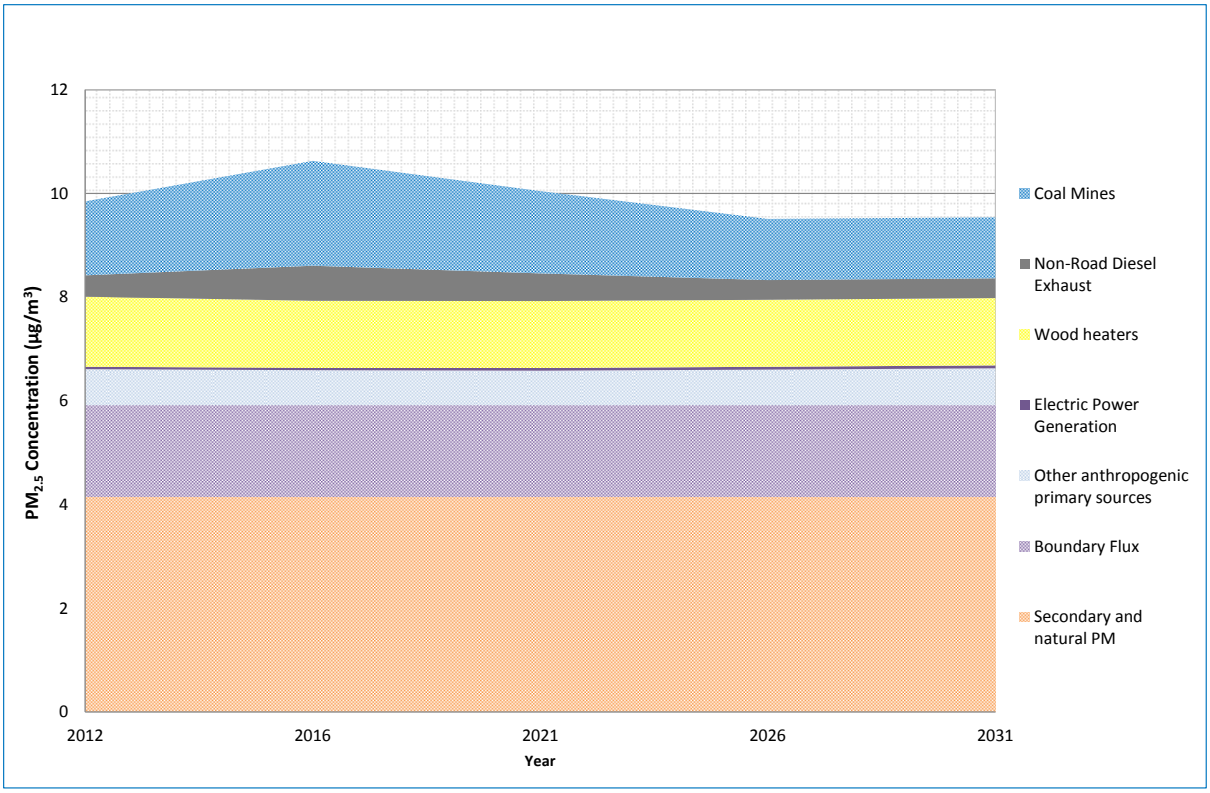


Figure 12.4: BAU "consent" scenario annual average $PM_{2.5}$ concentration in Singleton

Table 12.5: BAU "likely" scenario ($PM_{2.5}$ concentration (µg/m³)) – Singleton

Source	Annual average $PM_{2.5}$ concentration (µg/m³)				
	2012	2016	2021	2026	2031
Coal Mines	1.4	1.6	1.6	1.6	1.6
Power Stations	0.05	0.05	0.05	0.05	0.06
Non-Road Diesel Exhaust	0.4	0.5	0.5	0.5	0.5
Wood heaters	1.4	1.3	1.3	1.3	1.3
Sub-total (4 sources)	**3.2**	**3.4**	**3.5**	**3.5**	**3.5**
Other anthropogenic primary sources	0.7	0.7	0.7	0.7	0.7
Secondary and natural PM	4.2	4.2	4.2	4.2	4.2
Boundary Flux	1.8	1.8	1.8	1.8	1.8
Total concentration	**9.8**	**10.0**	**10.1**	**10.1**	**10.1**

Table 12.6: BAU "likely" scenario (% contribution to $PM_{2.5}$ concentration (µg/m³)) – Singleton

Source	% contribution to $PM_{2.5}$ concentration (µg/m³)				
	2012	2016	2021	2026	2031
Coal Mines	15%	16%	16%	16%	16%
Power Stations	0.5%	0.5%	0.5%	0.5%	0.6%
Non-Road Diesel Exhaust	4%	5%	5%	5%	5%
Wood heaters	14%	13%	13%	13%	13%
Sub-total (4 sources)	**33%**	**34%**	**35%**	**35%**	**35%**
Other anthropogenic primary sources	7%	7%	7%	7%	7%
Secondary and natural PM	42%	42%	41%	41%	41%
Boundary Flux	18%	17%	17%	17%	17%

Table 12.7: BAU "consent" scenario ($PM_{2.5}$ concentration (µg/m³)) – Singleton

Source	Annual average $PM_{2.5}$ concentration (µg/m³)				
	2012	2016	2021	2026	2031
Coal Mines	1.4	2.0	1.6	1.2	1.2
Power Stations	0.05	0.05	0.05	0.05	0.06
Non-Road Diesel Exhaust	0.4	0.7	0.5	0.4	0.4
Wood heaters	1.4	1.3	1.3	1.3	1.3
Sub-total (4 sources)	**3.2**	**4.0**	**3.5**	**2.9**	**2.9**
Other anthropogenic primary sources	0.7	0.7	0.7	0.7	0.7
Secondary and natural PM	4.2	4.2	4.2	4.2	4.2
Boundary Flux	1.8	1.8	1.8	1.8	1.8
Total concentration	**9.8**	**10.6**	**10.0**	**9.5**	**9.5**

Table 12.8: BAU "consent" scenario (% contribution to $PM_{2.5}$ concentration (µg/m³)) – Singleton

Source	% contribution to $PM_{2.5}$ concentration (µg/m³)				
	2012	2016	2021	2026	2031
Coal Mines	15%	19%	16%	12%	12%
Power Stations	0.5%	0.5%	0.5%	0.6%	0.6%
Non-Road Diesel Exhaust	4%	6%	5%	4%	4%
Wood heaters	14%	12%	13%	14%	14%
Sub-total (4 sources)	**33%**	**38%**	**34%**	**31%**	**31%**
Other anthropogenic primary sources	7%	6%	7%	7%	7%
Secondary and natural PM	42%	39%	41%	44%	44%
Boundary Flux	18%	16%	17%	18%	18%

12.3 Muswellbrook – PM_{10}

The PM_{10} concentrations for the BAU "likely" scenario in 2016, 2021, 2026 and 2031 are shown **Figure 12.5** (presented as a Muswellbrook town average).

Similar to $PM_{2.5}$, under the BAU "likely" scenario, the annual average PM_{10} concentrations in Muswellbrook increase in 2016 but drop in 2021. The annual average PM_{10} concentrations in Muswellbrook increase again in 2026, as new mines are established, before dropping slightly in 2031. The largest increase in percentage contribution to annual average PM_{10} concentrations comes from coal mining.

The source contributions to total predicted PM_{10} concentration in Muswellbrook for the "likely" scenario are summarised in **Table 12.9** (absolute values) and **Table 12.10** (percentages).

The PM_{10} concentrations for the BAU "consent" scenario in 2016, 2021, 2026 and 2031 are shown **Figure 12.6** (presented as a Muswellbrook town average).

Similar to $PM_{2.5}$, under the BAU "consent" scenario, the annual average $PM_{2.5}$ concentrations in Muswellbrook increase in 2016, drop in 2021 and 2016 and level off in 2031. The largest increase in percentage contribution to annual average PM_{10} concentrations comes from coal mining.

The source contributions to total predicted PM_{10} concentration in Muswellbrook for the "consent" scenario are summarised in **Table 12.11** (absolute values) and **Table 12.12** (percentages).

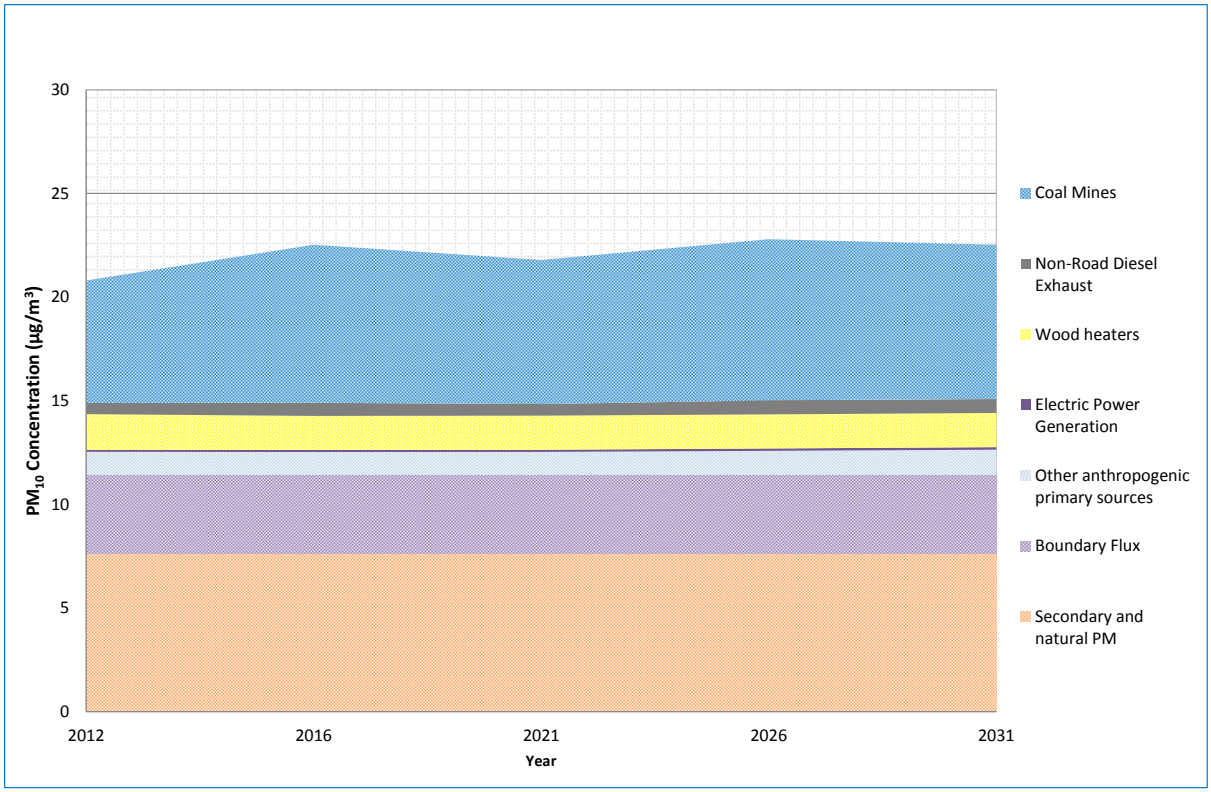


Figure 12.5: BAU "likely" scenario annual average PM_{10} concentration in Muswellbrook

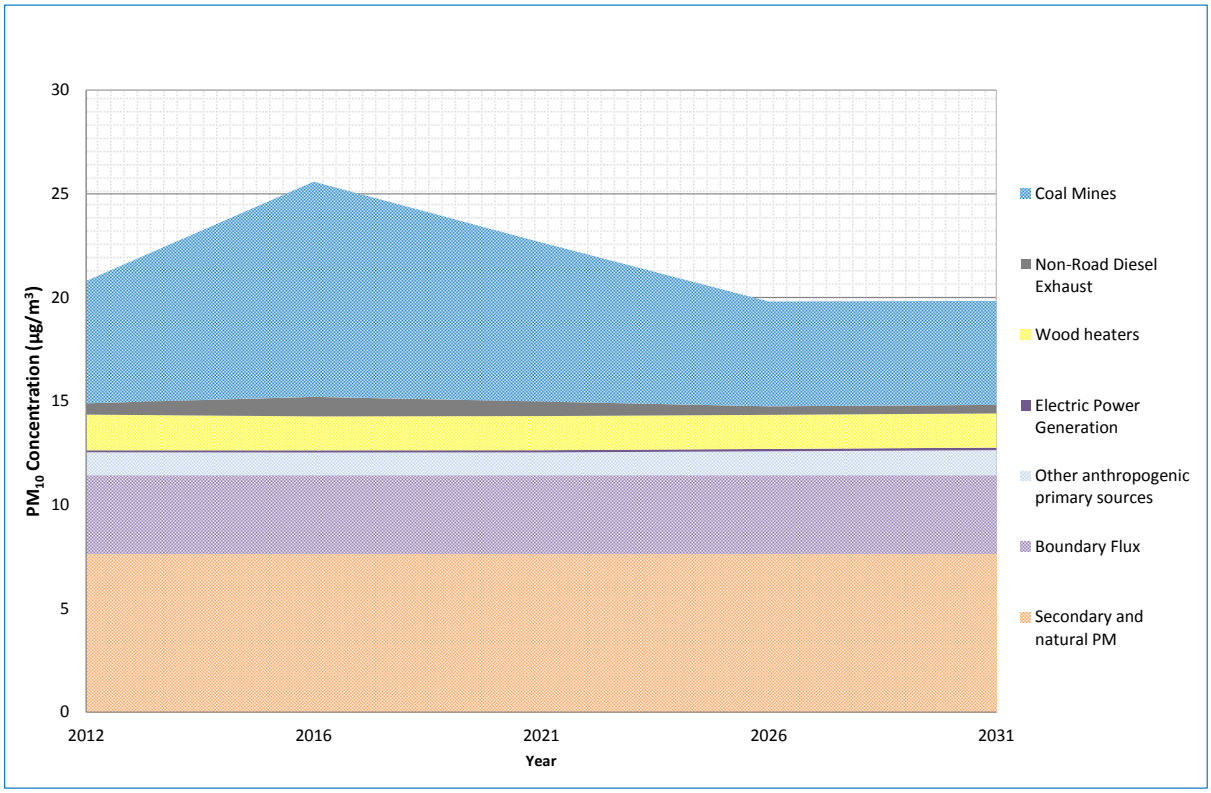


Figure 12.6: BAU "consent" scenario annual average PM_{10} concentration in Muswellbrook

Table 12.9: BAU "likely" scenario (PM_{10} concentration ($\mu g/m^3$)) – Muswellbrook

Source	Annual average PM_{10} concentration ($\mu g/m^3$)				
	2012	2016	2021	2026	2031
Coal Mines	5.9	7.6	6.9	7.8	7.4
Power Stations	0.1	0.1	0.1	0.1	0.1
Non-Road Diesel Exhaust	0.5	0.6	0.6	0.7	0.7
Wood heaters	1.7	1.6	1.6	1.6	1.6
Sub-total (4 sources)	**8.3**	**10.0**	**9.3**	**10.2**	**9.9**
Other anthropogenic primary sources	1.1	1.1	1.1	1.2	1.2
Secondary and natural PM	7.6	7.6	7.6	7.6	7.6
Boundary Flux	3.8	3.8	3.8	3.8	3.8
Total concentration	**20.8**	**22.5**	**21.8**	**22.8**	**22.5**

Table 12.10: BAU "likely" scenario (% contribution to PM_{10} concentration ($\mu g/m^3$)) – Muswellbrook

Source	% contribution to PM_{10} concentration ($\mu g/m^3$)				
	2012	2016	2021	2026	2031
Coal Mines	28%	34%	32%	34%	33%
Power Stations	0.5%	0.5%	0.5%	0.5%	0.5%
Non-Road Diesel Exhaust	3%	3%	3%	3%	3%
Wood heaters	8%	7%	8%	7%	7%
Sub-total (4 sources)	**40%**	**44%**	**42%**	**45%**	**44%**
Other anthropogenic primary sources	5%	5%	5%	5%	5%
Secondary and natural PM	37%	34%	35%	33%	34%
Boundary Flux	18%	17%	17%	17%	17%

Table 12.11: BAU "consent" scenario (PM_{10} concentration ($\mu g/m^3$)) – Muswellbrook

Source	Annual average PM_{10} concentration ($\mu g/m^3$)				
	2012	2016	2021	2026	2031
Coal Mines	5.9	10.4	7.7	5.1	5.0
Power Stations	0.1	0.1	0.1	0.1	0.1
Non-Road Diesel Exhaust	0.5	0.9	0.7	0.4	0.4
Wood heaters	1.7	1.6	1.6	1.6	1.6
Sub-total (4 sources)	**8.3**	**13.1**	**10.1**	**7.2**	**7.2**
Other anthropogenic primary sources	1.1	1.1	1.1	1.2	1.2
Secondary and natural PM	7.6	7.6	7.6	7.6	7.6
Boundary Flux	3.8	3.8	3.8	3.8	3.8
Total concentration	**20.8**	**25.6**	**22.7**	**19.8**	**19.8**

Table 12.12: BAU "consent" scenario (% contribution to PM_{10} concentration ($\mu g/m^3$)) – Muswellbrook

Source	% contribution to PM_{10} concentration ($\mu g/m^3$)				
	2012	2016	2021	2026	2031
Coal Mines	28%	41%	34%	26%	25%
Power Stations	0.5%	0.4%	0.5%	0.6%	0.6%
Non-Road Diesel Exhaust	3%	4%	3%	2%	2%
Wood heaters	8%	6%	7%	8%	8%
Sub-total (4 sources)	**40%**	**51%**	**45%**	**36%**	**36%**
Other anthropogenic primary sources	5%	4%	5%	6%	6%
Secondary and natural PM	37%	30%	34%	39%	38%
Boundary Flux	18%	15%	17%	19%	19%

12.4 Singleton – PM_{10}

The PM_{10} concentrations for the BAU "likely" scenario in 2016, 2021, 2026 and 2031 are shown in **Figure 12.7** (presented as a Singleton town average).

Under the BAU "likely" scenario, the annual average PM_{10} concentrations in Singleton increases 2016 and 2021 before levelling off in 2026 and 2031. The percentage contribution of individual sources to annual average PM_{10} concentrations in Singleton remains relatively consistent for the BAU "likely" scenario.

The source contributions to total predicted PM_{10} concentration in Singleton for the "likely" scenario are presented in **Table 12.13** (absolute values) and **Table 12.14** (percentages).

The PM_{10} concentrations for the BAU "consent" scenario in 2016, 2021, 2026 and 2031 are shown in **Figure 12.8** (presented as a Singleton town average).

Under the BAU "consent" scenario, the annual average PM_{10} concentrations in Singleton increase in 2016, drop in 2021 and 2016 and level off in 2031.

The source contributions to total predicted PM_{10} concentration in Singleton for the "consent" scenario are presented in **Table 12.15** (absolute values) and **Table 12.16** (percentages).

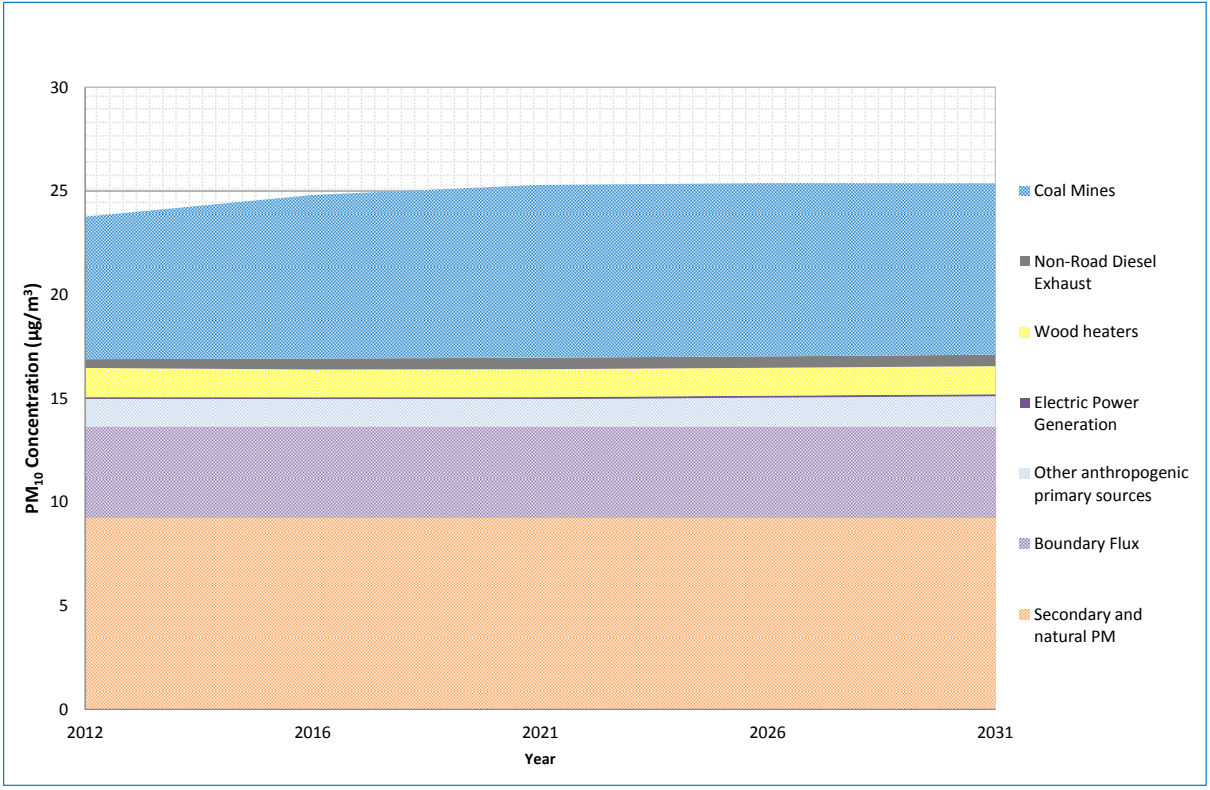


Figure 12.7: BAU "likely" scenario annual average PM_{10} concentration in Singleton

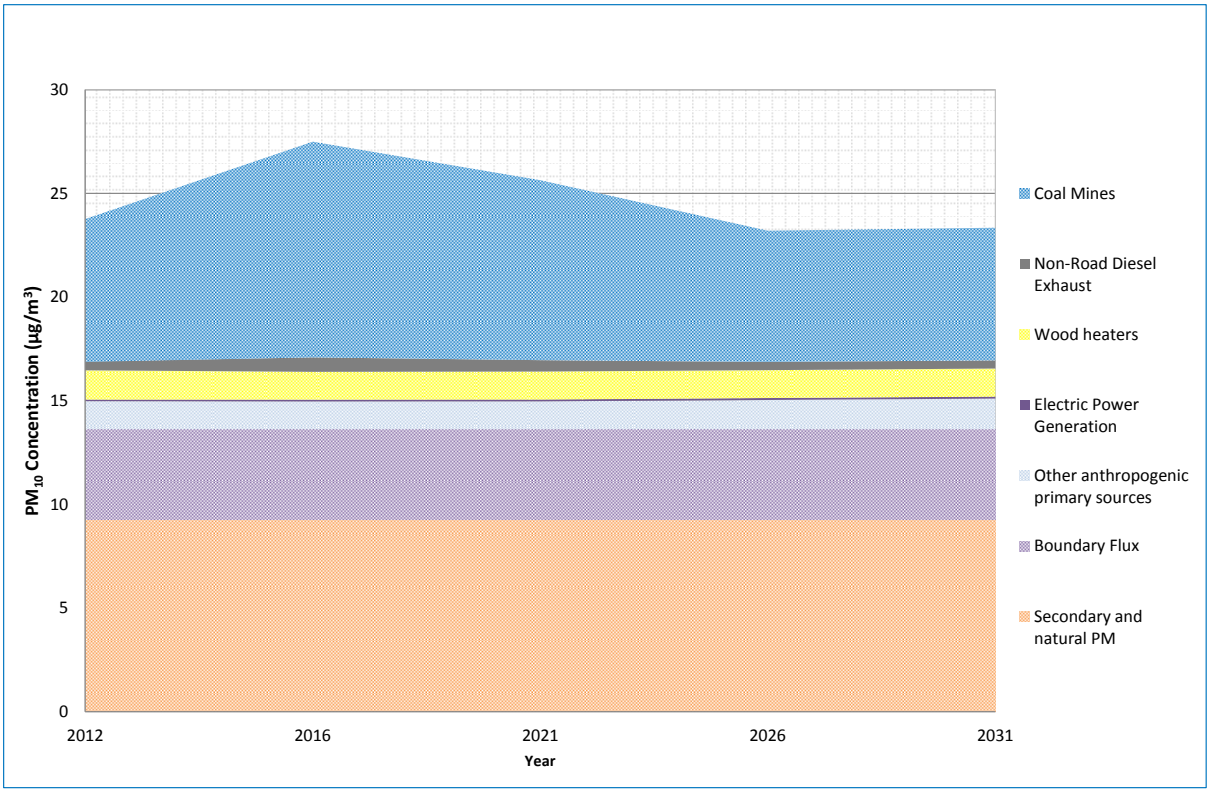


Figure 12.8: BAU "consent" scenario annual average PM_{10} concentration in Singleton

Table 12.13: BAU "likely" scenario (PM_{10} concentration (µg/m³)) – Singleton

Source	Annual average PM_{10} concentration (µg/m³)				
	2012	2016	2021	2026	2031
Coal Mines	6.9	7.9	8.3	8.4	8.3
Power Stations	0.1	0.1	0.1	0.1	0.1
Non-Road Diesel Exhaust	0.4	0.5	0.6	0.6	0.6
Wood heaters	1.4	1.3	1.3	1.3	1.3
Sub-total (4 sources)	**8.8**	**9.8**	**10.3**	**10.3**	**10.3**
Other anthropogenic primary sources	1.4	1.3	1.3	1.4	1.5
Secondary and natural PM	9.3	9.3	9.3	9.3	9.3
Boundary Flux	4.4	4.4	4.4	4.4	4.4
Total concentration	**23.8**	**24.8**	**25.3**	**25.4**	**25.4**

Table 12.14: BAU "likely" scenario (% contribution to PM_{10} concentration (µg/m³)) – Singleton

Source	% contribution to PM_{10} concentration (µg/m³)				
	2012	2016	2021	2026	2031
Coal Mines	29%	32%	33%	33%	33%
Power Stations	0.3%	0.4%	0.4%	0.4%	0.4%
Non-Road Diesel Exhaust	2%	2%	2%	2%	2%
Wood heaters	6%	5%	5%	5%	5%
Sub-total (4 sources)	**37%**	**40%**	**41%**	**41%**	**40%**
Other anthropogenic primary sources	6%	5%	5%	6%	6%
Secondary and natural PM	39%	37%	37%	37%	37%
Boundary Flux	18%	18%	17%	17%	17%

Table 12.15: BAU "consent" scenario (PM_{10} concentration (µg/m³)) – Singleton

Source	Annual average PM_{10} concentration (µg/m³)				
	2012	2016	2021	2026	2031
Coal Mines	6.9	10.4	8.7	6.3	6.4
Power Stations	0.1	0.1	0.1	0.1	0.1
Non-Road Diesel Exhaust	0.4	0.7	0.6	0.4	0.4
Wood heaters	1.4	1.3	1.3	1.3	1.3
Sub-total (4 sources)	**8.8**	**12.5**	**10.7**	**8.2**	**8.2**
Other anthropogenic primary sources	1.4	1.3	1.3	1.4	1.5
Secondary and natural PM	9.3	9.3	9.3	9.3	9.3
Boundary Flux	4.4	4.4	4.4	4.4	4.4
Total concentration	**23.8**	**27.5**	**25.6**	**23.2**	**23.3**

Table 12.16: BAU "consent" scenario (% contribution to PM_{10} concentration (µg/m³)) – Singleton

Source	% contribution to PM_{10} concentration (µg/m³)				
	2012	2016	2021	2026	2031
Coal Mines	29%	38%	34%	27%	27%
Power Stations	0.3%	0.3%	0.4%	0.4%	0.4%
Non-Road Diesel Exhaust	2%	3%	2%	2%	2%
Wood heaters	6%	5%	5%	6%	6%
Sub-total (4 sources)	**37%**	**46%**	**42%**	**35%**	**35%**
Other anthropogenic primary sources	6%	5%	5%	6%	6%
Secondary and natural PM	39%	34%	36%	40%	40%
Boundary Flux	18%	16%	17%	19%	19%

It is noted that the modelling results are very sensitive to assumptions made in estimating emissions in future years, for example in compiling "likely" ROM production estimates out to 2030, the DRE need to make assumptions on export demand and coal price, as well as taking into account recent Government approvals and increasing community opposition, all of which influences mine expansion and new projects.

Therefore the modelling uncertainty increases for future year predictions, when compared with 2012 where emission estimates are made based on known ROM and waste production.

13 EMISSION REDUCTION SCENARIOS

Potential emission reduction options for coal mining, wood heaters and non-road diesel are discussed in the following sections.

13.1 Coal mines

The NSW EPA's "*Dust Stop*" PRP program is underway which requires coal mines to identify and implement best practice measures to reduce PM emissions from their top four dust-generating activities. Hauling is typically the largest single contributor to PM emissions at mine sites and, as such, the EPA has issued PRPs for all sites that require an 80% control to be applied all haul roads from 2013. An 80% control has been included in the BAU modelling for 2016, 2021, 2026 and 2031.

Other best practice management measures, for example ceasing overburden handling during adverse weather, are also in the process of being implemented but are not included in the BAU modelling. Potential emission reductions have been reported for implementing best practice dust control at specific mines sites in the Hunter Valley (through the Dust Stop PRP response) however it is difficult to quantify the combined effect of implementing various best practice measures.

Reported emission reductions range from 10% to 50% however, in some cases these reductions include increasing wheel generated dust control efficiency to 80% control. Others sites are reported as having existing controls comparable to best practice and no further reduction is presented.

13.2 Wood heaters

The BAU emission projections have assumed the take up of the Australian Standard (AS/NZS 4013:1999), resulting in approximately 5% decrease in emissions for domestic wood heating.

The National Environment Protection Council Service Department have released a Consultation regulation impact statement for reducing emissions from wood heaters (**BDA Group, 2013**)). The study reports that under a business-as-usual scenario, PM emissions from wood heaters in NSW are expected to fall by 15% over the next 20 years, as a result of older units being replaced by more efficient ones.

Additional reductions in PM emissions (above BAU) for various policy options were examined in **BDA Group (2013)** with the reductions ranging from 3% (based on audits and education programmes) to 18% (based on labelling, efficiency standards and emissions standards).

Emission reduction ranging from 20% to 40% could therefore be considered for wood heaters over a period of 20 years, assuming a phased implementation of various policy options presented in **BDA Group (2013)**.

13.3 Non-road diesel

Under BAU emission projections, diesel emissions are scaled in line with projected increases in mining production. Potential emission-reduction options for non-road diesel include the introduction of national emissions standards (in line with US or EU emissions limits) and retrofitting high-polluting diesel engines with diesel particulate filters (DPFs).

The Cleaner Non-Road Diesel Engines Project (**Environ, 2010**) reported that under a BAU scenario, annual PM_{10} emissions would be in the range of 7.8 kilo-tonnes per annum to 14.6 ktpa by 2030. The implementation of US EPA Tier 4 emissions limits would achieve PM_{10} emission reductions in the range of 7.3 kilo-tonnes per annum to 14.1 ktpa by 2030 (equating to 93% to 96% control by 2030) (**Environ, 2010**).

Environ (2010) recommended harmonisation of the non-road diesel regulations with US and /or EU emission regulation with timeframes tailored to local circumstances. A phased implementation was suggested with progression towards Tier 3 in 2020 and Tier 4 after 2020. Only 9% of existing construction and mining equipment were reported as Tier 4 compliance in the study.

Retrofitting diesel engines with partial diesel particulate filters (pDPFs) can provide moderate PM emission reductions of 30% - 50%. Diesel particulate filters (DPFs) can achieve significant reductions in PM (85%-95%) (http://www.epa.gov/otaq/diesel/technologies/retrofits.htm).

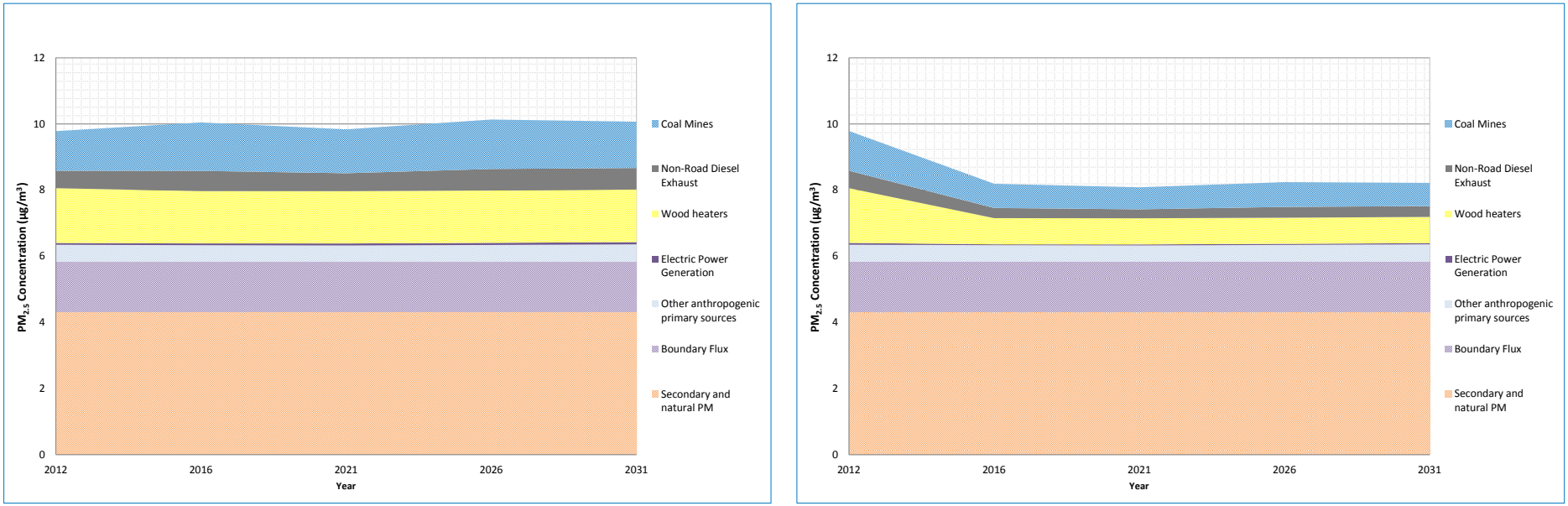
On 13 June 2014 the EPA hosted a diesel emissions management workshop to seek feedback on proposed actions to address diesel emissions in NSW (**NSW EPA, 2014**). NSW is working with the Commonwealth and other jurisdictions to develop national measures to reduce diesel emissions, including emission standards for non-road diesel engines. The NSW EPA has identified a need to act independently on non-road diesel emissions in light of the lack of national standards, growth in emissions from this sector, increasing evidence of adverse health impacts from diesel, and the availability of standards and proven technologies to reduce diesel emissions (**NSW EPA, 2014**). Initiatives for non-road diesel emissions include actions specific to coal mines which are identified as the principal industrial source contributing to non-road diesel emissions in the GMR (**NSW EPA, 2014**).

Based on the phased implementation of diesel emission regulation plus retro fitting of pDPFs, various emission reduction options are possible, in the range of 30% to beyond 50% over the over a period of 20 years or less.

13.4 Emission reduction matrix

The estimated annual average PM_{10} and $PM_{2.5}$ ground level concentrations that result from various illustrative emission-reduction scenarios are presented as a matrix in **Table 13.1** to **Table 13.4**, for both PM matrices in Muswellbrook and Singleton. The emission reduction matrix allows any combination of emission reduction targets (10%, 20%, 30%, 40%, 50%) to be applied to each of the four key sources for each study year.

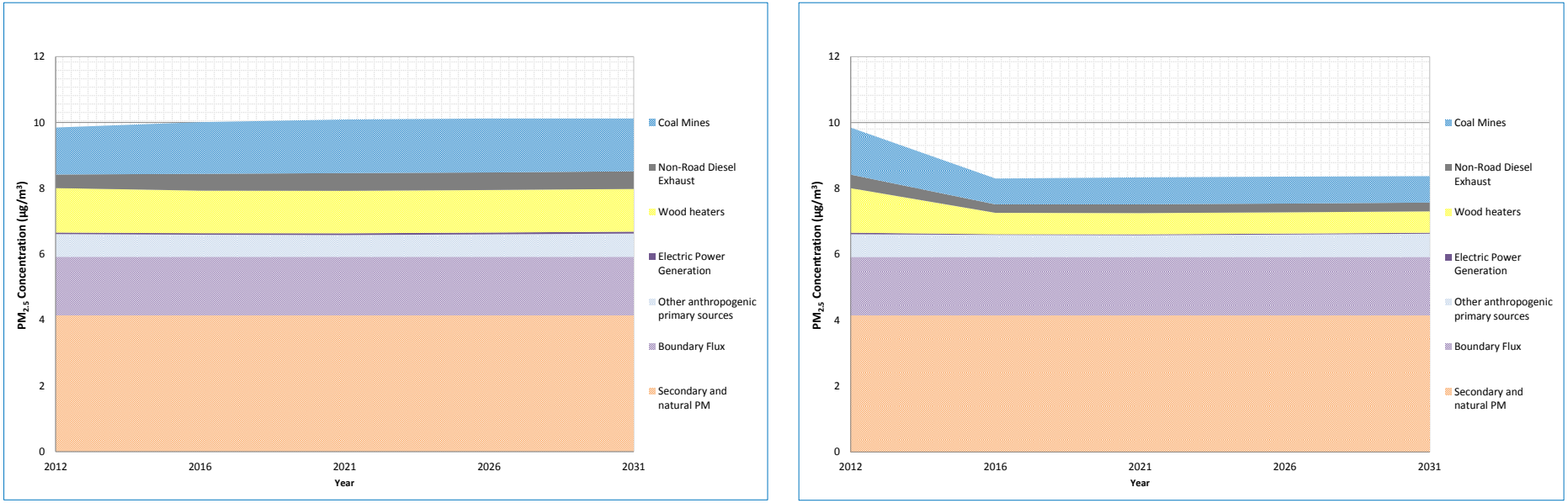
The effect of applying emission reductions to the four key sources is illustrated in **Figure 13.1** to **Figure 13.4** for both PM matrices in Muswellbrook and Singleton. The plots compare annual average $PM_{2.5}$ concentrations for BAU (left panel) with a 50% emission reduction applied across all four key sources (right panel).



BAU – Likely Scenario

50% emission reduction for four key sources

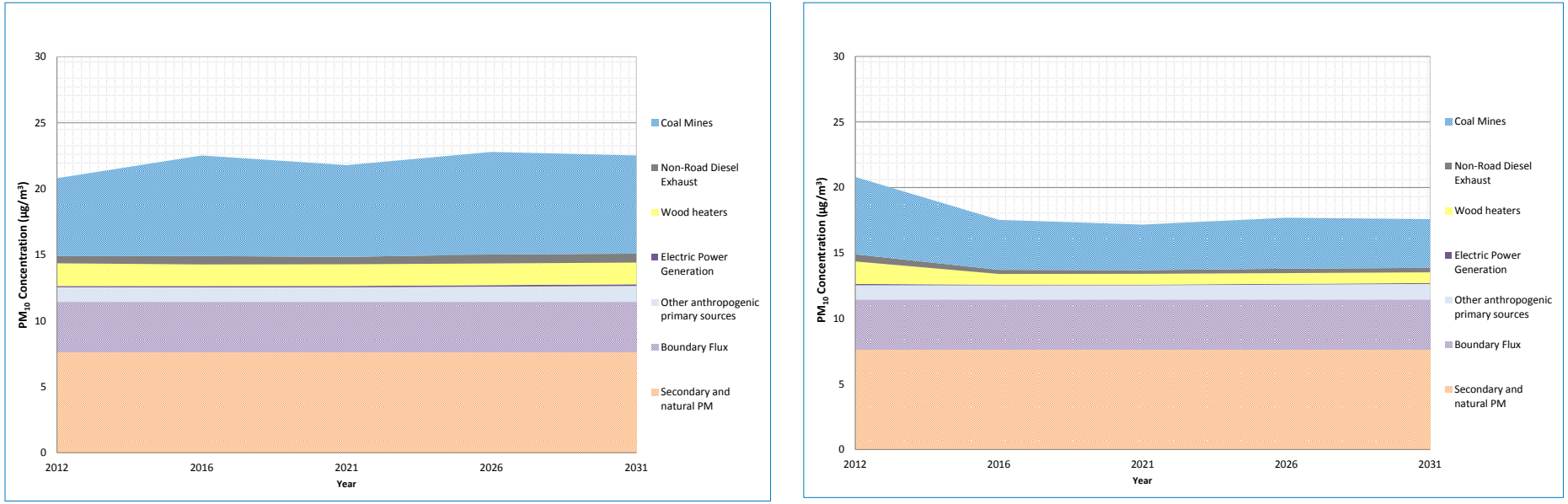
Figure 13.1: Base year and BAU "likely" scenario compared with 50% emissions reduction for $PM_{2.5}$ in Muswellbrook



BAU – Likely Scenario

50% emission reduction for four key sources

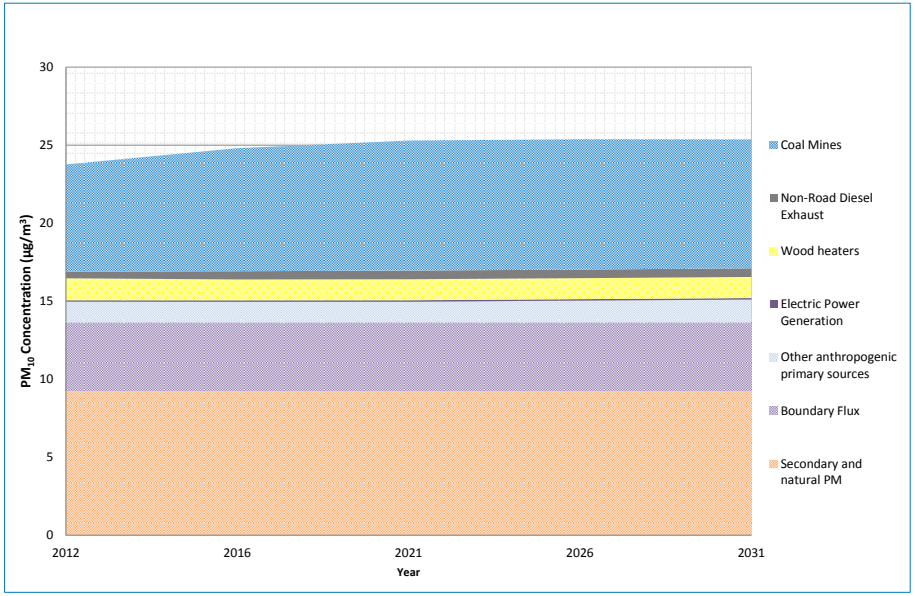
Figure 13.2: Base year and BAU "likely" scenario compared with 50% emissions reduction for $PM_{2.5}$ in Singleton



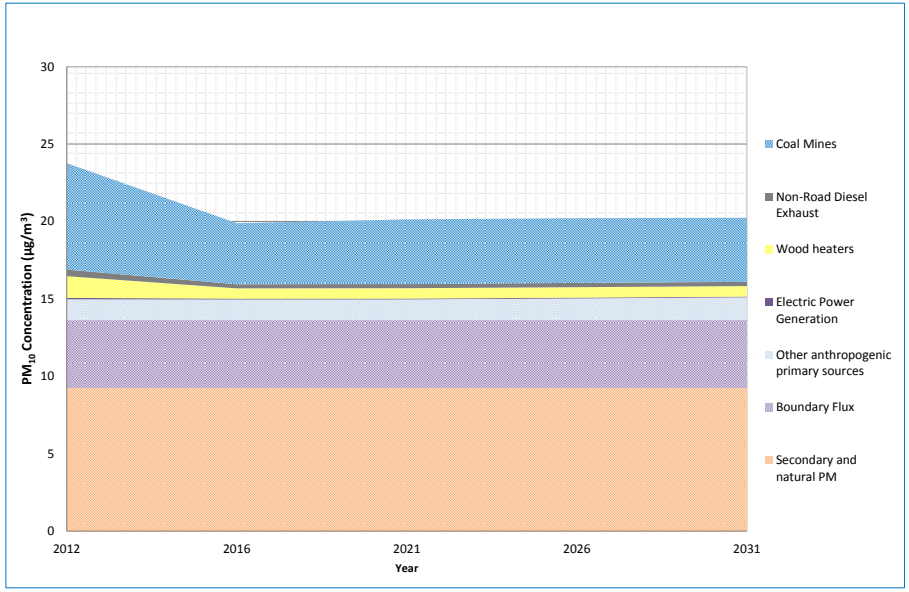
BAU – Likely Scenario

50% emission reduction for four key sources

Figure 13.3: Base year and BAU "likely" scenario compared with 50% emissions reduction for PM_{10} in Muswellbrook



BAU – Likely Scenario



50% emission reduction for four key sources

Figure 13.4: Base year and BAU "likely" scenario compared with 50% emissions reduction for PM_{10} in Singleton

Table 13.1: Emission reduction matrix for $PM_{2.5}$ in Muswellbrook (town average) – Likely Scenario

Source Type	Year	Annual average $PM_{2.5}$ concentration ($\mu g/m^3$)					
		BAU	10%	20%	30%	40%	50%
Coal mines	2016	1.5	1.3	1.2	1.0	0.9	0.7
	2021	1.3	1.2	1.1	0.9	0.8	0.7
	2026	1.5	1.3	1.2	1.0	0.9	0.7
	2031	1.4	1.3	1.1	1.0	0.8	0.7
Domestic wood heaters	2016	1.6	1.4	1.3	1.1	0.9	0.8
	2021	1.6	1.4	1.3	1.1	0.9	0.8
	2026	1.6	1.4	1.3	1.1	0.9	0.8
	2031	1.6	1.4	1.3	1.1	1.0	0.8
Electric power generation	2016	0.06	0.05	0.05	0.04	0.03	0.03
	2021	0.05	0.05	0.05	0.04	0.04	0.03
	2026	0.06	0.06	0.05	0.05	0.04	0.03
	2031	0.07	0.06	0.05	0.05	0.04	0.03
Non-road diesel exhaust	2016	0.6	0.6	0.5	0.4	0.4	0.3
	2021	0.5	0.5	0.4	0.4	0.3	0.3
	2026	0.7	0.6	0.5	0.5	0.4	0.3
	2031	0.7	0.6	0.5	0.5	0.4	0.3

Table 13.2: Emission reduction matrix for $PM_{2.5}$ in Singleton (town average) – Likely Scenario

Source Type	Year	Annual average $PM_{2.5}$ concentration ($\mu g/m^3$)					
		BAU	10%	20%	30%	40%	50%
Coal mines	2016	1.6	1.4	1.3	1.1	0.9	0.8
	2021	1.6	1.5	1.3	1.1	1.0	0.8
	2026	1.6	1.5	1.3	1.1	1.0	0.8
	2031	1.6	1.4	1.3	1.1	1.0	0.8
Domestic wood heaters	2016	1.3	1.2	1.0	0.9	0.8	0.6
	2021	1.3	1.2	1.0	0.9	0.8	0.6
	2026	1.3	1.2	1.0	0.9	0.8	0.6
	2031	1.3	1.2	1.0	0.9	0.8	0.6
Electric power generation	2016	0.05	0.04	0.04	0.03	0.03	0.02
	2021	0.05	0.05	0.04	0.04	0.03	0.03
	2026	0.05	0.05	0.04	0.04	0.03	0.03
	2031	0.06	0.05	0.05	0.04	0.03	0.03
Non-road diesel exhaust	2016	0.5	0.5	0.4	0.4	0.3	0.3
	2021	0.5	0.5	0.4	0.4	0.3	0.3
	2026	0.5	0.5	0.4	0.4	0.3	0.3
	2031	0.5	0.5	0.4	0.4	0.3	0.3

Table 13.3: Emission reduction matrix for PM_{10} in Muswellbrook (town average) – Likely Scenario

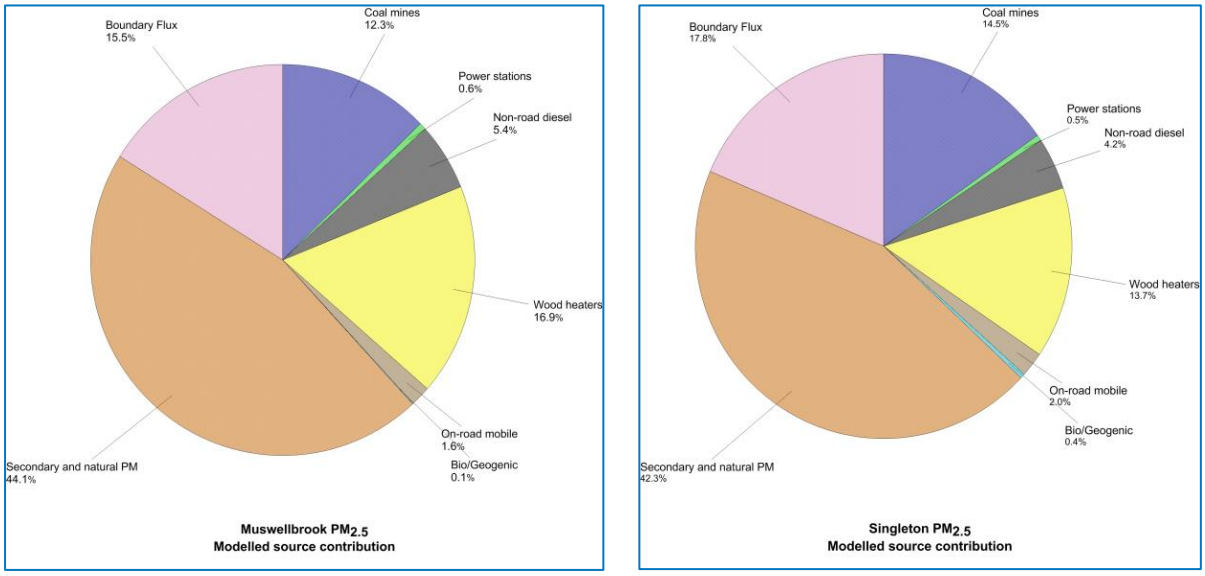
Source Type	Year	Annual average $PM_{2.5}$ concentration ($\mu g/m^3$)					
		BAU	10%	20%	30%	40%	50%
Coal mines	2016	7.6	6.9	6.1	5.3	4.6	3.8
	2021	6.9	6.3	5.6	4.9	4.2	3.5
	2026	7.8	7.0	6.2	5.4	4.7	3.9
	2031	7.4	6.7	6.0	5.2	4.5	3.7
Domestic wood heaters	2016	1.6	1.5	1.3	1.1	1.0	0.8
	2021	1.6	1.5	1.3	1.1	1.0	0.8
	2026	1.6	1.5	1.3	1.2	1.0	0.8
	2031	1.6	1.5	1.3	1.2	1.0	0.8
Electric power generation	2016	0.10	0.09	0.08	0.07	0.06	0.05
	2021	0.10	0.10	0.09	0.08	0.07	0.05
	2026	0.12	0.10	0.09	0.08	0.07	0.06
	2031	0.12	0.11	0.10	0.09	0.07	0.06
Non-road diesel exhaust	2016	0.6	0.6	0.5	0.4	0.4	0.3
	2021	0.6	0.5	0.4	0.4	0.3	0.3
	2026	0.7	0.6	0.5	0.5	0.4	0.3
	2031	0.7	0.6	0.5	0.5	0.4	0.3

Table 13.4: Emission reduction matrix for PM_{10} in Singleton (town average) – Likely Scenario

Source Type	Year	Annual average $PM_{2.5}$ concentration ($\mu g/m^3$)					
		BAU	10%	20%	30%	40%	50%
Coal mines	2016	7.9	7.1	6.3	5.5	4.7	3.9
	2021	8.3	7.5	6.7	5.8	5.0	4.2
	2026	8.4	7.5	6.7	5.8	5.0	4.2
	2031	8.3	7.4	6.6	5.8	5.0	4.1
Domestic wood heaters	2016	1.3	1.2	1.1	0.9	0.8	0.7
	2021	1.3	1.2	1.1	0.9	0.8	0.7
	2026	1.3	1.2	1.1	0.9	0.8	0.7
	2031	1.3	1.2	1.1	0.9	0.8	0.7
Electric power generation	2016	0.09	0.08	0.07	0.06	0.05	0.04
	2021	0.09	0.08	0.08	0.06	0.06	0.05
	2026	0.10	0.09	0.08	0.07	0.06	0.05
	2031	0.10	0.09	0.08	0.07	0.06	0.05
Non-road diesel exhaust	2016	0.5	0.5	0.4	0.4	0.3	0.3
	2021	0.6	0.5	0.4	0.4	0.3	0.3
	2026	0.6	0.5	0.4	0.4	0.3	0.3
	2031	0.6	0.5	0.4	0.4	0.3	0.3

14 CONCLUSION

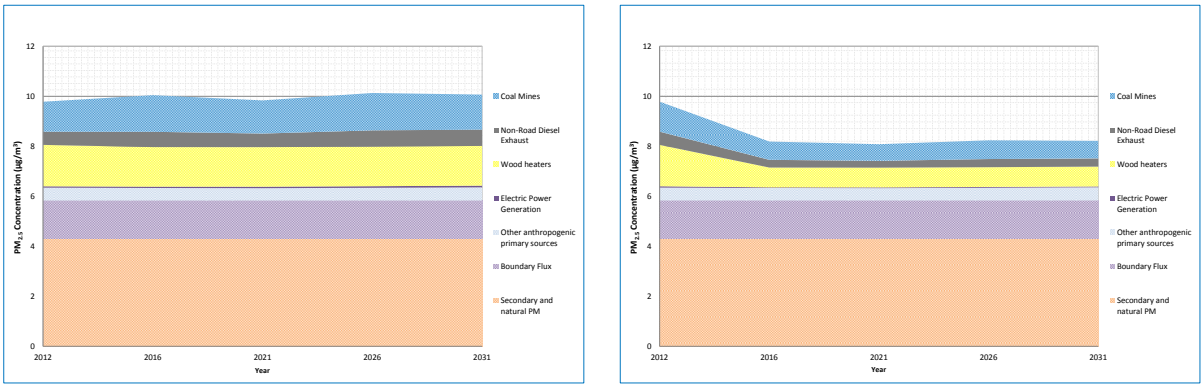
The most significant contributors to primary anthropogenic PM emissions in the Upper Hunter Valley region are coal mines, domestic wood heaters, non-road diesel exhaust and electric power generation. The modelled source contributions to annual average ground level $PM_{2.5}$ concentrations in 2012 are summarised in **Figure 14.1**. Wood heater emissions are the largest (primary anthropogenic) contributor to annual average $PM_{2.5}$ concentrations for Muswellbrook (16.9%) and coal mine emissions are the largest contributor in Singleton (14.5%). When the combined contribution from coal mines and non-road diesel exhaust is considered, this is higher than wood heaters in Muswellbrook. Significant seasonal variation is evident with wood heater emissions dominant in winter for both Muswellbrook (36%) and Singleton (37%). In other seasons, coal mine emissions are the largest (primary anthropogenic) contributor for both Muswellbrook and Singleton.



Muswellbrook Singleton

Figure 14.1: Predicted source contribution to $PM_{2.5}$ for base year 2012

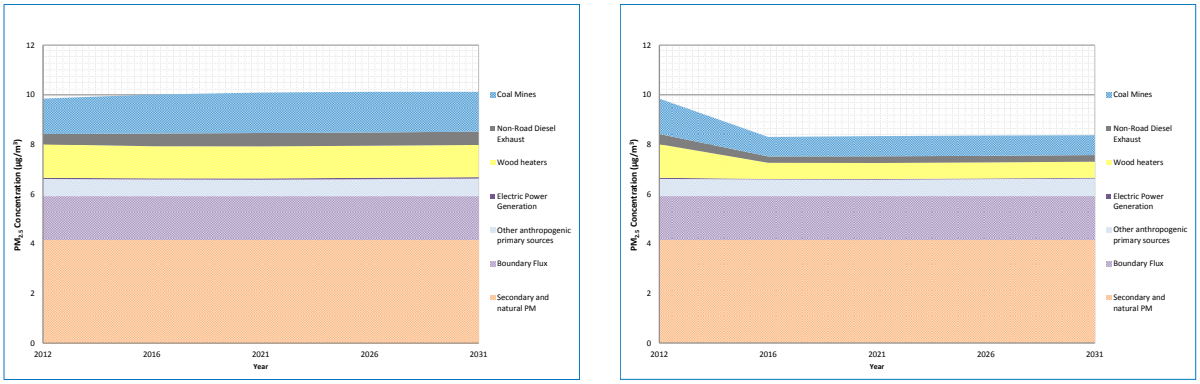
The annual average $PM_{2.5}$ concentration in Muswellbrook for BAU "likely" scenario is presented in **Figure 14.2** (left panel) and compared to a 50% emission reduction applied to each of the four key sources (right panel). Under the BAU "likely" scenario, the annual average $PM_{2.5}$ concentrations in Muswellbrook increase in 2016, drop slightly in 2021 and increase in 2026.



BAU – Likely Scenario 50% emission reduction for four key sources

Figure 14.2: BAU "likely" scenario compared with 50% emissions reduction for $PM_{2.5}$ in Muswellbrook

The annual average $PM_{2.5}$ concentration in Singleton for BAU "likely" scenario is presented in **Figure 14.3** (left panel) and compared to a 50% emission reduction applied to each of the four key sources (right panel). Under the BAU "likely" scenario, the annual average $PM_{2.5}$ concentrations in Singleton increase very slightly each year (~0.1 µg/m^3), from a combination of all sources.



BAU – Likely Scenario

50% emission reduction for four key sources

Figure 14.3: BAU "likely" scenario compared with 50% emissions reduction for $PM_{2.5}$ Singleton

It is noted that the BAU projections are very sensitive to assumptions made in estimating emissions for future years. Modelling uncertainty is considered to increase for future years and results should be interpreted with this in mind.

Source contribution to annual average PM_{10} concentrations in 2012 is shown in the body of the report, as are the BAU "likely" and "consent" scenarios and emission reduction for PM_{10}.

15 RECOMMENDATIONS FOR FURTHER WORK

The two most significant sources of uncertainty identified in this study relate to estimates of background/boundary flux from outside the modelling domain and the contribution from secondary particles.

There are limited monitoring sites located outside the modelling domain to accurately assign and model a boundary flux. A further complication results from the potential recirculation of winds in the valley (along the northwest, southeast axis). Potential recirculation of air flow introduces uncertainty in the analysis of wind direction dependent PM concentrations (for example looking at the PM concentrations when winds only blow into the domain.

- A recommendation for future work would be to better account for regional background or model boundary flux. This could be achieved by comparing modelled and measured data at locations close to the domain boundary or by using regional scale modelling to derive model boundary conditions.

The contribution of secondary PM to annual average PM_{10} and $PM_{2.5}$ is significant and this study estimates the contribution based on the Upper Hunter Particle Characterisation Study data. While some components of secondary PM are well described in these data, there are limitations to this approach, particularly for estimates of secondary organic aerosol. Also, no data for PM_{10} are available from this study.

- A recommendation for future work would be to refine this approach, including the investigation into developing a secondary particle model.

Further recommendations for reducing some of the model uncertainty for this study are:

- Refinement of the approach to prognostic modelling. This could be achieved by replacing TAPM with the more advanced Weather Research Forecast (WRF) model. Although the study aims to reduce error associated with the tendency of TAPM V4 to under predict wind speeds (by comparing various approaches to data assimilation), further refinement of the prognostic modelling is recommended. The use of WRF as the prognostic input into CALMET (or as a direct interface to CALPUFF[k]) may further reduce uncertainty.

- Further sensitivity testing for wood heater modelling to resolve over predictions for PM_{10} in Muswellbrook and at certain locations in Singleton.

[k] It is understood that the US EPA has commissioned the development of a direct interface between prognostic models and CALPUFF which is being considered for regulatory CALPUFF modelling. This would effectively bypass CALMET whereby a CALMET 3-D meteorological field is generated by WRF and read directly by CALPUFF.

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