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Hazelwood Analysis

Final report to EPA Victoria from CSIRO

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Important disclaimer

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Acronyms

AMS	Air monitoring station
API	Airborne Particle Index
Ave	Average
BAM	beta attenuation monitor
B(a)P	Benzo(a)pyrene
CFA	Country Fire Authority
CO	Carbon monoxide
DNPH	Dinitrophenylhydrazine
EC	Elemental carbon
IR	Infrared
MFB	Metropolitan fire brigade
MOUDI	Cascade Impactor
NEPM	National Environment Protection Measure
NO_2	Nitrogen dioxide
O_3	Ozone
OC	Organic carbon
PAHs	polycyclic aromatic hydrocarbons
$PM_{2.5}$	particulate matter with an aerodynamic diameter of 2.5 µm
PM_{10}	particulate matter with an aerodynamic diameter of 10 µm
POPs	Persistent organic pollutants
ppm	parts per million
ppb	parts per billion
PUF	Polyurethane foam
SO_2	sulphur dioxide
Stdev	standard deviation
TCDD	Dioxins
TCDF	Furans
TEOM	Tapered Element Oscillating Micro-balance
TEQ	toxic equivalency
TEF	toxic equivalency factors
VOCs	Volatile organic compounds
WHO	World Health Organisation
QZ	Quartz

1 Introduction

The Hazelwood mine fire was a major air pollution event that affected nearby communities in the Latrobe Valley. At the time of the event, few peer-reviewed publications were available to assess the impacts from such an incident. A large data set was collected during the Hazelwood mine fire by various parties to assess the impact on air, water and soil that will aid in the assessment of impacts on human health. The Hazelwood meta-analysis project will significantly enhance our understanding of the environmental impacts from such an event.

The inquiry into the Hazelwood mine fire resulted in a number of actions for the State of Victoria to act upon. Following on from these recommendations, EPA Victoria has commissioned a meta-analysis that aims to address Affirmation 18 in the Inquiry which states that:

> "*EPA to coordinate a meta-analysis, including smoke plume modelling, of air monitoring data and other relevant information collected during the Hazelwood mine fire to create a body of knowledge of the impacts of extended brown coal fire events*".

The meta-analysis aims to

- Review and collate the collected data set during and after the Hazelwood mine fire (including air, water, soil and ash samples)
- Identify potential uses for the collated data and information (research publications, models or other products to share the information)
- Provide support for other institutions researching the effects of the Hazelwood mine fire incident
- Identify knowledge gaps associated with brown coal mine fires

This report covers the data set that was collated for the Hazelwood mine fire and details on the products developed for the project. Any knowledge gaps are highlighted within each product. In this work we define meta-analysis as the collation of data collected during the fire and the identification of gaps.

2 Work undertaken in this project

The project was a collaborative project between CSIRO and EPA Victoria to review and collate the data collected about the Hazelwood mine fire and identify potential uses of the collated data and information.

2.1 Data collection

Data was collected during the Hazelwood mine fire from a number of stakeholders. The details are shown in Table 2.

Table 1 Data collected

ORGANISATION	DATA COLLECTED
CFA	CO, ARGOS modelling, Thermal imagery, operational data
MFB	CO
EPA Tasmania	TravelBLANkET $PM_{2.5}$
LVAMN	Hourly data of NO_2, SO_2, O_3, PM_{10}
DHHS	Health advice guidelines

2.2 Data collation

The following sections describe the data base, review the data sets collected and discuss the potential uses for the collated data and information and what products may be developed that can further our understanding on coal mine fires, their impact on air quality, human health and the environment.

3 Database

During the Hazelwood mine fire, data was collected by various parties to assess the impact of the Hazelwood mine fire on air, water and soil quality. On-going measurements continue at selected locations to assess the air, water and soil quality after the incident. A database of the collated data was created and will be available on

3.1 Meteorology

Meteorological conditions are important parameters to understand fire emissions, fire spread and plume dispersion. Of particular interest are wind speed and wind direction.

- Meteorological data was collected by EPA Victoria at three locations during the Hazelwood mine fire, Morwell South air monitoring station (AMS), Morwell East AMS and Traralgon AMS.
- Additional Bureau of Meteorology (BoM) sites are at LaTrobe Valley airport, East Sale, Warragul and Yarram Airport.

The database includes hourly data of temperature, relative humidity, wind speed and wind direction.

3.2 Continuous air quality monitoring

Continuous measurements were conducted for a range of criteria pollutants (e.g. CO, NO_2, O_3, SO_2, $PM_{2.5}$ and PM_{10}) by EPA Victoria, EPA Tasmania, CSIRO and CFA. A summary of the data available is shown in Table 3.

Additional continuous air quality monitoring data sets relevant for the meta-analysis are available:

- Continuous data of criteria pollutants and $PM_{2.5}$ collected by the Latrobe Valley Air Monitoring Network (LVAMN) at Rosedale South and Jeeralang Hill (before, during and after event)
- Air quality data collected at Moe by EPA Victoria until 2009
- Air quality data collected at Morwell East by EPA Victoria from February 2012 until May 2013
- Air quality data collected at Wangaratta by EPA Victoria from December 2006 until March 2007
- $PM_{2.5}$ and ozone data collected at Ovens, VIC by CSIRO from December 2006 until June 2008
- Long-term air quality data collected at Traralgon AMS since 1981

These data sets have not been included in the database. Some of the data sets have been used in the air quality assessment (see section 4.1.).

Table 2 Continuous air quality data collected for the Hazelwood mine fire. Methods are described in Appendix A.

ORGANISATION	LOCATION	COMPOUNDS MEASURED[1]	MONITORING EQUIPMENT	AVERAGING PERIOD	START OF MEASUREMENTS	END OF MEASUREMENTS
EPA Victoria	Morwell South AMS[3]	Indicative $PM_{2.5}$	DustTrak	Continuous[2]	13/02/14	19/02/14
		CO,	Infrared absorption spectrometry	Continuous	19/02/14	On-going
		SO_2,	Pulsed fluorescence spectrometry	Continuous	19/02/14	On-going
		$PM_{2.5}$, visibility (API)	Beta attenuation monitor	Continuous	19/02/14	
		NO_2,	Chemiluminescence	Continuous	6/03/14	
		O_3	UV absorption photometry	Continuous	6/03/14	
EPA Victoria	Morwell East AMS	API, $PM_{2.5}$	Beta attenuation monitor	Continuous	13/02/14	On-going
		CO	Infrared absorption spectrometry	Continuous	19/02/14	On-going
		SO_2	Pulsed fluorescence spectrometry	Continuous	19/02/14	
EPA Victoria	Traralgon AMS	$PM_{2.5}$, PM_{10},	TEOM	Continuous	On-going	On-going
		NO_2,	Chemiluminescence	Continuous	28/02/14	On-going
		O_3,	UV absorption photometry			
		SO_2,	Pulsed fluorescence spectrometry			
		CO	Infrared absorption spectrometry			
EPA Victoria	Kernot Hall	Indicative $PM_{2.5}$	DustTrak	Continuous	21/02/14	3/03/14
	St Luke's Church	Indicative $PM_{2.5}$	DustTrak	Continuous	5/03/14	15/03/14
	Helen St	Indicative $PM_{2.5}$	ADR-1500	Continuous	20/02/14	27/02/14
EPA Victoria	Churchill	Indicative $PM_{2.5}$	ADR-1500	Continuous	6/03/14	On-going
	Moe[4]	Indicative $PM_{2.5}$	ADR-1500	Continuous	28/02/14	On-going
CSIRO	Morwell South (Elgin St/Chapel St)	$PM_{2.5}$	E-sampler	Continuous	3/03/14	28/03/14
CSIRO[3]	Morwell East AMS	$PM_{2.5}$	E-sampler	Continuous	28/02/14	28/03/14
CSIRO	Traralgon AMS	$PM_{2.5}$	E-sampler	Continuous	20/02/14	28/03/14
EPA Tasmania[5]	BLANkET drive	Indicative PM	DustTrak	Continuous		
CFA	Kerrie St	CO	Area RAE	Continuous	16/02/14	21/02/14
	Morwell Bowling Club	CO	Area RAE		16/02/14	22/02/14
	Keegan St	CO	Area RAE		15/02/14 22/02/14	16/02/14 5/03/14
	Maryvale Crescent Preschool	CO	Area RAE		14/02/14 22/02/14	16/02/14 5/03/14
	Police Station	CO	Area RAE		16/02/14	5/03/14
	Sacred Heart Primary	CO	Area RAE		12/02/14	3/03/14

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[1] Indicative means determined using a non-gravimetric method

[2] Continuous is more frequent than 5 minutes

[3] Operational at Morwell Bowling Club until 6 October and relocated to Maryvale Crescent Preschool, being operational on 7 October 2014

[4] Monitor temporarily located at Morwell South AMS

[5] Data not included in database

3.3 Discrete air quality monitoring

Table 4 details the data set of air quality measurements that are included in the data base.

Available data that has not been included in the data base are:

- Silica samples collected on PM_{10} filters on a 6-day sampling cycle between 28/02/14 and 26/03/14 at Morwell South AMS. These samples were below the detection limit of 0.003 mg cm^{-2}.
- Silica samples collected on $PM_{2.5}$ filters on a 6-day sampling cycle from 9/04/14. These samples were below the detection limit of 0.003 mg cm^{-2}.
- Four samples of gaseous elemental mercury sampled on carbon traps impregnated with iodide samples were collected for periods of 6-10 days. These data are reported in Appendix B.
-

Table 3 Air quality data sets included in the data base

ORGANISATION	LOCATION	COMPOUNDS MEASURED	AVERAGING PERIOD	START OF MEASUREMENTS	END OF MEASUREMENTS
EPA Victoria	Morwell South AMS[1]	PAHs, PCDD/F, Metals (PM_{10})	24-hours	26/02/14	30/06/15
		Metals (PM_{10} Partisol)	24-hours (27 samples)	28/02/14	26/03/14
		VOCs (canisters)	24-hours (5 samples)	26/02/14	14/03/14
		VOCs (tubes)	7-days	26/02/14	30/06/15
EPA Victoria	Morwell East AMS	VOCs (Canisters)	24-hours (5 samples)	26/02/14	14/03/14
		VOCs (tubes)	7-days	26/02/14	30/06/15
EPA Victoria	Maryvale Crescent Preschool	VOCs (canisters)	24-hours (5 samples)	26/02/14	14/03/14
		VOCs (tubes)	7-days	26/02/14	30/06/15
CSIRO	Morwell South (Elgin St/Chapel St)	VOCs	25-min/hr over 24-hrs	3/03/14	20/03/14
		Carbonyls	24-hours	3/03/14	19/03/14
		Metals ($PM_{2.5}$)	4-7 days	3/03/14	21/03/14
		PAHs, PCDD/F	10-15 days (2 samples)	3/03/14	18/03/14
CSIRO	Morwell East AMS	Metals ($PM_{2.5}$)	7-14 days	28/02/14	14/03/14
	Traralgon AMS	Metals ($PM_{2.5}$)	7-14 days	28/02/14	14/03/14

[1] Operational at Morwell Bowling Club until 6 October and relocated to Maryvale Crescent Preschool, being operational on 7 October 2014

3.4 Water, soil and ash samples

Table 5 details the data set of water, soil and ash measurements that are currently included in the data base.

Data that has not been included in the data due to the analytical laboratory reporting that no compounds were detected include

- halogenated volatiles, mono-aromatic hydrocarbons (MAHs) and solvents for some soil and water samples.
- PAHs for some water samples.
- halogenated volatiles for some ash samples.

Table 4 Water, soil and ash data sets included in the data base

	LOCATION	SAMPLING PERIOD	COMPOUNDS MEASURED
Water	Waterhole Creek	24/02/14 – 4/03/15	metals, CrVI
	Morwell wetlands	24/02/14	metals
	Main drain to Morwell wetlands	4/03/14 – 3/03/15	metals, CrVI
	Latrobe River, Thoms Bridge	10/03/14 – 4/03/15	metals, CrVI
	Hazelwood Pondage, Eel Hole Creek	4/03/14 – 3/03/15	metals, CrVI
	Morwell River upstream of Eel Hole Creek	4/03/14 – 3/03/15	metals, CrVI
	Morwell River downstream of Eel Hole Creek	4/03/14 – 3/03/15	metals, CrVI
	Residential water tank	24/02/14 – 3/04/14	metals
	Traralgon Golf Course dam	4/03/14	metals
	Lake Narracan	11/03/14 - 7/04/14	metals
Soil	Willis Ct.	18/02/14 – 3/03/15	metals, PAHs
	Morwell CFA Station	24/02/14 – 4/03/15	metals, PAHs
	Davey St.	24/02/14	metals, PAHs
	Morwell East AMS	24/02/14 – 4/03/15	metals, PAHs
	Tangil East Rd & Latrobe River	25/02/14	metals, PAHs
	Traralgon Golf Club	25/02/14 & 4/03/14	metals, PAHs
	Keegan St. Reserve	10/03/14	metals, PAHs
	Thoms Bridge	10/03/14 – 4/03/15	metals, PAHs
	Lake Narracan	11/03/14 – 7/04/14	metals, PAHs,
Ash	Willis Ct.	18/02/14 (sediment ash) 3/03/14	metals, PAHs, MAHs
	Morwell CFA Station	3/03/14	metals, PAHs, MAHs
	Morwell East AMS	3/03/14	metals, PAHs, MAHs
	Wallace St.	12/03/14 13/03/14	metals, PAHs, MAHs
	Morwell Football Club	13/03/14	metals, PAHs, MAHs
	Club Astoria, Maryvale Crescent	13/03/14	
	Ash		metals, PAHs, MAHs
	Floor sweepings		metals, PAHs, MAHs
	Benches		metals, PAHs
	Morwell Bowling Club	13/03/14	metals, PAHs, MAHs
	Hazelwood Road	18/03/14	metals, PAHs, MAHs
	Dust residue	14/11/14	PAHs

3.5 Miscellaneous- satellite data,

Satellite data provides important information contributing to the meta-analysis of the Hazelwood mine fire. This data is valuable for assessing smoke plume dispersion.

Of relevance to the Hazelwood meta-analysis are images and data of fire hotspots that can be retrieved from Sentinel, the Australian national bushfire monitoring system. Other relevant images are of smoke and land cover available from NASA MODIS website from the Image Gallery which collates MODIS images from other websites (http://modis.gsfc.nasa.gov/gallery/index.php#), the NASA Earthdata website (https://earthdata.nasa.gov/ e.g. Figure 1) where the interactive tool allows the selection of locations and times for which data can be downloaded and the NASA Earth Observatory website (http://earthobservatory.nasa.gov/).

On 7 July 2015, the Japan Meteorological Agency (JMA) began operation of Himawari-8, a geostationary satellite that supports weather monitoring and forecasting operations over East Asia, Southeast Asia, Australia and New Zealand. It takes and image every ten minutes and provide valuable data on fires and smoke plume dispersion. This information will provide valuable information for any future fire events. Figure 2 gives an example of an image capturing a volcanic eruption showcasing the high resolution imagery provided by Himawari-8.

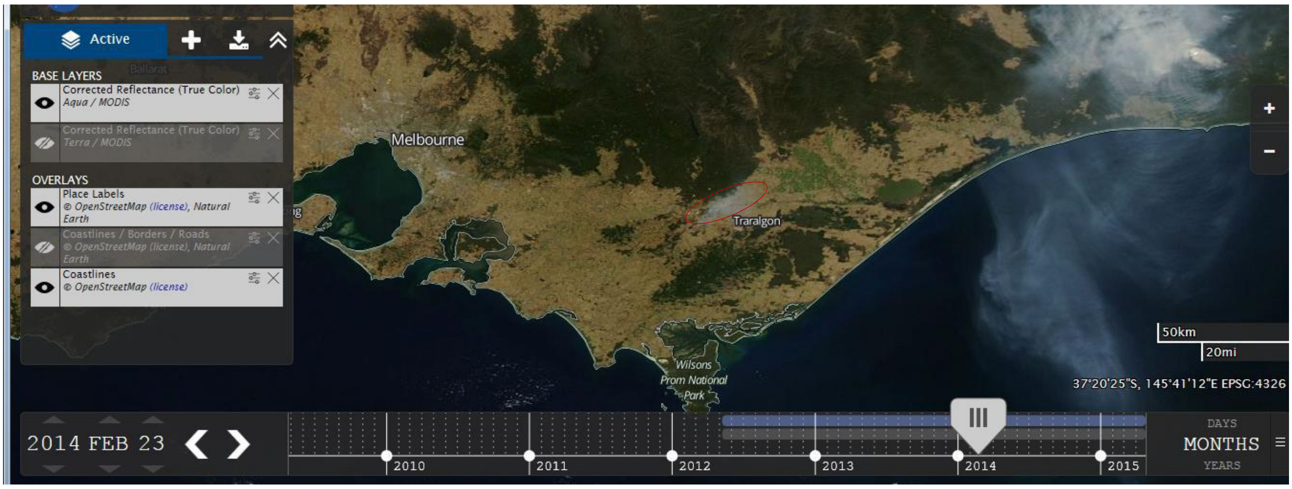

Figure 1 Image of the smoke plume from the Hazelwood mine fire on 23 February 2014 retrieved from the NASA EarthData website (shown in red). The interactive tool allows the selection of locations and times for which data can be downloaded.

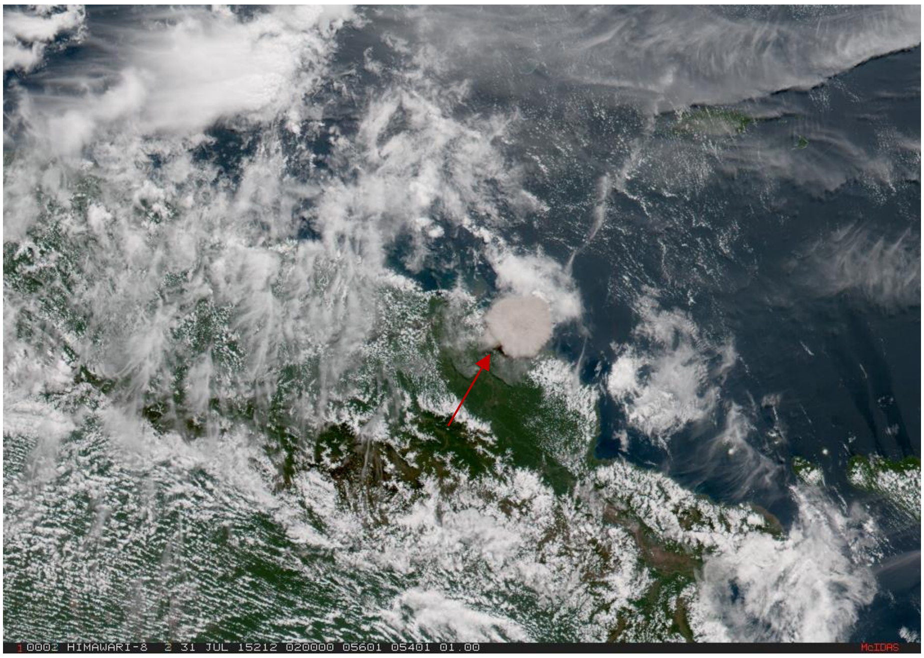

Figure 2 Himawari-8 satellite image of the eruption of Manam volcano near Papua New Guinea

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4 Information products

A large number of uncontrolled coal fires that have burned for more than 50 years have been reported *(Nolter and Vice 2004; Stracher and Taylor 2004)*. In the US alone it is estimated that 150 uncontrolled surface and underground coal fires are still burning *(Finkelman 2004)*. In Australia, the 'Burning Mountain', a large coal seam in New South Wales has been smouldering for more than 6000 years *(Ellyett and Fleming 1974)*. However the Hazelwood mine fire could be considered unique as it involved an open cut mine located very close to a populated centre.

Despite the extent of uncontrolled coal fires, limited research has focused on the pollutants emitted from coal fires and the human health impacts. Recent research studies have investigated exhaust gases in vents from underground coal mine fires in the US *(Hower et al. 2009; O'Keefe et al. 2010; O'Keefe et al. 2011; Engle et al. 2012)*. The results have shown a large spatial and temporal variability in concentrations of gases, some indicating incomplete combustion of the coal and some suggesting a more complete combustion. During incomplete combustion, elevated levels of benzene and aliphatic and aromatic compounds were measured. In general, studies have mainly focused on greenhouse gas pollutants such as carbon dioxide and methane or other toxic gases, but information on particulate matter emissions is scarce.

The large data set collected during the Hazelwood mine fire by various parties to assess the impact on air, water, soil and human health significantly enhanced our understanding of the environmental and health impacts from such an event. This document presents a brief summary of the outputs from the study that are aimed to improve the advice and response to communities in any future similar events.

4.1 Combustion and emission rates

The extent of a coal mine fire and its impact on the environment and human health is dependent on

- the amount of coal that was burned,
- the conditions (e.g. oxygen levels, combustion temperature) under which the coal was burning,
- the elemental composition of the coal
- the moisture content of the coal
- the density/structure of the coal

It is important to understand how much coal burned, how it burned and what the coal composition is in order to assess the release of likely pollutants of concern into the environment. Characterisation of emission rates of key pollutants is also critical for both air quality forecasting and community exposure modelling.

4.1.1 Daily coal consumption by the fire

The amount of coal that was consumed by the fire each day is important in order to assess emissions of pollutants into the atmosphere. A range of indirect techniques exist that can estimate coal consumption for a given fire. These include: 1) thermal heat flux derived from airborne thermal infrared (TIR) imagery and satellite imagery *(Engle et al. 2011; Engle et al. 2012; Engle et al. 2012; Huo et al. 2015)*; 2) coal loss estimates reported by coal mine engineers *(van Dijk et al. 2011)*; 3) rate of coal fire advance *(Engle et al.*

2012); and 4) growth rates of areas which have been magnetically reset due to heating above the Curie temperature *(Ide and Orr 2011)*.

In the absence of direct information on the amount of coal that was burned, the daily consumption of coal can be estimated using the thermal imagery taken by CFA on a daily basis during the Hazelwood mine fire.

4.1.2 Burning conditions

The conditions of combustion of the coal fire, in particular combustion temperature and oxygen levels, determine the type and amount of emissions into the atmosphere. In bushfires, the major reaction mechanisms are flaming combustion of volatilised gases and smouldering combustion of the char residue. Coal combustion is primarily a solid-phase combustion where reactions occur on the surface. Due to the higher density and carbon fraction, fire within coal spreads slower but burns hotter. Combustion temperature of coal can reach peaks at around 1000°C *(Rein 2016)*. Resulting from this, coal fires are more frequently accompanied by flames compared to other smouldering fuels. A glowing combustion is expected in the presence of oxygen and a charring combustion in the absence of oxygen. Coal combustion requires a lot of energy to initiate but once initiated it releases twice the amount of energy compared to vegetative fuel.

As combustion temperature and oxygen conditions vary over time and space as the fire progresses, emissions are highly variable. Furthermore firefighting efforts (e.g. use of water and foam) would impact on the burning conditions and hence smoke emissions. Thermal imagery and photography will provide some information on the conditions under which the coal burned.

Burning conditions also impact on plume rise and hence smoke dispersion and impacts on nearby communities. Plume height is strongly influenced by fire intensity and the heat and moisture released from the fire *(Heilman et al. 2014)*. During the coal mine fire, there was no fire-induced convection that would rapidly transport emissions upward and effectively transport pollutants in the free troposphere. Dispersion of pollutants emitted from the coal mine fire was low resulting in high pollution impact on the Morwell community. The impact on the Morwell community was mainly driven by meteorological conditions in particular wind speed and wind direction.

4.1.3 Elemental composition of the coal

Research has shown that elements contained within the coal can be mobilised during burning processes and be released into the environment *(Finkelman 2004)*. Some volatile elements that have been found to be enriched in coal deposits include arsenic, fluorine, mercury and selenium. These elements can be released into the environment during burning of coal beds. They can impact on human health, be adsorbed on crops and taken up by livestock.

Victorian brown coal is mainly composed of carbon with low levels of sulphur and nitrogen and trace levels of minerals and heavy metals. The composition of brown coal from the Gippsland basin is shown in Table 6 and indicates the variability in composition of brown coals across the different coal seams.

Table 5 Composition of brown coals from the Gippsland basin *(Durie 1991)*

Location	Yallourn	Gelliondale	Loy Yang	Morwell	Flynn	Gormandale
Moisture (%)	66.5	64.5	62.8	61.3	64.1	55.1
Ash (%db)	1.7	5.7	1.3	3.0	1.3	1.6
Volatile matter (%db)	50.3	49.4	49.8	48.3	50.6	51.5
Fixed carbon (%db)	48.0	44.9	48.9	48.7	48.1	46.9
Minerals and non-mineral inorganics (%db)	1.3	3.3	1.4	2.0	1.0	1.3
Fe	0.53	0.07	0.04	0.21	0.03	0.13
Ca	0.12	1.44	0.04	0.54	0.02	0.09
Mg	0.20	0.46	0.07	0.31	0.12	0.12
Na	0.09	0.35	0.14	0.09	0.28	0.04
Cl	0.11	0.31	0.18	0.07	0.35	0.04
S	0.26	0.73	0.31	0.30	0.32	0.73
Nitrogen (% dmif)	0.57	0.48	0.59	0.60	0.50	0.53
Oxygen (% dmif)	26.9	26.6	25.8	25.0	26.2	25.7

db=dry basis; dmif=dry mineral and non-mineral inorganic free basis

4.1.4 Knowledge gaps

Currently there are no available data in the literature on emission characterisation from open-cut coal mine fires. Our understanding of the combustion of solid fuels such as Victorian brown coal has been focused on burning in furnaces and industrial processes and open combustion is a relatively recent area of concern. Experience with open burning of biomass (vegetation) suggests that the combustion process itself has a larger influence on emissions than the composition of the fuel. In particular there is a significant difference between emissions from biomass fuel burned in laboratory conditions to fuel burned in more field-like conditions. Application of laboratory-derived emission factors in the modelling activities may result in significant uncertainties in model outcomes.

To determine emission factors for Victorian brown coal during open combustion a series of experimental burns is required that will replicate as closely as possible the conditions under which the mine fire occurred. Besides emission factors, these experimental burns would provide information on the concentration of hazardous pollutants in the smoke and signature chemical compounds that could be used to identify impact from open burning of Victorian brown coal in a future scenario. In addition these experiments would provide information on the composition of the residue after complete and incomplete combustion. The experiments would also provide information on the difference between fly ash, bushfire ash and mine fire ash which would guide the identification of samples of ash collected from homes during the fires.

4.2 Air quality monitoring and assessment

Air quality data was collected prior, during and after the Hazelwood mine fire and the following sections will review the timeline of the event and monitoring, discuss the air quality impacts in the context of other major pollution events and suggest a monitoring approach adapted to an emergency event of this nature. A better understanding of the impact of the Hazelwood mine fire on air quality and community exposures will improve the advice and response provided to communities in any future similar incidents.

4.2.1 Timeline of events and monitoring

The Hazelwood mine fire started on 9 February 2014 when embers from nearby bushfires spotted into the mine. Due to strong south-westerly winds with wind gusts up to 74 km/h, the fire spread rapidly and extensively. By the morning of 10 February 2014, the fire had spread across three levels in the northern batters over approximately 2 km length, in the eastern batters over approximately 1 km length and on the floor mine over an area of approximately 0.25 km^2 (Figure 3) (http://report.hazelwoodinquiry.vic.gov.au/). On 13 February 2014 the Hazelwood mine fire was declared to be a HazMat incident.

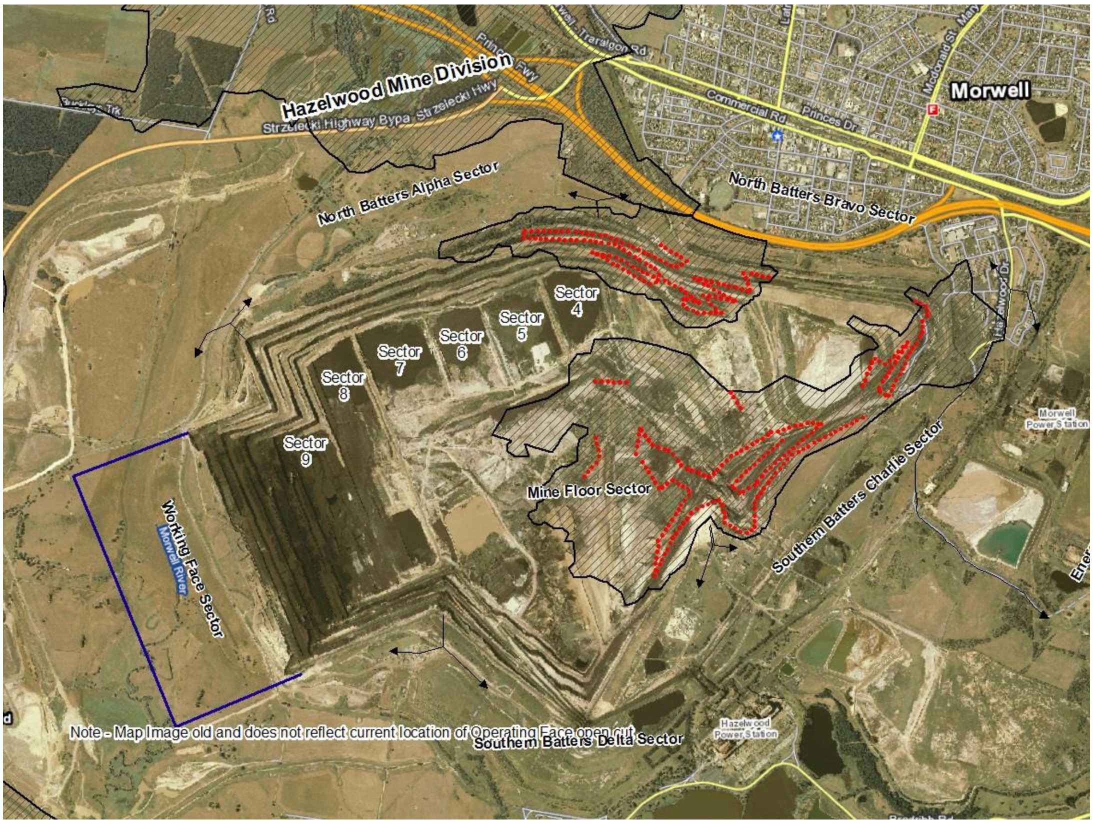

Figure 3 Map of the Hazelwood mine. Red colour indicates the batters on fire.

The extent of the smoke plume from the Hazelwood mine fire and the adjacent bushfires could be clearly identified from NASA's MODIS satellite images (Figure 4).

Figure 4 Image of the smoke plume from the Hazelwood mine fire on 10th February 2014 (top) and 23rd February 2014 (bottom) retrieved from the NASA EarthData website (https://earthdata.nasa.gov/). It is not possible to distinguish between smoke from the coal fire and bushfire at this scale.

The Hazelwood mine fire was declared under control on 10 March 2014 and declared safe on 25 March 2014, after burning for 45 days. Figure 5 shows the timeline of the event and the environmental monitoring carried out during the Hazelwood mine fire. Community monitoring of CO and PM started approximately four days after the fire entered the coal mine with more extensive community monitoring starting within the 2nd week of the fire.

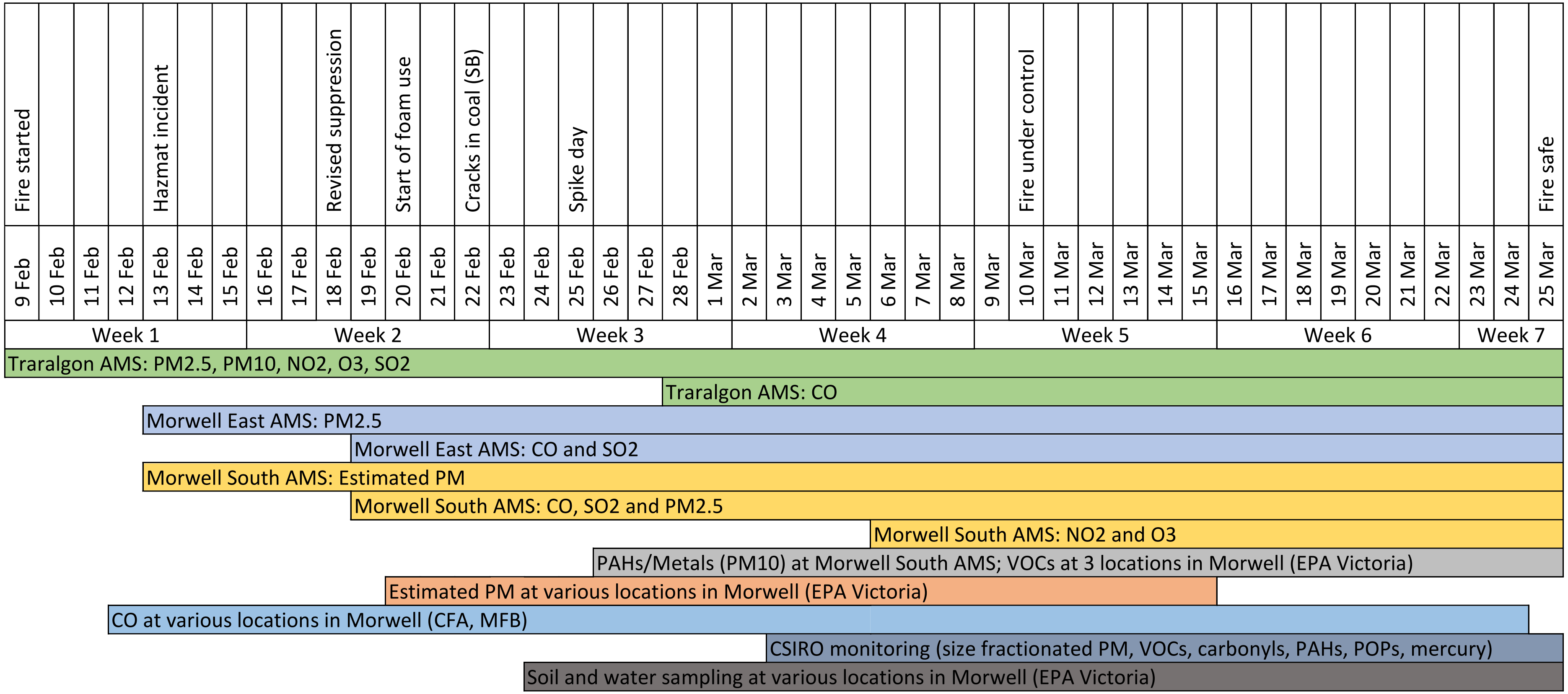

Figure 5 Timeline of events and monitoring of the Hazelwood mine fire. AMS is air monitoring station, CFA is Country Fire Authority, MFB is Metropolitan Fire Brigade

4.2.2 Long-term air quality monitoring in Traralgon

Air quality in the Latrobe Valley has been monitored with modern techniques since 1981 and the ten-year PM_{10} data measured at the Traralgon air monitoring station (AMS) are shown in Figure 6. While the four power stations, Yallourn, Hazelwood and Loy Yang A and B are likely to add to the general background PM_{10} concentrations, the data shows that seasonal bushfires have the largest impact on ambient PM_{10} concentrations. Highlighted in Figure 6 are the impacts from the 2006/07 Eastern Victoria Great Divide bushfires that burned an area of ~ 1.3 million ha over 69 days, the 2009 Black Saturday bushfires and the 2014 East Gippsland fires including the Hazelwood mine fire. These were the periods when PM_{10} concentrations exceeded 50 µg m^{-3}, for 11 days in 2006/07, 2 days in 2009 and 3 days in 2014. Daily PM_{10} concentrations exceeded 50 µg m^{-3} on several occasions during autumn (March-May) most likely due to smoke from prescribed burns.

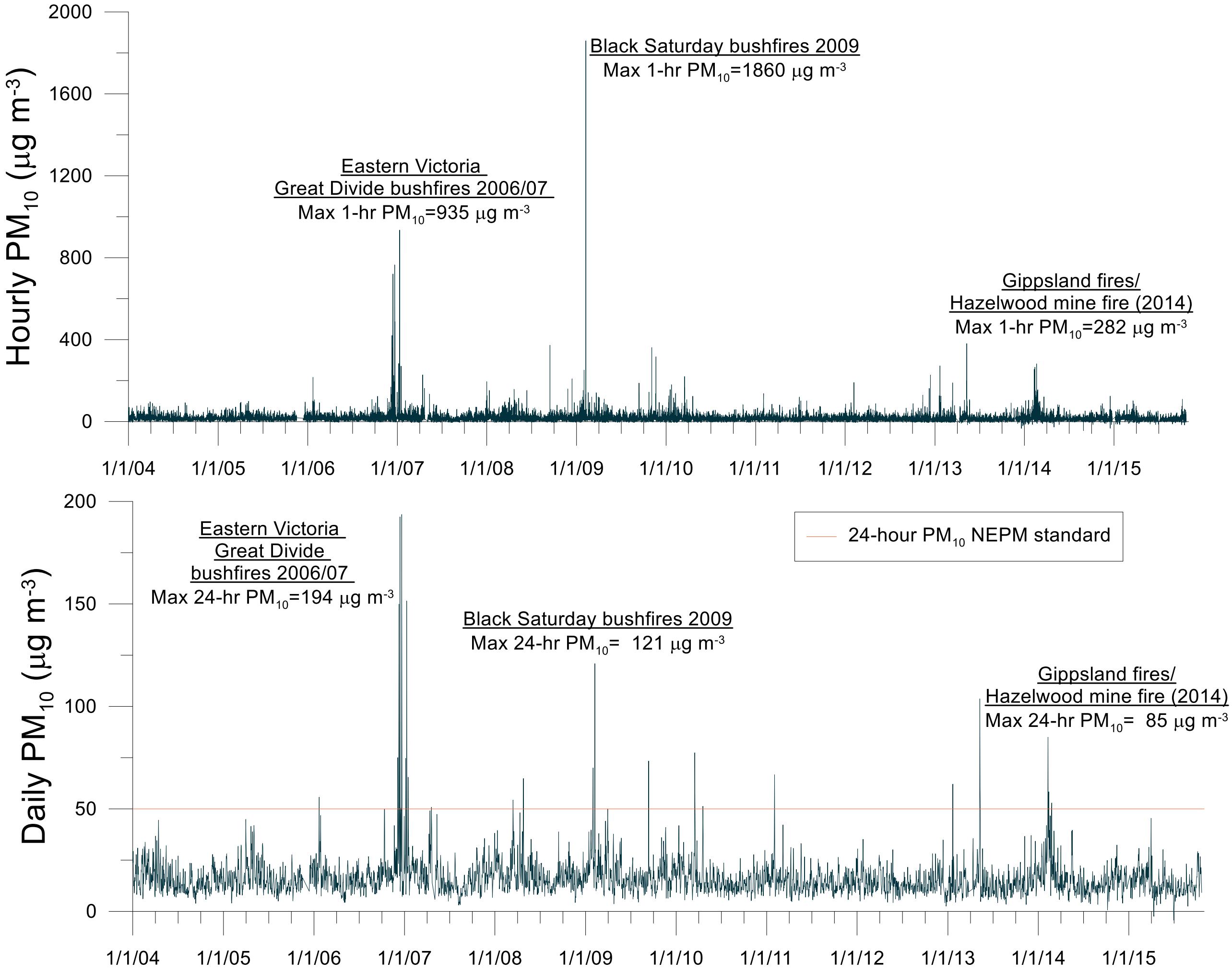

Figure 6 Ten-year time series of hourly and daily PM_{10} concentrations at Traralgon AMS

4.2.3 Air quality monitoring results

This section summarises the major results from the air quality monitoring. More detailed information is provided in *Reisen et al. (2015)*.

Continuous measurements of criteria pollutants (PM, CO, ozone (O_3), nitrogen dioxide (NO_2) and sulfur dioxide (SO_2)) were conducted at three air monitoring stations during the Hazelwood mine fire, i.e. Morwell South AMS, Morwell East AMS and Traralgon AMS. As monitoring of criteria pollutants in Morwell did not start until 3 to 10 days after the fire, peak concentrations observed during the initial phase of the fire have not been measured.

Monitoring of air toxics (e.g. VOCs, carbonyls, polycyclic aromatic hydrocarbons (PAHs), dioxins and furans (PCDD/F) and metals) started on 26 February, when particle and CO concentrations had already considerably subsided. Therefore it is highly likely that peak concentrations would have been higher during the initial phase of the fire.

Particulate matter

Figure 7 shows the 24-hour $PM_{2.5}$ concentrations measured during the Hazelwood mine fire. Highest $PM_{2.5}$ concentrations were observed at Morwell South AMS with a maximum hourly $PM_{2.5}$ concentration of 1349 $\mu g\ m^{-3}$ and a maximum daily concentration of 731$\mu g\ m^{-3}$, approximately 30 times higher than the 24-hour advisory National Environment Protection Measure for Ambient Air Quality (Air NEPM) for PM2.5 of 25 $\mu g\ m^{-3}$ and and 3 times greater than the community Smoke, Air Quality and Health standard for PM2.5 category of Hazardous Extreme [1]. $PM_{2.5}$ concentrations were particularly high in February with a significant decrease in March. $PM_{2.5}$ concentrations were significantly higher in Morwell South AMS, but exceedances of the 24-hour advisory Air NEPM were also observed in Traralgon AMS (8 days), located approximately 13 km from the fire, where a maximum daily $PM_{2.5}$ concentration of 65.6 $\mu g\ m^{-3}$ was recorded and the concentrations were in the Unhealthy All category of the graduated standards[1] [2]Considering the elevated $PM_{2.5}$ concentrations measured at Traralgon on 9th and 12th February, it is expected that higher concentrations were likely to have occurred between 9th and 12th February at Morwell South.

$PM_{2.5}$ concentrations were highly variable during the day. Elevated concentrations occurred mainly in the afternoon/early evening and were strongly associated with south-westerly winds.

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[1] **The Community Smoke Air Quality & Health Standard (December 2015)** http://files.portal.em.vic.gov.au/refdocs/EMK-01.19-Community-SAQH-Protocol.pdf

[2] **Hazelwood Coal Mine Fire –PM2.5 Health Protocol DOH.0005.001.0151 Endorsed 13 March 2014**

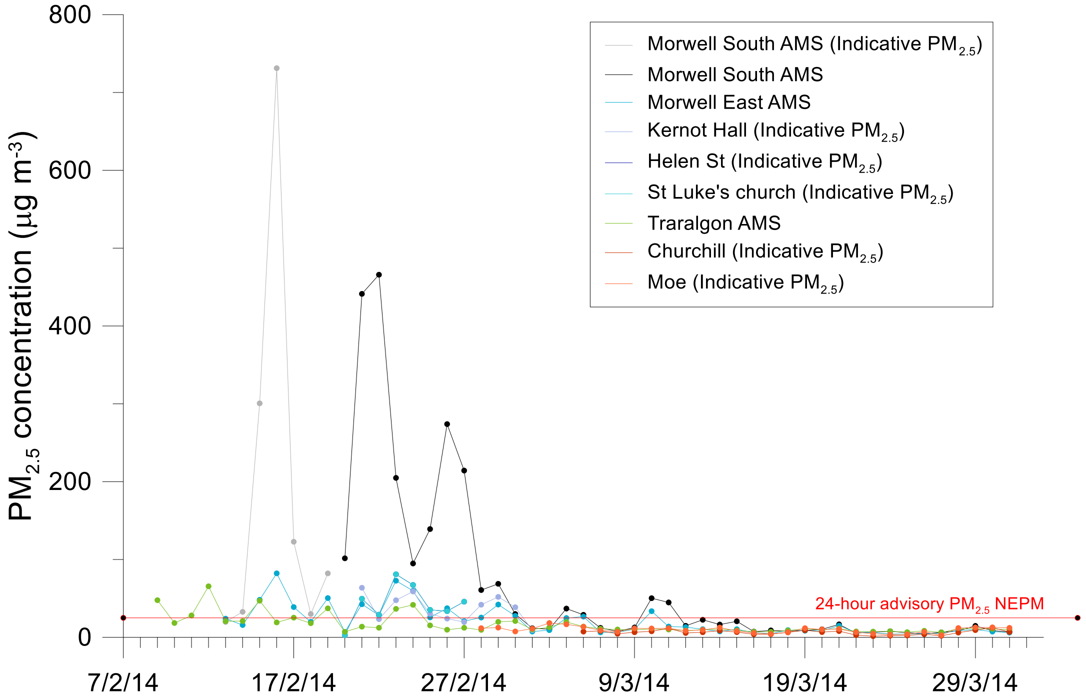

Figure 7 Daily $PM_{2.5}$ concentrations measured during the Hazelwood mine fire

Carbon monoxide

Figure 8 shows the hourly CO concentrations measured at various locations in Morwell. Elevated CO levels were primarily observed in the early stages of the fire. The maximum 8-hour averaged CO concentration was measured at 33 ppm in Morwell South, approximately 4 times higher than the Air NEPM standard and slightly higher than the AEGL-2 graduated guideline of the Standard for Managing Exposure to Significant Carbon Monoxide Emissions for CO[3][4]. No exceedances of the 8-hour Air NEPM standard for CO were observed at either Morwell East AMS (max=2.9ppm) or Traralgon AMS (max=0.7ppm). The highest impact was observed in Morwell South AMS with elevated concentrations occurring primarily late afternoon/early evening and under south-westerly winds.

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[3] the **Standard for Managing Exposure to Significant Carbon Monoxide Emissions (July 2015)** http://files.portal.em.vic.gov.au/refdocs/EMK-01.19-CarbonMonoxideEmissions.pdf

[4] Latrobe Valley Coal Fires Carbon Monoxide Response Protocol Department of Health (Version 1.0) 27 February 2014

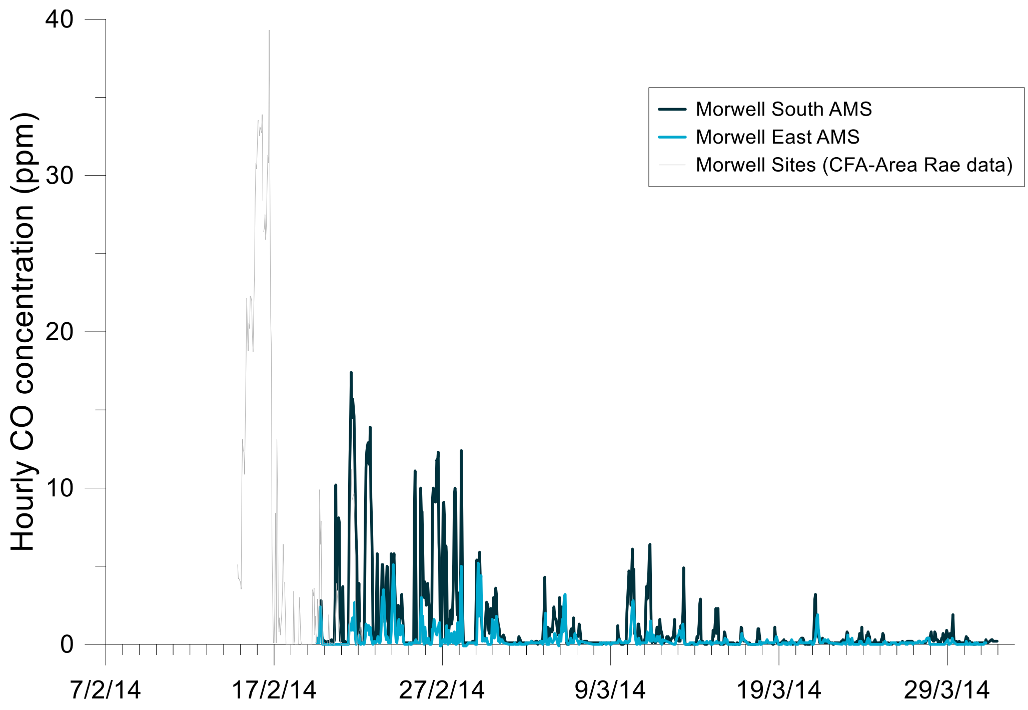

Figure 8 Hourly CO concentrations measured during the Hazelwood mine fire. Morwell sites represent those sites where monitoring was done by CFA (see Table 3)

Other criteria pollutants

Concentrations of O_3, NO_2 and SO_2 remained within air quality guidelines and no significant impact from the Hazelwood mine fire was observed.

Volatile organic compounds

Volatile organic compounds (VOCs) are are a large group of carbon-based compounds that are volatile at room temperature.

The time series of the 24-hour concentrations of benzene measured at three locations in Morwell (i.e. Morwell South AMS, Morwell East AMS and Maryvale Crescent Preschool) is shown in Figure 9. As for PM and CO, concentrations at Morwell South AMS were significantly higher than those observed at Morwell East AMS. Benzene was the only measured VOC that exceeded air quality guidelines. While concentrations of formaldehyde were highest in February at Morwell South AMS, they never exceeded the 24-hour air quality Air Toxics NEPM guideline of 40 ppb.

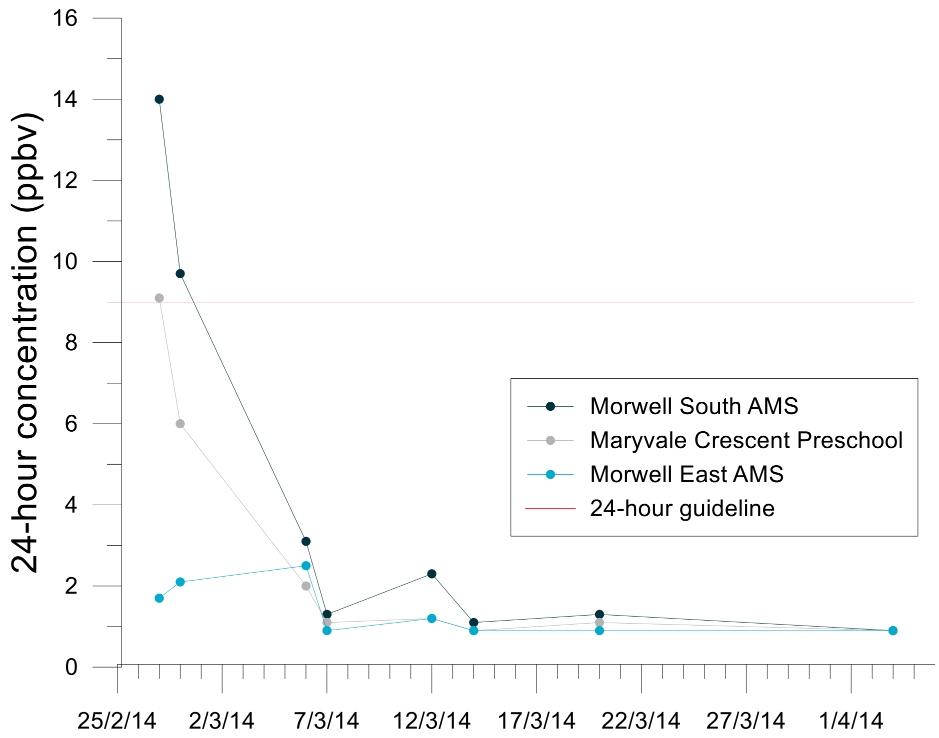

Figure 9 Time series of 24-hour concentrations of benzene at Morwell South AMS, Maryvale Crescent Preschool (MCP) and Morwell East AMS

PAHs and dioxins/furans (PCDD/F)

Measurements of particle bound PAHs collected on PM_{10} filters between 26 February and 20 March showed a significant decrease in PAH concentrations over time in particular between February and March. Major particle-bound PAHs included chrysene, benzo(a)anthracene and benzo(e)pyrene, followed by benzo(a)pyrene, benzo(b)fluoranthene and pyrene. Fluorene was an important contributor to total PAH concentrations for samples collected in March.

The 2-week PAH samples that were collected in March on both filters and PUFs showed higher concentrations of semi-volatile PAHs compared to particle-bound PAHs. The major semi-volatile PAHs included naphthalene, phenanthrene and fluorene.

Dioxins and dioxin-like compounds are regarded as highly toxic and persistent organic pollutants. They include polychlorinated dibenzo-*p*-dioxins (PCDDs), polychlorinated dibenzofurans (PCDFs) and polychlorinated biphenyls (PCBs). The toxic equivalency (TEQ) of PCDD/F of 24-hour PM_{10} samples collected at Morwell South AMS using a High-Volume sampler was calculated. The presented TEQ is based on toxic equivalency factors (TEFs) set by the World Health Organisation (WHO)-International Programme on Chemical Safety in 2005. The TEF expresses the toxicity of PCDDs, PCDFs and PCBs in terms of the most toxic dioxin, e.g. 2,3,7,8-tetrachlorodibenzo-*p*-dioxin (2,3,7,8-TCDD). The TEQ results from the product of the concentration and individual TEF values of each congener. Similar to PAHs there is a significant decrease in concentrations of TEQ between the samples collected in February and March. The highest TEQ was measured at 40 fg m^{-3}. As a comparison TEQ values of filter samples collected at Aspendale in winter and summer (3-year average) were 1.2 and 4.3 fg m^{-3} respectively, while TEQ of filter samples collected during the fire season in Darwin was 1.2 fg m^{-3}. Further discussion of these data is presented in Section 4.4.

Metals

Measurements of metals were performed on PM_{10} filter samples collected at Morwell South AMS over a 24-hour period on a one-day in-six cycle. The major metals identified included calcium (Ca), sulphur (S), magnesium (Mg), silicon (Si), sodium (Na), iron (Fe) and aluminium (Al) followed by titanium (Ti), potassium (K), strontium (Sr), zinc (Zn) and manganese (Mn). This is consistent with the composition of Victorian brown coal.

4.2.4 Discussion of air quality monitoring results

The Hazelwood mine fire burned for 45 days, during which time the population was periodically exposed to elevated levels of air pollutants. The event was unprecedented not only due to the intensity of the event, but also due to the close proximity of the population to the Hazelwood mine fire. While bushfires can have a major impact on air quality, the primary pollutant of concern for population exposures is particulate matter. Most research studies have found that levels of fine particulate matter were consistently elevated downwind of bushfires, while levels of other pollutants varied little or showed increases that were much lower than Air NEPM air quality standards or guidelines *(Reisen and Brown 2006)*. This is likely due to dispersion in buoyant plumes and dilution during transport when clean air is entrained in the smoke plume resulting in lower concentrations downwind where populations are exposed.

In the case of the Hazelwood mine fire, there was no immediate fire threat to the Morwell community which meant that population exposure to smoke was at much closer proximity to the fire front than would be the case for bushfires.

The air quality data showed that the smoke impact was localised with higher pollutant levels measured in Morwell South (approximately 500 m from the fire) than in Morwell East, located approximately 3 km from the fire. The air quality was especially impacted in February, with a significant decrease in pollutant concentrations observed in March.

Major air pollutants of concern included PM, CO, benzene and PAHs due to the elevated concentrations measured during the Hazelwood mine fire and will be further discussed below.

Particulate matter

During the Hazelwood mine fire $PM_{2.5}$ concentrations were very high and exceeded air quality guidelines on multiple occasions. While particle levels were elevated during the Hazelwood mine fire, the long-term air monitoring in Traralgon showed that this was not a unique event that caused elevated particle levels. In fact elevated particle concentrations were previously observed during the 2006/07 Eastern Victorian Great Divide bushfires and during the 2009 bushfires, with higher daily and hourly PM_{10} concentrations than those observed in Traralgon AMS during the Hazelwood mine fire.

Since the biggest impact on particle levels was observed in Morwell South, the hourly $PM_{2.5}$ concentrations measured in Morwell South AMS during the Hazelwood mine fire are compared against those measured in Northeast Victoria during the 2006/07 Eastern Victoria Great Divide bushfires (Figure 10). Wangaratta and Ovens are towns located in Northeast Victoria that were severely impacted by the 2006/07 bushfires. In both instances monitoring started a few days after the fire clearly shown by the elevated concentrations at the start of the monitoring periods. Both events were of similar duration and magnitude with slightly higher maximum hourly and daily $PM_{2.5}$ concentrations at Ovens, VIC than at Morwell South AMS. However the number of hours at $PM_{2.5}$ concentrations greater than 250 $\mu g\ m^{-3}$ was higher at Morwell South AMS.

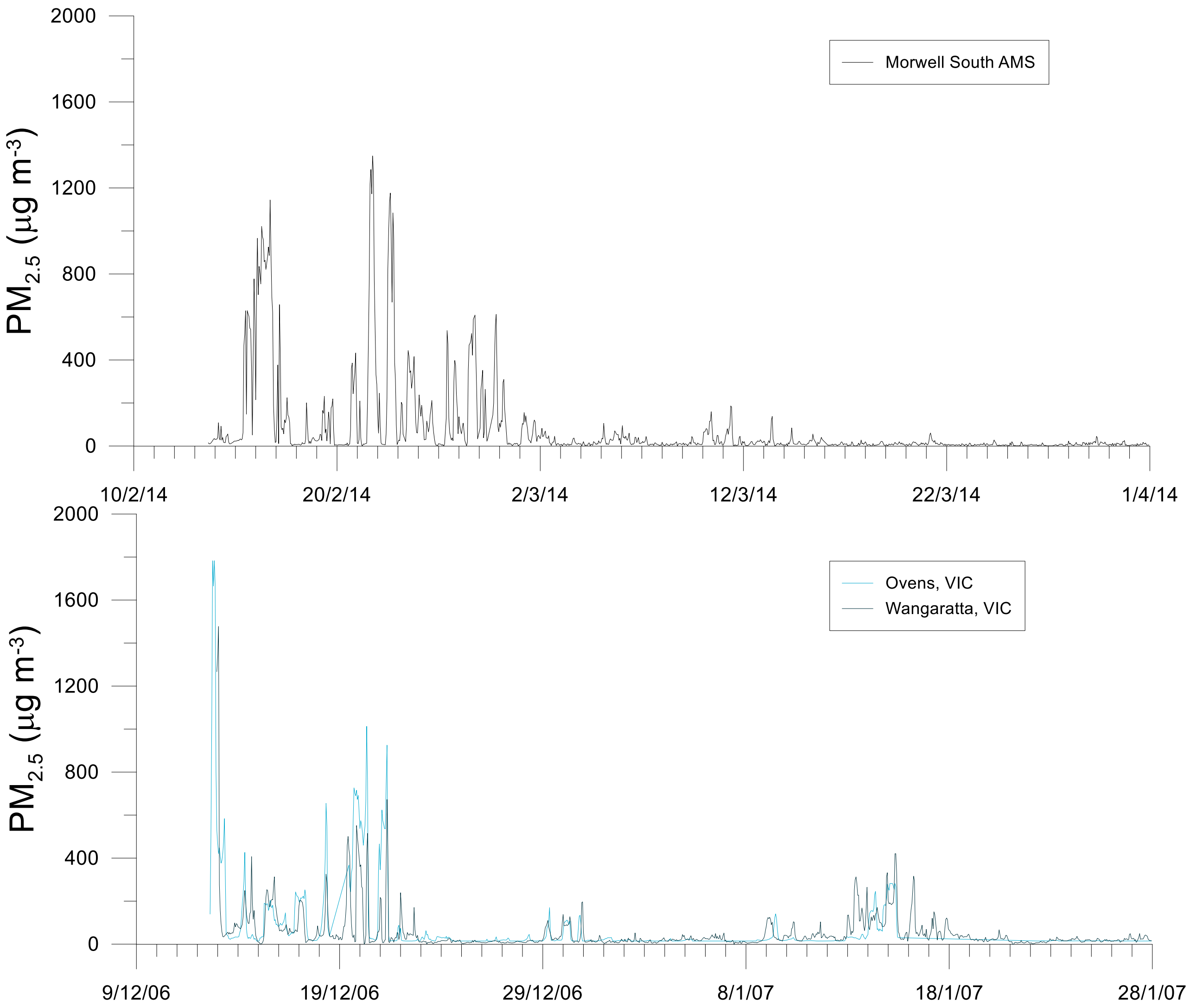

Figure 10 Time series of hourly $PM_{2.5}$ concentrations measured at Morwell South during the Hazelwood mine fire (top panel) and at Ovens, VIC and Wangaratta, VIC during the 2006/07 Eastern Victoria Great Divide bushfires (bottom panel). Measurements at Wangaratta were done by EPA Victoria (https://www.epa.vic.gov.au/about-epa/publications/1187). PM2.5 was measured at Ovens by DustTrak calibrated with site specific gravimetric mass measurements (Reisen et al. 2011b).

Carbon monoxide

One of the major differences between the Hazelwood mine fire and other major bushfire events was the fact that CO concentrations measured within the community were elevated. During the event the highest ever 8-hour average CO concentrations measured by EPA Victoria was recorded. In general, concentrations of CO measured in downwind communities during wildfire smoke remain low. During the 2006/07 bushfires which had a significant impact on Melbourne, maximum hourly CO concentrations of 4.5 ppm were measured using infrared absorption spectrometry *(Keywood et al. 2015)*, in comparison to maximum hourly CO concentration of 39 ppm measured in Morwell also measured using infrared absorption spectrometry. At a staging area in Jamieson in Northeast Victoria, hourly concentrations of 17.3 ppm were measured during the 2006/07 bushfires, while CO concentrations on the fire ground were much higher in some instances. Based on a review of the scientific and technical literature, a few studies reported enhancements of CO concentrations above air quality guidelines resulting from impacts of plumes from wildfires *(Aditama 2000; Kunii et al. 2002; Konovalov et al. 2011)*.

Air toxics

Measurements of air toxics only commenced on 26 February 2014, when concentrations of CO and $PM_{2.5}$ had already considerably subsided. As a result reported peak concentrations are likely not to be representative of the fire incident period.

Weekly average concentrations of benzene were higher at Morwell South compared to those measured at Ovens, VIC during the 2006/07 bushfires. They were also higher than benzene concentrations measured in Melbourne during the 2008/09 indoor air study *(Cheng et al. 2015)*. The benzene to toluene ratio at Morwell South was 2.2, which is higher than the ratio of 0.8 measured at Ovens, VIC during the 2006/07 bushfires *(Meyer et al. 2008)*, but similar to that observed during peat fires *(Blake et al. 2009)* and underground coal fires *(O'Keefe et al. 2011; Engle et al. 2012)*. Benzene to toluene ratios measured on the fire ground during prescribed burns ranged from 0.03 (recorded for lighting crews) to 4.5 (recorded for patrolling crews) *(Reisen and Brown 2009)*. In general benzene to toluene ratios are less than 0.5 in urban areas consistent with traffic related emissions. After the end of the Hazelwood mine fire the ratio of benzene to toluene was similar to that observed in Melbourne and consistent with traffic-related air pollution.

The annual averaged concentration of benzene calculated between February 2014 and February 2015 (which included the fire period) was about twice as high as the annual averaged concentration calculated between April 2014 and April 2015 (which excluded the fire period), but was still below the annual averaged concentration measured in Melbourne in 2006 and below the annual average value listed in the Air Toxics NEPM guideline of 0.003 ppm.

The annual averaged concentrations of B(a)P was especially affected by the fire and exceeded the annual air quality guideline (Air Toxics NEPM) of 0.3 ng m^{-3}. The annual average concentrations measured at Morwell South AMS was approximately twice as high as the annual average concentration measured in Melbourne in 2006.

Metals

Research has shown that elements contained within the coal can be mobilised during burning processes and be released into the environment *(Finkelman 2004)*. Some volatile elements that have been found to be enriched in coal deposits include arsenic, fluorine, mercury and selenium. These elements can be released into the environment during burning of coal beds. They can impact on human health, be adsorbed on crops and taken up by livestock. During the Hazelwood mine fire higher concentrations of cobalt, manganese, selenium, strontium, titanium, vanadium and zinc were measured. Although increased concentrations of these metals were measured during the Hazelwood mine fire, concentrations remained below air quality guidelines.

Summary

Ambient measurements conducted in Morwell and surrounding areas have shown that the Hazelwood mine fire caused increased concentrations in a range of air pollutants resulting in exceedances of air quality guidelines for $PM_{2.5}$, CO, benzene and BaP. The air quality was significantly impacted in February with a decrease in pollutant levels recorded in March. Air quality concentrations dropped to background levels once the fire was declared safe at the end of March. A summary of the air quality data is shown in Table 7. The ambient particle concentrations related to the Hazelwood mine fire were of similar magnitude than those recorded during the 2006/07 Eastern Victoria Great Divide bushfires. However measured concentrations of CO (measured using the standard Infrared absorption spectrometry method) and benzene were higher than those measured during the extensive bushfire event.

Table 6 Concentrations of key air pollutants measured during the Hazelwood mine fire in comparison to background air, urban air and other major air pollution events. The data shows average ± stdev, median, range.

Event	Hourly $PM_{2.5}$ ($\mu g\ m^{-3}$)	Daily $PM_{2.5}$ ($\mu g\ m^{-3}$)	Hourly CO (ppm)	Benzene (ppb)	Formaldehyde (ppb)	B(a)P ($ng\ m^{-3}$)
Morwell South AMS (February 2014)	212±295, 70.1, 0-1349	206±194, 128, 19.8-731	3.7±4.3, 1.9, 0-17.4	9.7-14.0 (24h) 1.9-3.4 (7day)	5.4-7.6	6.4-8.2
Morwell East AMS (February 2014)	37.8±48.5, 17.3, 0.2-328	37.5±21.7, 32.3, 7.1-87.8	0.54±0.90, 0.10, 0-5.1	1.7-2.1 (24h) 0.7-1.0 (7day)	2.3-2.7	NM
Morwell South AMS (March 2014)	17.6±24.3, 9.3, 0-186.5	16.9±15.3, 10.2, 4.6-70.3	0.50±0.94, 0.10, 0-6.4	1.1-3.1 (24h) 0.4-0.8 (7day)	1.4-3.1	0.01-1.8
Morwell East AMS (March 2014)	12.2±17.0, 7.5, 0-192	11.7±9.3, 8.4, 3.5-41.2	0.17±0.50, 0.10, 0-5.2	0.9-2.5 (24h) 0.2-0.3 (7day)	1.4-3.0	NM
Morwell South AMS (Sep-Nov 2014)	6.3±5.2, 6.0, 0-27.6	6.3±2.2, 6.0, 1.9-14.1	0.1±0.2, 0.1, 0-2.1	0.02-0.15 (7day)	NM	<0.006
Morwell East AMS (Sep-Nov 2014)	6.1±7.0, 5.9, 0-145	6.2±2.5, 6.2, 1.3-11.7	0.1±0.1, 0.1, 0-0.7	0.02-0.18 (7day)	NM	NM
Melbourne[1] (Feb/March 2013)	0-27.6	0-13.1	0-0.7	NM	NM	NM
Melbourne 2008/09[2]				0.06-0.72	0.5-3.8	NM
Ovens VIC 2006/07[3]	14.5-1783	14.6-1102	NM	0.03-1.1 (7day)	NM	NM
Aspendale[4] (Fires 2006/07)	12-556		0.06-4.5	NM	NM	NM
Fire ground[5] (work shift exposure)		20-16,000	0.18-120	0.63-81.5	ND-665	ND-1600 (mean of 9.3)
Peat fires (WA)[6]	0.3-106	7.3-17.1		16.9-30.5 (1h)		

[1] EPA Victoria

[2] *Molloy et al. (2012) ; Cheng et al. (2015)*

[3] *Meyer et al. (2008)*

[4] *Keywood et al. (2015)*

[5] *Reisen and Brown (2009) ; Reisen et al. (2011)*

[6] *Blake et al. (2009)*

4.2.5 Outcome

A better understanding of the impact of the Hazelwood mine fire on air quality and community exposures will improve the advice and response provided to communities in any future similar incidents. The air quality assessment is also an important component for the exposure assessment and input into forecasting models (see section 5).

Development of a low-cost sensor network for $PM_{2.5}$ and CO would allow for effective and fast response to a major pollution event. A low-cost sensor network is more flexible, affordable and portable than existing monitoring stations and therefore can more effectively capture the spatial variability and personal exposures during a major pollution event. A 3-tier monitoring is an effective approach to an emergency response as data can be collected immediately once the event occurs and provide essential data to assess emergency warnings. This has also been highlighted as a recommendation of the Hazelwood mine fire inquiry. The 3-tier monitoring would consist of:

1. Quick deployment of hand-held devices that measure key pollutants such as CO and PM and provide indicative but immediate results of the pollution exposure. There is a need to identify fast response equipment that can provide indicative data of CO and PM within hours of event. These instruments will be able to provide spot readings of CO and PM and enable to rapidly assess the extent of the pollution event. While the sensitivity and precision of these instruments are poorer than the instruments used to measure ambient air quality in a standard AMS, the high concentration of pollutants expected during an episode like the mine fire negates the greater uncertainty in the measurements made by these devices.
2. Deployment of low cost portable monitors with higher accuracy that can be installed quickly and easily within a couple of days at a number of locations to ensure spatial coverage. These devices would include CO, PM and additional high risk pollutants (e.g. benzene) identified in the data review of this study.
3. Implementation of high quality monitoring stations to provide validated data of criteria pollutants and PM and air quality measurements of additional pollutants (e.g. VOCs, PAHs).

4.3 Ash

During the Hazelwood mine fire, ash was deposited in and around homes causing health concerns among Morwell residents. Ash samples were collected by EPA Victoria at locations where there were significant deposits of ash (Table 8). A total of 12 ash samples were collected during the Hazelwood mine fire, with an additional dust residue collected during the recovery phase on 14 November 2014.

Table 7 Location of ash samples taken during the Hazelwood mine fire

Sample ID	Date	Sample	Location
Ash1	18/2/14	Ash	Willis Ct.
Ash2	3/3/14	Ash	Willis Ct.
Ash3	3/3/14	Ash	Morwell CFA Station
Ash4	3/3/14	Ash	Morwell East AMS
Ash5	12/3/14	Ash	Wallace St.
Ash6	13/3/14	Ash	Wallace St.
Ash7	13/3/14	Ash	Morwell Bowling Club
Ash8	13/3/14	Ash	Morwell Football Club
Ash9	13/3/14	Ash	Club Astoria Morwell
Ash10	13/3/14	Floor sweepings	Club Astoria Morwell
Ash11	13/3/14	Benches	Club Astoria Morwell

Ash12	18/3/14	Ash	Hazelwood road
Ash13	14/11/14	Dust Residue	Willis Ct.

While control samples of ash from the burning fire would be useful in interpretation the ash data, the ash samples provide a unique opportunity to assess the composition of ash and characterise the ash samples for signature compounds (e.g. semi-volatile organic compounds, metals) associated with open-cut coal mine fires.

4.3.1 Composition of ash

Of particular interest are polycyclic aromatic hydrocarbons (PAHs) some of which are known or potential human carcinogens. The PAH distribution of ash samples is shown in Figure 11. Concentrations were variable among the different ash samples with highest concentrations observed at the Morwell Football Club and at Club Astoria. The major PAHs identified in the ash samples were semi-volatile PAHs such as naphthalene and phenanthrene. Heavier particle bound PAHs such as benzo(a)pyrene were below the detection limit. Only a sample taken from the top of benches at the Club Astoria (Ash9) had detectable levels of larger molecular weight PAHs. For ash samples 3 and 4, PAH concentrations were below the detection limit. The dust residue sample collected in November 2014 had similar PAH concentrations to those observed in ash samples collected during the Hazelwood mine fire.

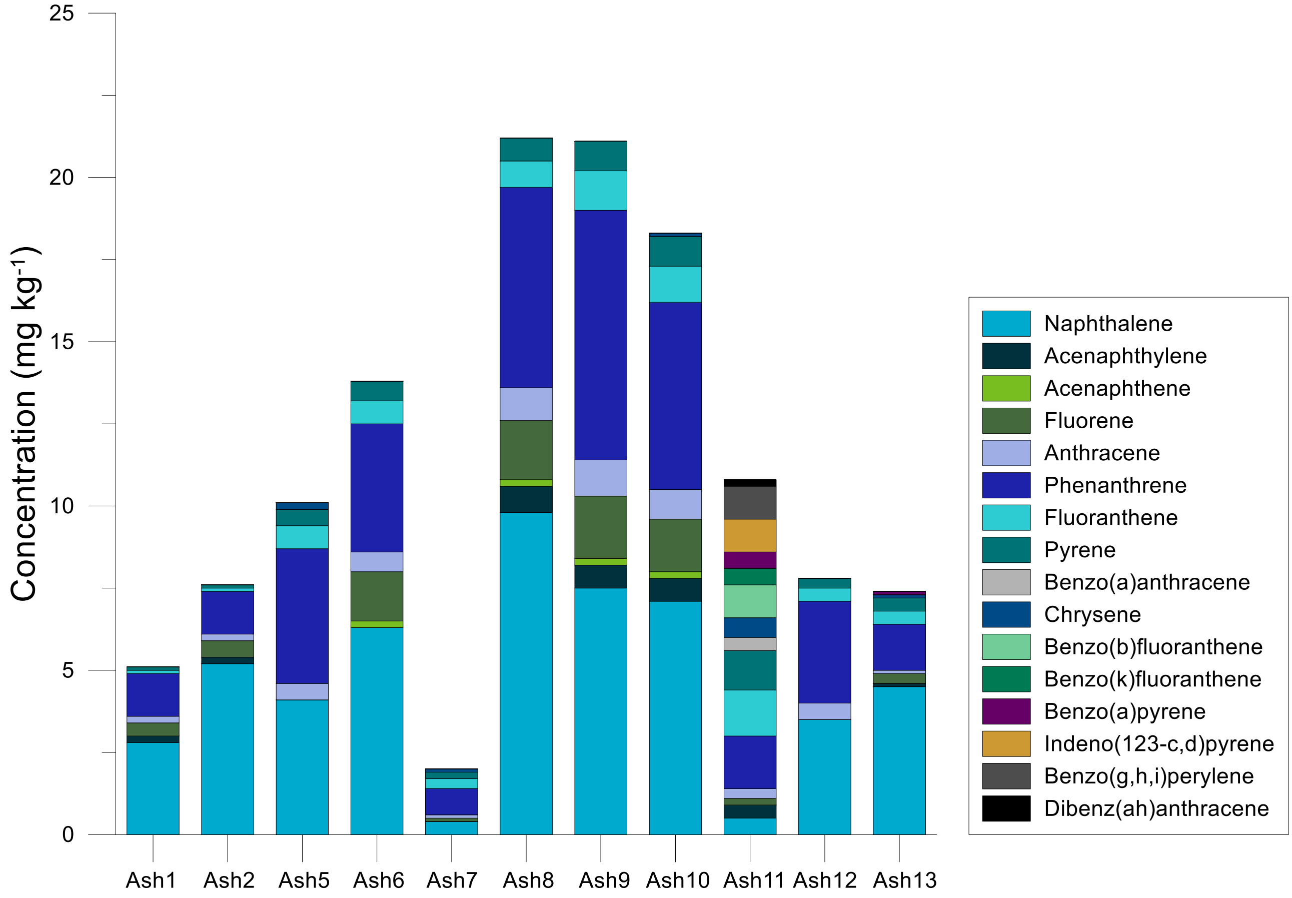

Figure 11 PAH concentrations measured in ash samples

The concentrations of PAHs in ash are relatively high in comparison to reported total PAH concentrations in ash from forest fires. *Campos et al. (2012)* reported a total PAH concentration of 0.6 µg g^{-1} from a eucalypt forest fire while *Olivella et al. (2006)* reported total PAH concentrations of 1.3-19 ng g^{-1} in ash samples collected approximately one month after forest fires in Portugal. Phenanthrene was the dominant compound measured in the ash samples. *Kim et al. (2003)* reported total PAH concentrations of 0.63-0.74 µg g^{-1} in ash samples from forest fires in Korea.

The metal distribution of ash samples is shown in Figure 12. The dominating metals in the ash samples were iron and aluminium, followed by barium, strontium, titanium, manganese, zinc and boron. Concentrations of the other metals including mercury were low. The presence of metals in the ash samples is consistent with metals found in brown coal for which major inorganics are aluminium and iron and major trace elements are barium, strontium, manganese and boron *(Durie 1991)*.

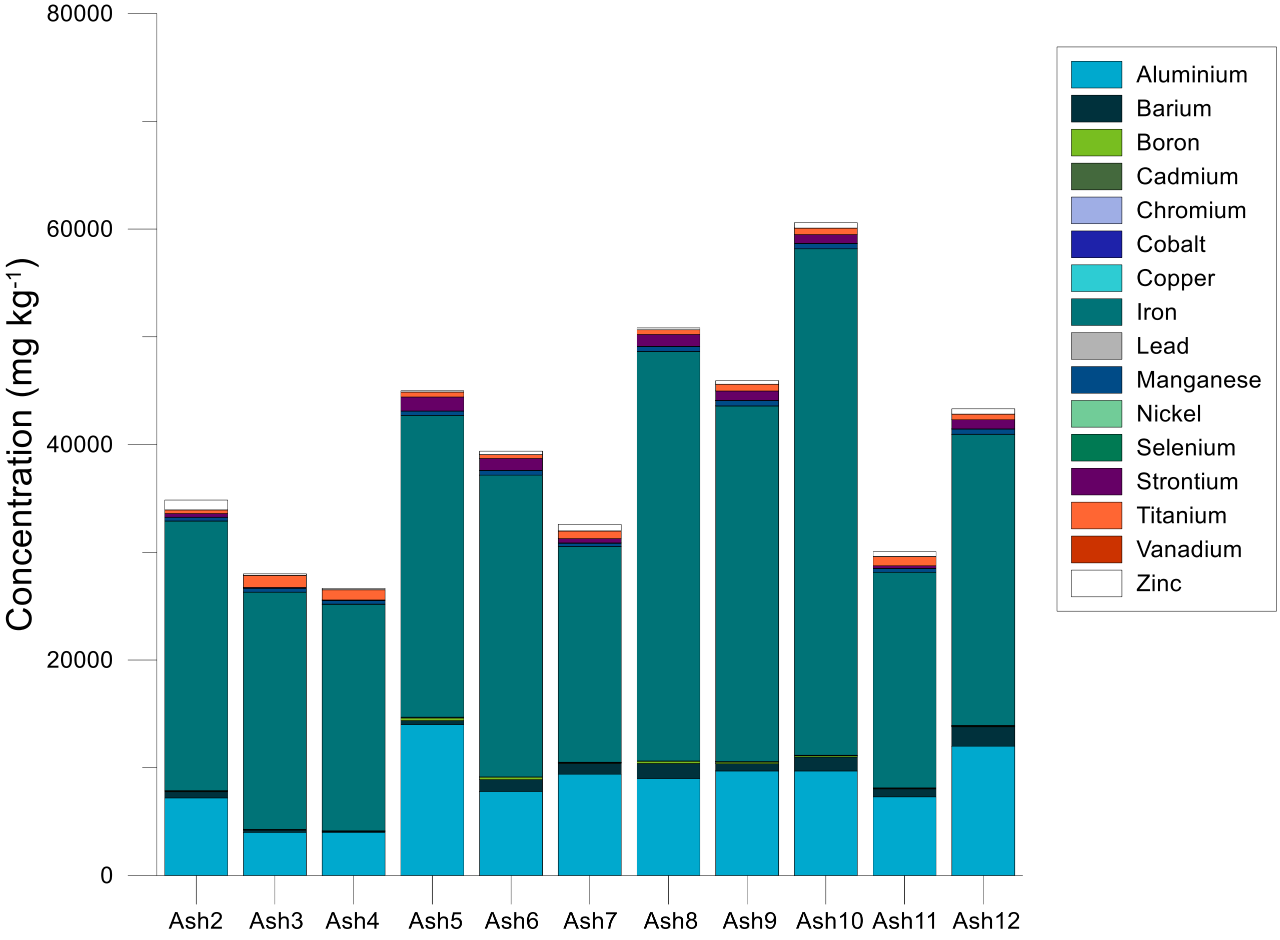

Figure 12 Concentrations of metals measured in ash samples

4.3.2 Transport and deposition of ash

A simple tracer model could be set up to investigate the transport and deposition of fire ash, along the lines of those designed to investigate fine volcanic ash. In the USA, the Air Resources Laboratory has a version of HYSPLIT able to calculate movements of volcanic ash (https://www.ready.noaa.gov/HYSPLIT_ash.php). This is based on trajectory modelling. Dispersion modelling could also be undertaken, making assumptions on the size and density of the ash particles, and how readily the ash is taken up by rain droplets.

4.3.3 Knowledge gaps

Ash emitted from the Hazelwood mine fire has not been well characterised in terms of its size distribution. In order to better understand how ash was dispersed in the environment and deposited outdoors and indoors, it is important to understand the physical characteristics of the ash.

Transmission electron microscopy (TEM) in combination with energy dispersive X-ray spectroscopy (EDS), can be used to investigate the elemental distribution, morphology, crystalline phases and electronic structure of individual coal fly ash particles, with emphasis on the ultrafine particles that may have the greatest impact on human health *(Silva et al.* 2009*)*.

Finally the analysis of control samples of the ash would assist in the interpretation of the ash measurements.

4.4 Dioxins and Furans (PCDD/F)

Measurements of gas-phase and particle-phase PCDD/F collected during the Hazelwood mine fire along with deposition models of PCDD/F will assist in assessing the potential impact of the Hazelwood mine fire on soil and water systems. In order to assess the potential impact it is important to understand the formation mechanism of PCDD/F during combustion, the conditions (e.g. temperature, fuel composition) that favour their formation, and the deposition and uptake of PCDD/F in water and soils.

4.4.1 Ambient concentrations

As mentioned in section 4.2.3, PCDD/F levels can either be represented in terms of mass concentration or as TEQ values, which takes into account the toxicity levels of the individual congeners. The 24-hour measurements of PCDD/F show a significant decrease in TEQ values from 40 fg m^{-3} in February to less than 10 fg m^{-3} in March. As a comparison, TEQ values of particle-bound congeners observed in Aspendale (VIC) were 4.2 fg m^{-3} in winter. These values are low compared to ambient concentrations of PCDD/F in excess of 5000 fg TEQ m^{-3} measured during heating season in Poland where coal fired stoves are widely used *(Grochowalski and Chrząszcz 1997)*.

The 24-hour measurements were collected using a Hi-Vol sampling technique, which only captures particle-bound congeners and therefore may underestimate total PCDD/F concentrations. While mass concentrations of gas-phase PCDD/F are very low in comparison to particle-phase PCDD/F, the contribution of gas-phase PCDD/F to TEQ values can be more significant as shown in Figure 13. This is due to the higher TEF values of the semi-volatile congeners.

Figure 14 shows the PCDD/F mass concentrations for 17 congeners measured in Morwell in comparison to those measured in Darwin during the dry season *(Meyer et al. 2004)* and in Melbourne in summer and *winter (Gras et al, 2004)*. Since the Melbourne and Darwin samples represent both gas- and particle-phase PCDD/F, only the 2 samples collected in March on both filters and PUFs are shown in Figure 14. The PCDD/F mass concentrations measured in Morwell are similar to those measured in Darwin and Melbourne, with a similar congener profile pattern. OCDD dominates the profile for all sites.

Congener profiles can sometimes be used to fingerprint the source of PCDD/F. As an example the congener profile patterns for emissions from coal stoves *(Thuss et al., 1995),* wood heaters *(Gras et al., 2002)* and wildfires *(Meyer et al. 2004)* are shown in Figure 15, indicating clear differences between the different combustion sources. The profile patterns for Morwell (3-18 March) and Melbourne in Figure 16 are different, which may be indicative of different sources. There’s a higher contribution of dioxins compared to furans in the Morwell sample compared to the Melbourne winter samples for which the major source contribution is domestic wood heaters.

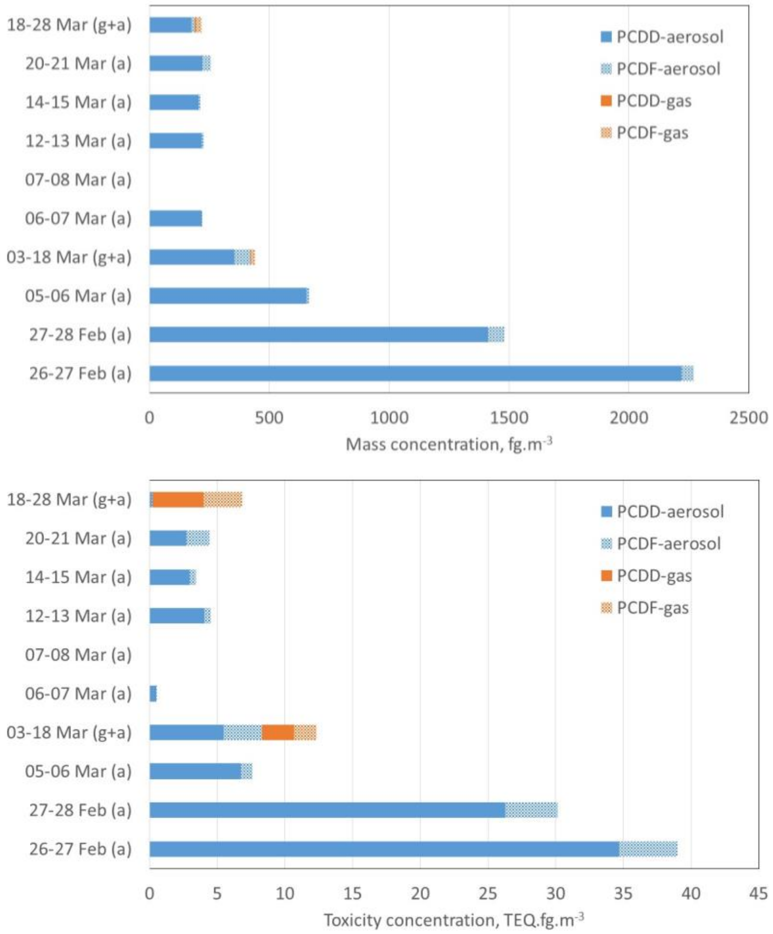

Figure 13 Mass concentrations (top) and Toxicity concentrations (bottom) of the gas-phase and particle phase dioxins (PCDD) and furans (PCDF); g+a denotes gas plus aerosol; a denotes aerosol only

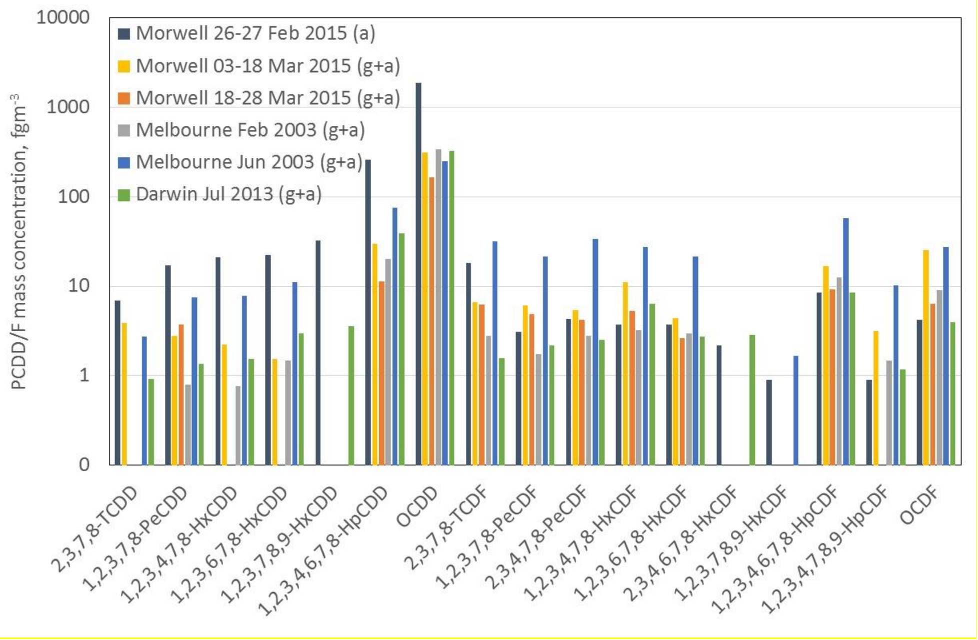

Figure 14 Mass concentrations of dioxin and furan congeners measured in Morwell, Melbourne and Darwin, gas+aerosol phase, values less than detection limit excluded (lower-bound), g+a denotes gas plus aerosol; a denotes aerosol only

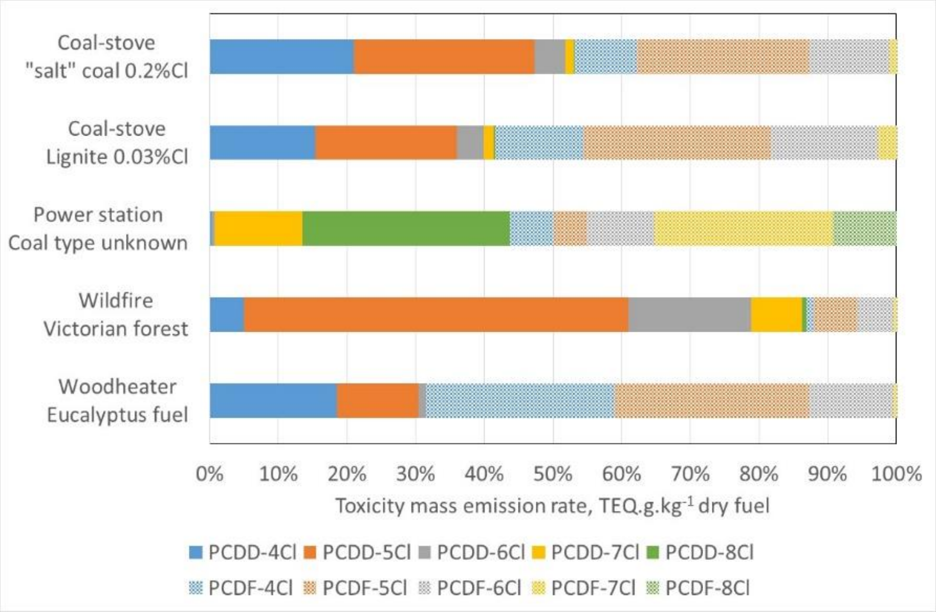

Figure 15 Profile pattern for dioxin and furan congeners of selected combustion sources; values less than detection limit excluded (lower-bound)

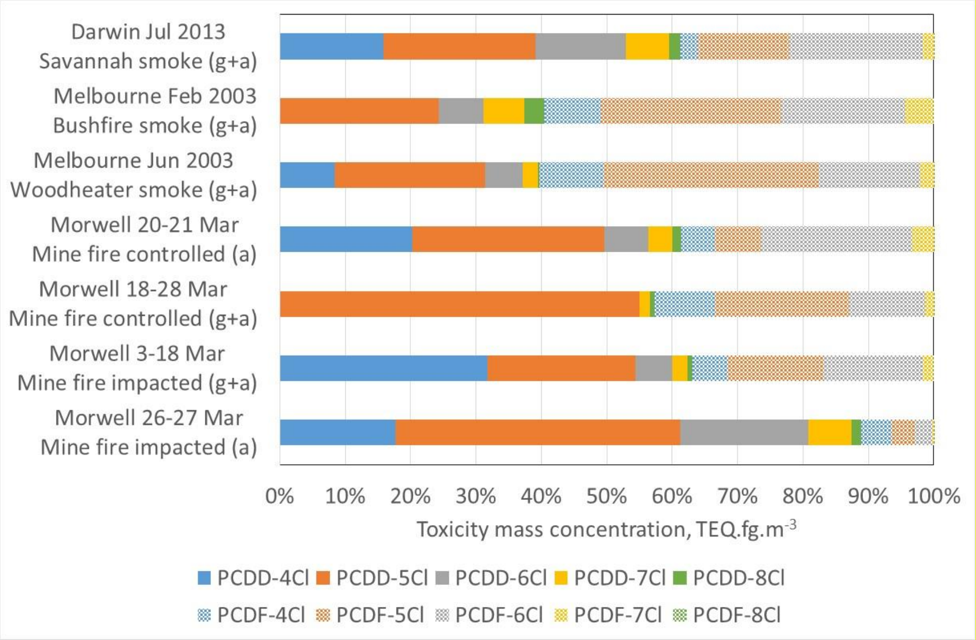

Figure 16 Profile pattern of ambient dioxins and furans measured in Morwell, Melbourne and Darwin; g+a denotes gas plus aerosol; a denotes aerosol only; values less than detection limit excluded (lower-bound)

4.4.2 Formation mechanism of dioxins/furans

Formation of PCDD/F during combustion can either occur via gas-phase reactions or via heterogeneous reactions that occur on particle surfaces *(Stanmore 2004)*. Temperature plays an important role in PCDD/F formation, with significantly higher PCDD/F emissions at higher temperatures. *Paradiz et al. (2008)* showed that the PCDD/F emission factor increased 10 fold when flue gas temperatures in domestic coal heating increased from 450°C to 600°C. Experimental work looking at PCDD/F emissions from prescribed burns, bushfires and domestic wood heaters has shown differences in emissions primarily linked to combustion temperatures *(Meyer et al. 2004)*. Higher combustion temperatures observed in wood heaters resulted in higher emissions of dioxins and furans.

Congener profiles and hence toxicity of emissions are also dependent on combustion temperatures. High furan to dioxin ratio was observed in emissions from wood combustion in furnaces and domestic heaters *(Gras et al. 2002)*, while lower furan to dioxin ratio was observed in field burns *(Meyer et al. 2004)*. The different congener profiles in field burns are likely due to duration of smoke plume at high temperature. Smoke plume can be rapidly cooled to temperatures that do not support the heterogeneous reactions required for dioxins synthesis. In the coal fire, temperatures are likely to stay at higher temperatures for longer, resulting in formation of dioxins via heterogeneous reactions. Whilst there are no published dioxin/furan emission rates for an open-cut coal mine fire, emission rates are available from combustion of coal in domestic heaters. *Lee et al (2005)* measured emissions of dioxins and furans from burning coal in an open fire place and reported high rates of lower chlorinated dioxins and furans, particularly mono- to tri-chlorinated dibenzofurans.

The chemical composition of coal also influences dioxin/furan production with chlorine content in coal playing the largest impact on dioxin/furan emissions. *Paradiz et al. (2015)* measured dioxin formation from burning low chlorinated (0.07%) hard coal and high-chlorinated (0.31%) hard coal. They measured highest emissions from high chlorine coal in the chimney when temperatures were above 500°C. They examined the dependence of emissions on Cl content by impregnating low chlorine coal with NaCl and found a strong but non-linear dependence, with a sharp increase in emissions if coal has a content of 0.2%. As the chlorine content of the Hazelwood mine coal is low (0.04-0.07%) in comparison to high-salt coals (above 0.3%) (see Table 6), PCDD/F production is expected to be lower.

Sulphur and nitrogen may play a minor influence on dioxin formation by acting as an inhibitor while copper can act as a catalyst.

4.4.3 Transport and deposition

PCDD/F are highly persistent under normal environmental conditions and can be transported long distances in the atmosphere if they are bound to particulate material. PCDD/F have an affinity to partition onto organic carbon such as soils, sediment and carbonaceous aerosols. In the presence of elevated concentrations of carbonaceous particles, PCDD/F may more readily partition into the particle-phase. In the absence of gas-phase measurements during the more intensive period of the Hazelwood mine fire, it is difficult to assess the proportion of PCDD/F in the gas and particle phase. Gas-phase PCDD/F may also undergo degradation via reaction with the OH radical.

Gas-phase and particle-phase PCDD/F can undergo dry deposition which refers to the transfer of PCDD/F onto vegetation, soil and water surfaces by atmospheric turbulence and molecular diffusion. Deposition rates for particle-phase PCDD/F may also be enhanced by gravitational settling of the particles.

The fate of PCDD/F in the environment is complex. In a study conducted on the fate of PCDD/F within an agricultural ecosystem, results indicated that roughly 15% of the total annual deposition to the farm was captured in the feed crops, while the remaining 85% was transferred directly to soil *(Welsch-Pausch and McLachlan 1998)*. Particle-bound deposition accounted for the majority of the atmospheric flux into the ecosystem, with the majority going directly to the soil; gaseous deposition dominated the transfer into crops and, hence, into the food chain.

PCDD/F are bioaccumulative and most human exposure occurs though the food chain rather than through inhalation. The WHO estimates that on average, the contribution from inhalation is approximately 1% of the dietary intake, thus no air quality guidelines limiting exposure to PCDDs and PCDFs via inhalation have been proposed *(WHO, 2000).* If the major source of dioxins and furans entering the food chain is from atmospheric deposition, then the level in the air does provide an indirect indication of levels that are ending up in food. Assuming the atmosphere is the major source, the WHO suggests that sources resulting in toxic equivalent air concentrations of 0.3 pg m^{-3} or higher should be controlled to limit the amount entering the food chain via deposition. The maximum toxic equivalent aerosol-phase air concentration observed during the Morwell fire was 0.039 pg m^{-3}, decreasing to about 0.004 pg m^{-3} by 21st March. The maximum aerosol phase concentration was 8 times lower than the WHO recommendation, and assuming a similar level in the gas phase (a conservative estimate based on aerosol/gas partitioning shown in Figure 13b), then the combined toxic equivalent concentration was at least 4 times lower than the WHO recommendation.

4.4.4 Knowledge gap

Dioxin and furan congener profile patterns are available for a range of combustion sources including fires, domestic wood heaters and coal stoves, but cannot be easily related to an open-cut coal mine fire due to differences in temperature and oxygen conditions under which the coal mine fire occurred. Research studies have shown that temperature can have a significant influence on the profile pattern.

5 Potential uses

5.1 Exposure assessment

CSIRO, in collaboration with Monash University and the Menzies Institute, University of Tasmania conducted a smoke exposure study in early 2015 *(Emmerson et al. 2015)*. The aim of the study was to investigate the strength and direction of the smoke dispersion from Hazelwood to nearby towns. The study therefore also showed the towns within the Latrobe Valley which did not experience high smoke concentrations, and therefore could be used as a control population in the long term health study.

As emission rates from the actual fire were not known, and a literature search yielded no suitable information on likely emission factors, a unit emission rate of 1g s^{-1} was used to represent the fire. As no chemistry acted upon this smoke tracer, the results could be scaled up linearly to match the concentrations of particulate matter monitored in nearby towns.

Two methods of emitting the smoke tracer were tested:

a) Tracer emitted at a constant rate of 1g s^{-1} over the whole fire period;
b) Tracer emitted using a diurnal profile to weight the 1g s^{-1} over a day, following a sine function that peaked mid-afternoon.

Modelling assumptions used:

- Smoke tracer is emitted as particle made of black carbon;
- No other emissions or chemistry act on this smoke tracer;
- Smoke tracer is emitted at 50m in height to represent low level Hazelwood smoke as per photographs taken at the time;
- No plume rise calculations have been applied to the smoke tracer.

The modelling showed that the highest concentrations of smoke from the fire occurred when the winds were blowing from a south westerly direction. However most towns within a 30km radius of the mine fire were exposed to high concentrations of the smoke tracer. A comparison of the modelled mine tracer concentrations with measured values of $PM_{2.5}$ in Morwell highlighted that the assumed unit emission rate could need to be scaled up by as much as a factor of 2000. Spatial plots were constructed that show the number of days (out of a possible 45 days that the fire burned for) within each town that the $PM_{2.5}$ concentrations would exceed 1,5,10 and 20 $\mu g\ m^{-3}$ as a peak hourly average. Figure 17 shows that at an exceedance level of 20 $\mu g\ m^{-3}$ the number of days this concentration was exceeded were Trafalgar (24 days), Rosedale (22days), Warragul (18 days), Sale (14 days), Leongatha (11 days) and Yarram (4 days).

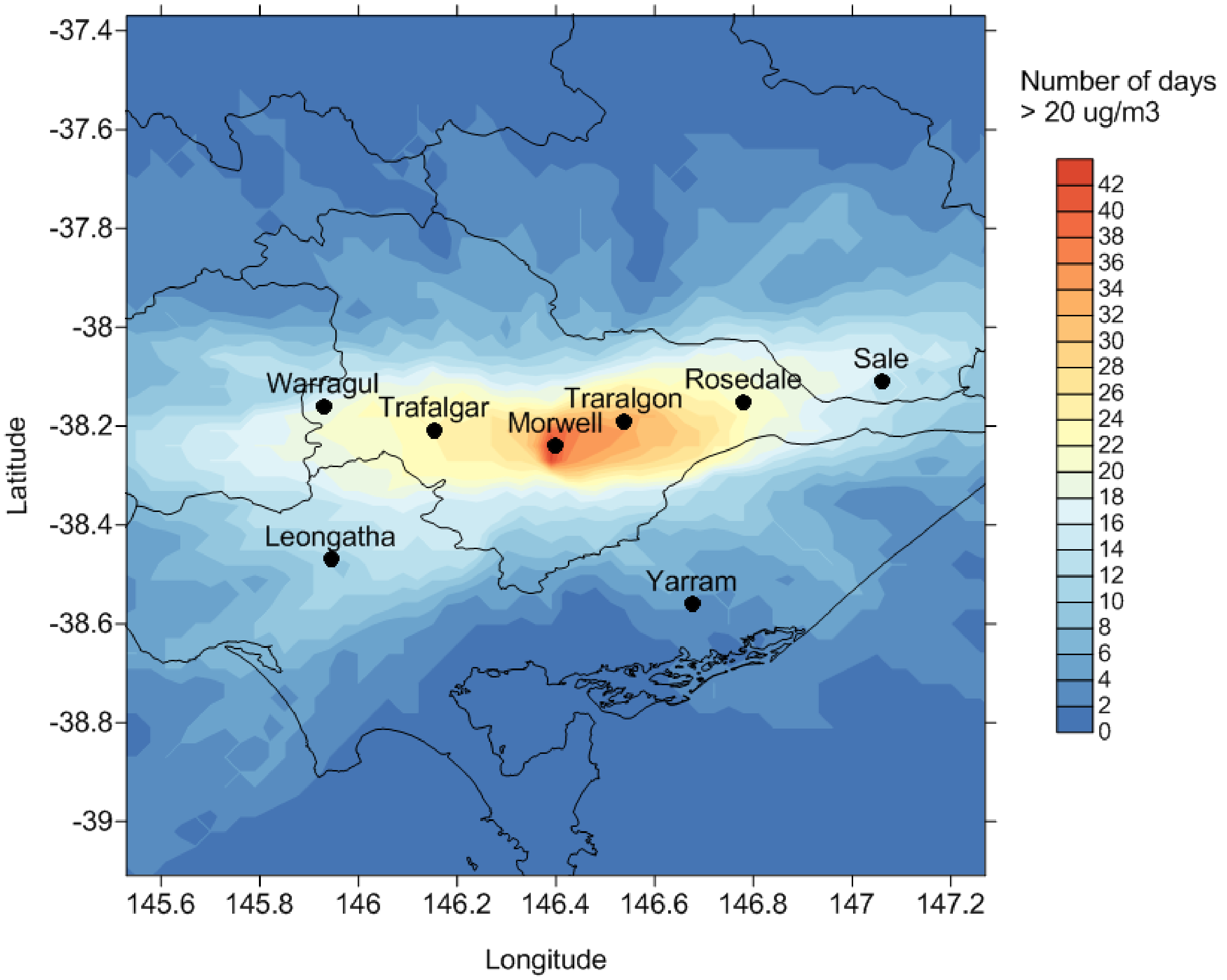

Figure 17 Modelled frequency of days on which the PM_{25} concentration would exceed 20 µg m^{-3} as an hourly average out of a maximum 45 days due to mine fire scenario.

A number of considerations were given to the choice of control population. These included smoke exposure, ease of logistics for such a long-term health study, and the economic demographics of the representative population.

Outcome:

The exposure assessment will provide input to the long-term health study conducted by Monash University. Previous studies have shown that emissions from burning coal beds of acidic gases, particulates, organic compounds, and trace elements can contribute to a range of respiratory and other human health problems *(Finkelman 2004)*.

5.2 Forecasting model

A major recommendation of this report is to produce an efficient forecast model along with training on its use, and made available to planners in cases of future large industrial fires. The model should be easy to use (i.e. run on a Windows computer platform) and provide forecasts for up to 24 hours ahead of time quickly. This would enable decisions about potential evacuations to be made, based on the amount of exposure from smoke. The model would require access to weather forecast data from the Bureau of Meteorology. To avoid the requirement of a full chemical transport model, the species to be forecast should be tracer species only, which do not take place in any chemical reactions, but are subject to wet and dry deposition. For smoke, the important species are CO and PM at two different size fractions; PM_{10} and $PM_{2.5}$.

The model should have an in-built post-processing module which would plot the resulting concentrations on a map in an easy to understand format. For example, the concentrations could be split into low, medium or high exposure, for example. The demarcations between low, medium and high should be based on current air quality standards. The National Environment Protection measures for ambient air quality, which are set for minimising harm to human health, are shown in Table 9 for CO and PM.

Table 8 Current air quality standards for carbon monoxide and particulate matter

Pollutant	Averaging period	Limit	Allowable exceedances
Carbon monoxide	8 hours	9 ppm	1 day per year
PM_{10}	24 hours	50 µg m^{-3}	5 days per year
$PM_{2.5}$	24 hours	25 µg m^{-3}	-

Taken from http://www.environment.gov.au/protection/air-quality/air-quality-standards

There are a number of challenges in producing such a forecast model. The operator needs to input information based on:

- Fire emission characterisation – what **exactly** is being burned, and how much?
- Plume rise – how buoyant is the plume in the atmosphere?
- Burning condition – how hot is the burn? Was the fuel damp?

Each of these challenges will affect the method by which the smoke will be dispersed and will contribute to uncertainties and inaccuracies in the forecast. Some challenges are easier to overcome than others. For example, taking frequent photographs of the fire plume can aid greatly in determining the amount of plume rise occurring. If it is possible and safe to do so, positioning a person (or automated measurement system) on the ground at the site to investigate the conditions of the burn would be very useful.

Note on inverse modelling

Inverse modelling is a process that can provide information on what and how much fuel was burnt. It is completed after a fire has burned and therefore cannot be used as part of a forecast model. However, if no other information exists on the fuel burnt in a current fire, results from a previous inverse modelling study could be used *if the conditions of the burn are similar*. CSIRO will undertake an inverse modelling study of the Hazelwood mine fire to try and ascertain the emission source strength. This inverse modelling will take place as part of the smoke exposure assessment study. There are uncertainties in the inverse modelling process, as it will assume uniformity in the source emission. This is not always the case in real fires, as conditions can change constantly.

Appendix A Measurement and analysis methods

A.1 Instruments

A.1.1 Particle instruments

- The e-sampler (E-sampler-9800, Met One Instruments Inc., USA) provides both continuous real-time particulate measurements through near-forward light-scattering and collection of sample on a 47mm filter substrate that can be used for subsequent measurements of gravimetric mass and for chemical composition. Air was sampled at a constant flow rate of 2 l min^{-1} through a sharp-cut $PM_{2.5}$ cyclone. The samples were collected on Teflon filters 47 mm in diameter with 2 µm pore size. Continuous real-time measurements were calibrated against gravimetric filter measurements (Australian reference method). Uncertainty ± 10%
- The DustTrak (TSI Inc., USA) is a laser photometer that provides real-time measurements based on 90 degree light scattering. The particle mass concentration is determined by the amount of light scatter, based on a calibration factor. The relationship between light scattering and particle mass concentrations varies with particle source and particle size distribution. DustTrak produces data that is considered indicative of levels of $PM_{2.5}$ in an area. Indicative data. If calibrated with a site specific mass calibration factor determined gravimetrically uncertainty ± 10%.
- BAM (Model 4014*i* Beta, Thermo Fisher Scientific Inc.) is a standard beta attenuation monitor that automatically measures and records airborne particles. This instrument works by collecting particles on a filter tape and measuring the reduction in beta rays travelling through the particles. From this, the concentration of airborne particles is calculated. BAMs meet the Australian National Standard (AS 3580.9.12–2013). Uncertainty ±10%
- The nephelometer measures the amount of particles in the air using very sensitive, light-scattering sensors and calculates a visibility reduction index.
- The Tapered Element Oscillating Micro-balance (TEOM) continually measures the concentration of airborne particles. It does this by collecting and weighing the particles using a very sensitive balance. TEOMs are standard across EPA's network and meet the Australian National Standard (AS 3580.9.8–2008). Uncertainty ±10%
- A High-Volume Air Sampler (HiVol) samples large volumes of air and collects the contained particulate matter by filtration. Air was sampled at a flow rate of 1.1 m^{3} min^{-1} through a 10 µm size-selective inlet. AS/NZ 3850.9.6:2015 or AS/NZ 3850.9.14:2013. Uncertainty ±10%.
- The Partisol is a gravimetric sampler that employs a sequential system of 47 mm filters that enables several 24-hour period samples to be collected automatically. The Partisol operates at a flow rate of 10-19 L min^{-1}. AS/NZ 3850.9.9:2006. Uncertainty ±10%
- The MOUDI (Model 110-R, MSP Corporation) is a 10 stage cascade impactor with the stages having 50% cut-points ranging from 0.056 µm to 18 µm in aerodynamic diameter. The HiVol MOUDI (Model 131, MSP Corporation) is a 6-stage impactor with the stages having 50% cut-points ranging

from 0.25 µm to 10 µm in aerodynamic diameter. The MOUDI works by inertial impaction using multi-nozzle stages in series. The MOUDI and HiVol MOUDI samples were taken at the designed flow rate of 30 L min^{-1} and 100 L min^{-1} respectively.

A.1.2 CO measurements

CO was measured by two methods

- Ecotech trace CO analyser which utilises infrared absorption spectrometry. Australian Standard AS3580.7.1:2011. Uncertainty of approx. 2% Operated in AMS.
- The CFA used AreaRAE portable personal monitors which use electrochemical sensors to detect CO.These monitors are traditionally used to assess occupational exposure so that the CO sensor is less sensitive than the NDIR method employed by EPAV to measure ambient levels of CO.

A.1.3 VOC measurements

Different methods were used to collect VOCs: canister sampling over a 24-hour period, passive sorbent tube sampling using Radiello tubes and active sampling on sorbent tubes and DNPH cartridges and are summarised in Tables A1 and A2.

- Canister samples were collected over a 24- hour period in stainless steel fused silica-coated canisters and transported to analytical laboratory for chemical analysis.
- Radiello tubes are adsorbent tubes that absorb VOCs in the air. They are a stand-alone, passively sampling tube that were deployed at different sites in Morwell and sampled over a 7-day period.
- VOC samples were also collected by drawing air through two Markes Carbograph 1TD / Carbopack X adsorbent tubes at a flow rate of 20 ml min^{-1} for 25-minutes per hour over a 24 hour period, giving a typical volume of 6 L. The absorbent tubes were placed in sequence, with a back-up tube to assess sample break-through. Sampling was conducted according to USEPA Compendium method TO-17 (USEPA TO-17).
- Samples for the analysis of carbonyl compounds (including formaldehyde) were collected by drawing air through Supelco LpDNPH s10 air monitoring cartridges at a flow rate of 500 ml min^{-1} over a 24-hour period. Carbonyls were trapped on high purity silica adsorbent coated with 2,4-dinitrophenylhydrazine(2,4-DNPH), where they are converted to the hydrazone derivatives. An ozone scrubber was placed in front of the LpDNPH cartridge. Sampling was conducted according to USEPA method TO-11A.

Apx Table A.1 VOC sampling and measurement details

SITE	SAMPLING DATE	SAMPLING PERIOD	SAMPLING METHOD	COLLECTED BY	ANALYSIS METHOD	ANALYSED BY
Morwell South AMS; Maryvale Crescent Preschool; Morwell East AMS	26-27 February 27-28 February 5-6 March 6-7 March 13-14 March	24-hours	Canister	EPA Victoria	USEPA Method TO-15	NMI
Morwell South AMS; Maryvale Crescent Preschool; Morwell East AMS	From 4 February	7-days	Radiello sorbent tubes (passive)	EPA Victoria	USEPA Method TO-17	SGS-Leeder Consulting
Morwell South (cnr of Chapel and Elgin st)	3 -19 March	25min per hour over 24h period	Sorbent tubes (active)	CSIRO	USEPA Method TO-17	CSIRO

Apx Table A.2 Carbonyl sampling and measurement details

SITE	SAMPLING DATE	SAMPLING PERIOD	SAMPLING METHOD	COLLECTED BY	ANALYSIS METHOD	ANALYSED BY
Morwell South AMS; Maryvale Crescent Preschool; Morwell East AMS	26-27 February 27-28 February 5-6 March 6-7 March 13-14 March	24h	Radiello (passive)	EPA Victoria	USEPA Method TO-11	SGS-Leeder Consulting
Morwell South (cnr of Chapel and Elgin st)	3 -19 March	24h	DNPH cartridges (active)	CSIRO	USEPA Method TO-11	CSIRO

Table A3 summarises the collection and analysis methods for PAHs and dioxins.

Apx Table A.3 PAHs and dioxins sampling and measurement details

SITE	SAMPLING DATE	SAMPLING PERIOD	SAMPLING METHOD	COLLECTED BY	ANALYSIS METHOD	ANALYSED BY
Morwell South AMS	26-27 February 27-28 February 5-6 March 6-7 March 7-8 March 12-13 March 14-15 March 20-21 March	24-hours	HiVol PM10 filters	EPA Victoria	USEPA Method (Isotope dilution)	NMI
Morwell South (cnr of Chapel and Elgin st)	3 -18 March 18-28 March	15 days 10 days	Quartz filters and PUFs	CSIRO	USEPA Method TO9A	Asure Quality

Table A4 summarises the collection and analysis methods for metals.

Apx Table A.4 Metals sampling and measurement details

SITE	SAMPLING DATE	SAMPLING PERIOD	SAMPLING METHOD	COLLECTED BY	ANALYSIS METHOD	ANALYSED BY
Morwell South AMS	26-27 February 27-28 February 5-6 March 6-7 March 7-8 March 12-13 March 14-15 March 20-21 March	24-hours	HiVol PM10 filters	EPA Victoria	ICP	SGS-Leeder Consulting
Morwell South AMS	28 February-26 March	24-hours	Partisol PM10	EPA Victoria	PIXE	ANSTO
Morwell South (cnr of Chapel and Elgin st)	3 -7 March 7-14 March 14-21 March 21-28 March	weekly	E-sampler PM2.5	CSIRO	PIXE	ANSTO
Morwell East AMS	28 Feb-7 March 7-14 March 14-28 March	weekly weekly 2-weeks	E-sampler PM2.5	CSIRO	PIXE	ANSTO
Traralgon	28 Feb-7 March 7-14 March 14-28 March	weekly weekly 2-weeks	E-sampler PM2.5	CSIRO	PIXE	ANSTO

Appendix B Gaseous Elemental Mercury

Samples of gaseous elemental mercury were collected by actively drawing air through carbon traps impregnated with iodide which are held in ¼″ glass tubes. Samples were collected at a flow rate of about 2 l min^{-1} over a period of 6-10 days, giving sample volumes of 18-26 m^3. Each glass tube contained two traps separated by glass wool so breakthrough and blanks could be assessed on each sample if required. Breakthrough of mercury is very small, and usually <5% at flow rates of up to 1 l min^{-1} (Bloom et al. 1995). The sample tubes were sealed before and after sampling with teflon plugs until they were ready for analysis. Analysis was done by Eurofins Global Frontier Sciences Inc. lab (WA, USA). Samples were analysed for Total Mercury by flow injection atomic fluorescence spectrometry (FI-AFS) according to SOP EFGS-136 (Modified EPA method 1631e).

Four duplicate mercury samples were collected at Morwell South between 3 March 2014 and 28 March 2014. The results are presented in Table 19. The sampling tubes for the period of March 3-5 were not properly connected to the sampling pump and those samples were used as field blanks.

Mercury concentrations remained low during the entire sampling period. For comparison, the average concentration measured in background air in the Southern Hemisphere is 1 ng/m^3 (Slemr et al. 2015).

Table 9 Measured gaseous mercury concentrations at Morwell South

Date/Time ON	Date/Time OFF	Volume (m^3)	T (°C)	Pressure (mbar)	Mercury concentration (ng/m^3)	Mercury concentration STP (ng/m^3)
3/03/14 15:30	5/03/14 10:35				0.00 (<MDL) 0.00 (<MDL)	
5/03/14 12:05	11/03/14 17:20	17.8 19.1	20.2	1008.2	2.32 1.80	2.51 1.94
11/03/14 17:40	18/03/14 11:0	18.2 19.3	17.6	1001.2	1.54 1.49	1.65 1.61
18/03/14 16:08	28/03/14 09:51	26.8 26.6	17.9	1010.9	1.48 1.25	1.59 1.34

All values are blank corrected; ½ MDL was used for blank concentrations below the MDL

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