Hazelinks Mortality Report
Time series analyses for the period July 2009 to June 2015

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This report presents a preliminary analysis which has not been submitted to independent peer review. Subsequent scientific manuscripts which undergo independent peer review may vary in their findings or interpretation.

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Abbreviations

ABS	Australian Bureau of Statistics
AIHW	Australian Institute of Health and Welfare
ASGC	Australian Standard Geographical Classification
ASGS	Australian Statistical Geography Standard
CSIRO	Commonwealth Scientific and Industrial Research Organisation
DHHS	Department of Health and Human Services
DLNM	Distributed lag non-linear model
GAM	Generalised additive model
ICD	International Classification of Diseases
IQR	Inter-quartile range
IHD	Ischaemic Heart Disease
LGA	Local Government Area
NDI	National Death Index
NMD	National Mortality Database
PCR	Patient Care Record
$PM_{2.5}$	Particulate matter with an aerodynamic diameter of 2.5 micrometres (thousandths of a millimetre) or less
PM_{10}	Particulate matter with an aerodynamic diameter of 10 micrometres (thousandths of a millimetre) or less
RR	Relative Risk
SA	Statistical area level
95% CI	95% Confidence Interval

Glossary of terms

1. **Mine fire period**: The 30 day period between 9 February and 10 March 2014 when the daily modelled fire-generated $PM_{2.5}$ concentration, averaged across the Latrobe Valley SA3 area, exceeded 1 $\mu g/m^3$

2. **Six months post the mine fire period:** Period from 11 March 2014 to 11 September 2014

3. **Entire analysis period**: Period from 1 July 2009 to 30 June 2015

4. **Remainder of the analysis period:** Period from 1 July 2009 to 30 June 2015 excluding the mine fire period from 9 February and 10 March 2014 and six months post the mine fire period (11 March 2014 and 11 September 2014)

5. **All deaths**: Total number of deaths irrespective of the cause of death

6. **Underlying cause of death:** the main condition or injury leading to the death

7. **Underlying and associated causes of death:** All listed causes of death for each mortality record which includes one underlying cause of death and up to 14 associated causes

8. **Fire impacted SA2s**: Statistical Area Level 2 (SA2) areas where the modelled daily $PM_{2.5}$ concentrations from the fire exceeded 1$\mu g/m^3$ for at least one day

9. **Latrobe Valley:** All SA2s in the Latrobe Valley including Morwell

10. **Rest of Latrobe Valley:** All SA2s in the Latrobe Valley excluding Morwell

Executive Summary

From 9 February 2014, smoke and ash from a fire in the Morwell open cut brown coal mine adjacent to the Hazelwood power station covered parts of the Latrobe Valley for up to 6 weeks. In response, the Hazelwood Health Study was established in order to monitor any long-term or short-term health effects of that smoke event. This report describes analyses of mortality data from the Australian Institute of Health and Welfare (AIHW) for the period of 1 July 2009 to 30 June 2015. Time series models were used to evaluate the relative risk of mortality during the first 30 days of the mine fire, and during the six months after the mine fire period, in comparison with the remainder of the analysis period. The relative risks of mortality associated with daily mine fire-related $PM_{2.5}$ levels were also assessed. The analysis investigated all-cause mortality, and also mortality categorised as having cardiovascular, respiratory, mental health or injury as underlying or associated causes. The models used for these analyses controlled for factors likely to influence mortality rates including seasonality, public holidays, day of the week, daily maximum temperature, long-term temporal trends and change of population age-structure.

When all deaths were considered (irrespective of the cause of death), the overall risks of death in Morwell and in other fire impacted areas during the 30 day mine fire period, were similar to expected. However, there was some evidence of an increase in the overall risk of death in Morwell in the six months after the mine fire period.

When cause of death categories were analysed separately, there was a three-fold increase in risk of death from injury in Morwell during the 30 day mine fire period compared to the remainder of the analysis period. Total numbers were small, with an estimated three injury-related deaths in Morwell that were additional to expected. Smaller increases in risk of death from injuries during the 30 day mine fire period were also observed in the rest of the Latrobe Valley and surrounding smoke-impacted areas. In total, the analysis estimated that there were 11 injury-related deaths during the 30 day mine fire period, across all of the Latrobe Valley (including Morwell) and surrounding impacted areas, that were “attributable to the mine fire event”; meaning that they were additional deaths to those expected and not explained by the other known factors likely to influence mortality rates. The excess injury-related deaths were predominantly categorised as unintentional, as opposed to cases of self-harm. In the Latrobe Valley, males and residents aged 80 years or older were at greatest increased risk of death from injury during the mine fire period. An association was also observed between increases in daily mine fire-related $PM_{2.5}$ pollution levels and increases in risk of injury-related death, suggesting a dose response relationship. For example, there was an estimated 59% (95%CI: 2%-146%) increase in risk of death from injury across all smoke impacted areas in the

three days following each 10 µg/m^3 increase in fire-related $PM_{2.5}$. Some evidence of an increased risk of death in females when mental health was an associated cause, was also observed in the Latrobe Valley during the 30 day period.

In the six months after the mine fire, a 62% increase in risk of death from cardiovascular conditions was observed in Morwell (95%CI 25%-110%) including an 88% increase in deaths from Ischaemic Heart Disease (IHD). In total there were 26 cardiovascular-related deaths in Morwell attributed to this six month post mine fire period, included 17 with IHD. These 26 cardiovascular deaths represented 38% of all cardiovascular deaths in Morwell during this six month period. Males and residents aged 80 and above in the Latrobe Valley were at an increased risk of death from IHD in the six months after the fire.

There were no associations observed between the mine fire and respiratory deaths. This is unlikely to mean that the smoke posed no threat to people with respiratory illnesses. Instead it is likely that vulnerable people with respiratory illnesses took preventive action including leaving the smoke impacted areas, wearing protective masks and/or increasing their use of preventive medications. It is also possible that the numbers of respiratory-related deaths were too small to detect an association with the mine fire period.

1 Introduction

On 9 February 2014, the Morwell open cut brown coal mine adjacent to the Hazelwood power station in the Latrobe Valley, eastern Victoria, caught fire resulting in nearby areas being covered in plumes of smoke and ash over a six-week period. Subsequently, a Monash University-led consortium of researchers was contracted by the Victorian Department of Health and Human Services to undertake a comprehensive study of the long-term health and wellbeing of Latrobe Valley residents following exposure to smoke from the Hazelwood mine fire.

The Hazelinks component of the Hazelwood Health Study aimed to use administrative health data sets to investigate short, medium and long-term health outcomes in the fire impacted region. This report drew upon national death data routinely collected by the AIHW.

2 Background

The adverse effect of air pollution on health has long been appreciated and, due to improved methods of monitoring and measurement, has become a more active research area in the last 20 years. Extensive clinical, epidemiological and toxicological studies have provided evidence of relationships between exposure to ambient urban air pollutants and human health [1, 2]. The short-term effects of air pollution from traffic, industry and bushfires have mainly been demonstrated by increases in respiratory [3-5], cardiovascular morbidity [6-9] and mortality [10, 11].

Large, destructive coal mine fires, such as the Hazelwood mine fire, are often beyond human control despite technologically-advanced fire-fighting services and the resources allocated to fire control. Pollutants generated by coal combustion are similar to those generated from domestic solid fuel combustion and outdoor biomass fires [12]. Pollutants may be broadly categorised as gases, particles with a median aerodynamic diameter of ≤10µm or ≤ 2.5µm (PM_{10} or $PM_{2.5}$), volatile organic compounds and trace elements. Many of these are known to be deleterious to human health. The immediate impact of coal mine fires can be devastating, with loss of life, livelihood and infrastructure at the fire fronts. However, to date there has been limited evidence on the impacts of exposure to smoke from coal mine fires on health outcomes.

3 Aim and objectives

The aims of the analyses were to examine whether: 1) mortality rates increased during the mine fire period relative to comparable time periods before and after the fire; 2) mortality rates increased after the mine fire period compared to before the mine fire; 3) the daily levels of mine fire-related $PM_{2.5}$ were related to increased mortality overall or by specific cause of death categories.

4 Human Research Ethics Committee and other approvals

The Monash University Human Research Ethics Committee (MUHREC) approved the Hazelwood Adult Survey & Health Record Linkage Study on the 21st of May 2015. This included approval to request national death data from the AIHW. An application to access AIHW death data was submitted and approved by the AIHW ethics committee (Approval number EO2016-2-261).

5 Methods

5.1 Datasets

National Mortality Database

Mortality data were extracted from the National Mortality Database (NMD) which is held by the AIHW. Demographic and cause of death information from a medical practitioner or coroner, certifying the cause of death, and from the funeral director completing a death registration statement, is provided to the Registrars of Births, Deaths and Marriages (RBDM) in each state and territory. Mortality data from RBDM are then forwarded to the Australian Bureau of Statistics (ABS) for compiling and coding cause of death (COD).

The NMD contains de-identified mortality records with information such as sex, age at death, Statistical Area Level 2 (SA2) based on usual place of residence. The NMD also includes COD data which includes one underlying COD and up to 14 associated causes. Deaths which occurred in the period July 2009 to June 2015 for all ages in SA2s of interest (see 5.2.3 Geographical Boundaries and Figure 1) were extracted from the NMD. At the time of data extraction, NMD data up to the end of 2015 were available.

The NMD is updated annually and includes all registered deaths for the relevant year only, in each update. There is a three-stage revision process for COD data in the NMD; this includes preliminary, revised and final. From the time that mortality data are received for any given year, it can take several months to years for COD to reach the finalised stage. Most changes relating to COD data occur when there is a coronial inquest. In a few cases, date of death may be corrected as the result of a coronial inquest. At the time of our data extraction, COD data from 2009 to 2014 was at the final stage and COD data for 2015 was at the revised stage.

Data on air pollution

The CSIRO Oceans & Atmosphere provided modelled exposure fields for $PM_{2.5}$ ranging from 100-500 m resolution in close proximity to the fire, to 3-9 km resolution further away from the fire. Average 24-hourly $PM_{2.5}$ concentrations were calculated for Morwell and each SA2 area surrounding Morwell. Further details of the modelling approach can be found in the CSIRO report [13].

Data on ambient maximum temperature

As ambient temperature can have significant impacts on health [14, 15], temperature was controlled for when the associations between air pollution and health outcomes were assessed. Daily maximum temperatures were collected from the Australian Bureau of Meteorology (http://www.bom.gov.au/climate/data-services/station-data.shtml) for the study period.

Data on population

Population data for this study were obtained from ABS Population Estimates by SA2 between 2009 and 2016 (http://www.abs.gov.au/AUSSTATS/abs@.nsf/DetailsPage/3218.02014-15?OpenDocument).

5.2 Dataset parameters for analysis

5.2.1 The mortality data analysis period

Mortality data from 1 July 2009 to 30 June 2015 for all ages were used in the analysis. At the time of data extraction COD data from 2009 to 2014 was finalised and COD data for 2015 was at the revised stage.

5.2.2 Mine fire period

The *mine fire period* used in the analyses was determined by the modelled average daily $PM_{2.5}$ concentrations. For this report, the *mine fire period* was defined as that period of time during which the modelled fire-generated $PM_{2.5}$ concentration, averaged across the Latrobe Valley SA3 area, exceeded 1 $\mu g/m^3$. This corresponded with the 30 day period between 9 February and 10 March 2014. After 10 March 2014, daily average $PM_{2.5}$ concentrations attributable to the coal mine fire fell below 1$\mu g/m^3$.

5.2.3 Geographical boundaries

The geographical boundaries of the requested data were defined using the Australian Statistical Geography Standard (ASGS) 2011 classification SA2s. The data were extracted from the NMD using SA2 of usual place of residence.

Coal mine fire $PM_{2.5}$ modelled by CSIRO [13] was used to calculate daily average exposure in each of the SA2s. The areas where the modelled daily $PM_{2.5}$ concentrations from the fire exceeded 1$\mu g/m^3$ for at least one day were used in the analysis (fire impacted areas). Figure 1 shows the fire impacted areas and the SA2s that were grouped together for analysis.

5.3 Cause of death categories

Table 1 presents the broad and specific cause of death categories of interest with the associated ICD-10 codes. Where the analysis used the category name *all deaths* this referred to total number of deaths irrespective of the cause of death. Where a mortality record had multiple causes in the one cause of death category, the death was only counted once in that specific cause of death category. Deaths with multiple causes in different cause of death categories were counted multiple times.

Figure 1 Geographical location of the fire impacted statistical areas (SA2s)

Table 1 Cause of death classification and associated ICD-10 codes included in analysis

Categories	ICD 10 Code Definition
All Deaths	**A00 - Z99**
All Cardiovascular	I00-I99
Ischaemic Heart Disease	I20-I25, I46, I490
Cerebrovascular Disease	I61-I69, G45, G450, G451, G452, G453, G458, G459, G46
All Respiratory	J00-J99
Asthma	J45, J46
COPD	J41 - J44
Pneumonia and Acute Bronchitis	J12-J18, J20 - J21
All Mental Health	F04-F99, X60-X84
Anxiety	F40-F44
Depression	F32-F33
All Injuries	V01-Y98
Falls	W00-W19
Self-harm	X60-X84
Overdose/ accidental poisoning	X40-49, Y10-19, Y40-59

5.4 Statistical analyses

5.4.1 Descriptive analysis

Distributions of the mine fire-related $PM_{2.5}$ were investigated for all fire-impacted SA2s. Distributions of crude monthly mortality rates were also explored across SA2s. The crude monthly mortality rates for the combined fire-impacted SA2 areas for cause of death categories of interest were examined using the underlying cause of death as well as both the underlying and associated causes. Age adjusted rates were not calculated as there were issues with small cell counts when numbers of deaths were broken down into age groups.

Initial exploration of mortality data involved time series plots of weekly counts over the *entire analysis period* (i.e. 1 July 2009 to 30 June 2015). These provided insights into the potential time dependent patterns to be accounted for in subsequent modelling, such as long-term trends and/or seasonality. In addition, daily mortality rates were used to ascertain whether mortality differed in the 30-day *mine fire period* compared to the 30 days immediately pre and post the fire, and compared to the same 30 day period one year pre and one year post the fire.

5.4.2 Time series analyses for impacts of coal mine fire on mortality

Time-series analyses relating daily data on air pollutants to health outcomes are frequently used to assess the short-term health effects of air pollution [16]. The method allows for adjustment for potential confounders (such as temperature and seasonality) when estimating the outcome-exposure relationship in the exposed population.

The time series analyses were divided into two parts. In the first part, we examined whether there was an increased risk of mortality overall, and an increased risk of mortality from cause of death categories of interest, during the coal mine fire period and in the six months post the mine fire. The second part of the analyses specifically assessed the impact of mine-fire related $PM_{2.5}$ on mortality rates.

Aggregated daily counts of underlying cause of death as well as both underlying and associated causes of death data were used in the time series analyses. Results from underlying and associated causes of deaths data are presented in the main body of this report, while those results based on underlying cause of death are included in the Appendix (Section 10).

Time series analysis for the mine fire period and six months post the mine fire period

An interrupted time series Poisson regression was used to estimate the relative risk (RR) of deaths associated with the mine fire period, and in the six months after, relative to the remainder of the analysis period. The model was structured as a generalised additive model (GAM) with a random effect of location (SA2). The interrupted time series were created by introducing two sets of dummy variables indicating the period during the mine fire and the period six months post the mine fire.

Potential confounders were also included: seasonality modelled using a natural cubic spline with four degrees of freedom (df) for day of the year; long-term trend modelled simply as year of the event; day of the week included as a seven-category variable and public holidays included as a binary variable (public holiday yes or no). The impact of maximum ambient temperature was modelled using a distributed lag non-linear model (DLNM) with non-linear dose-response relationship (modelled using natural cubic spline with three df, and nonlinear lag response relationship (modelled using natural cubic spline with three df for a seven-days lag period). To adjust for potential population age structure differences across SA2s, the fraction of the population aged 80 years and over was also included as a confounding variable. The population on each day of the analysis period was estimated using ABS mid-year population data in each SA2 via a local weighted regression (LOESS) model which was used as a model offset term in GAM.

Based on this model, attributable counts and fractions were estimated for the mine fire period and for the period six months after the mine fire, in Morwell, in the broader Latrobe Valley and in surrounding areas. Attributable counts indicate the number of deaths additional to those expected during the mine fire, and during the 6 months after the mine fire, in each area after controlling for confounding variables. Attributable fraction indicates the proportion of all observed deaths which are represented by those attributable counts. For example: if there were 30 deaths, of which 15 were attributed to the mine fire and not explained by other known factors, the attributable count would be 15 and the attributable fraction would be 0.5 (or 50%).

Stratified analyses by age group (under 80 vs. 80 years and above), gender and condition of interest were also conducted. In the age-stratified analyses, to control for further age structure differences across SA2s, the fraction of the population aged between 70 to 79 was used as the covariate for the under 80 group, and the fraction of the population aged 85 and over was used for the 80 and over group. Sensitivity analyses were conducted comparing results using underlying cause of death and underlying and associated causes of death.

Time series analysis for fire-related $PM_{2.5}$

The above analysis can only provide evidence on whether the time period of the coal -mine fire was associated with an increased risk of death overall, and an increased risk of death from particular causes, but cannot provide evidence of any immediate dose-response relationship between air pollution concentration levels and mortality outcomes. For this reason, we used a similar model as above to examine whether increases in coal mine fire-related $PM_{2.5}$ led to increased risks of death. For these models, the daily exposure estimates for $PM_{2.5}$ for different SA2s replaced the fire period variable used in the above models.

An increase in air pollution may increase the risk of death on the current day, but also on the following days. Hence the lagged effects of $PM_{2.5}$ were also estimated through the DLNM assuming a linear dose-response relationship and a non-linear lag-response relationship described using a natural cubic spline. Lag periods of 0-3 (3 df), 0-5 (3 df), 0-7 (3 df), 0-14 (3 df) and 0-21 (4 df) days were all examined to provide a more comprehensive understanding of the associations.

All analyses were conducted using the statistical analysis software package R (version 3.5.1).

6 Results

6.1 Descriptive analysis

The distributions of modelled daily average $PM_{2.5}$ concentrations attributable to the coal mine fire during the 30 day mine fire period for selected fire impacted SA2s are shown in Figure 2 using violin plots. The violin plot displays the mirrored smoothed density distribution, which illustrates the skewed distributions of $PM_{2.5}$ concentrations with extreme values being present. The length of each plot represents the range of modelled $PM_{2.5}$ concentrations in that SA2. The thicker the violin shape is at each $PM_{2.5}$ level, the more likely residents were exposed at that value. As shown in Figure 2 the daily average fire-related $PM_{2.5}$ concentration was highest in Morwell, with other SA2 areas in the Latrobe Valley also high compared to the surrounding areas.

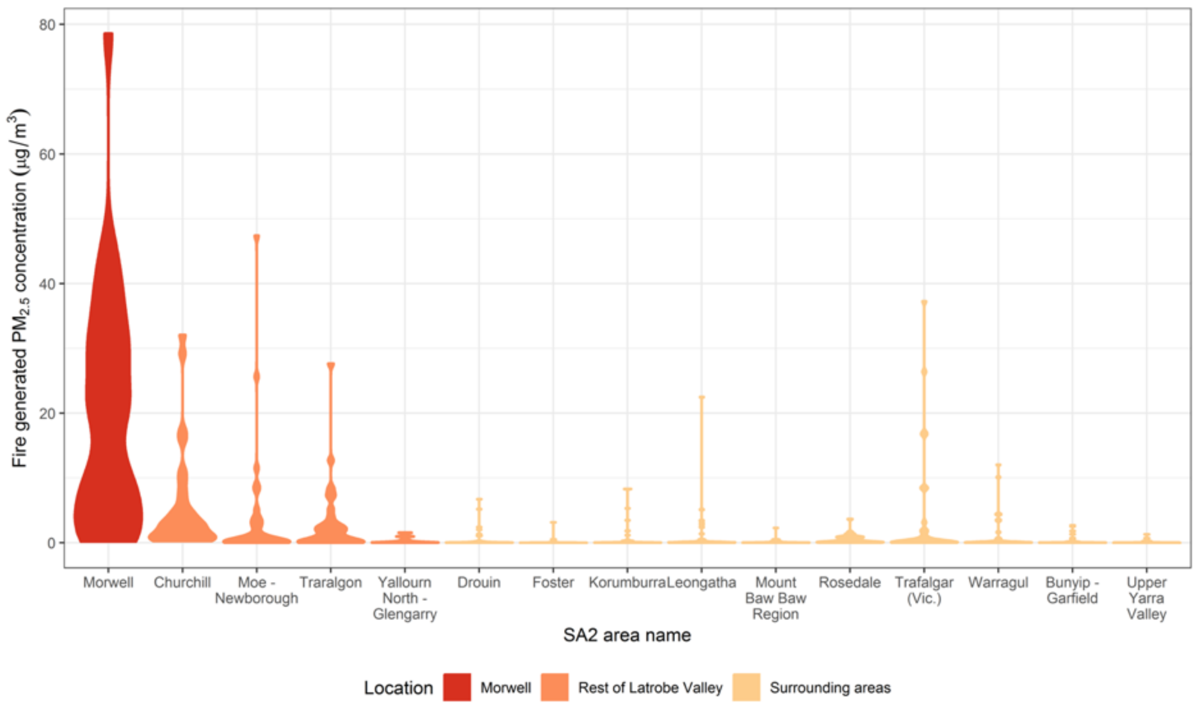


Figure 2 Distribution of modelled daily average $PM_{2.5}$ concentrations ($\mu g/m^3$) emitted from the coal mine fire during the mine fire period for selected fire impacted SA2s

Crude mortality rates for the entire analysis period, the mine fire period and the period six months post the mine fire in each SA2 are shown in Table 2. There was spatial variation in mortality rates with differences observed across SA2s for the entire analysis period, mine fire period and six months post the mine fire. For the entire analysis period, Moe-Newborough had the highest mortality rates compared to other SA2s, followed by Morwell, which is likely due to the different population structure across SA2 levels. The monthly mortality rate in Upper Yarra Valley was very low and therefore death records in this area were excluded from the remainder of the analysis. As there was spatial variation across SA2s, these differences were adjusted for when assessing the impact of the mine fire on mortality in the statistical models (see sections 6.2 and 6.3).

Table 2 Distribution of crude monthly mortality rates per 100,000 population by SA2

	Entire analysis period*	Mine fire period	6 months post the mine fire†
SA2 name	**Median rate (IQR)**	**Rate**	**Median rate (IQR)**
Morwell	91.5 (63.6-106.7)	56.6	120.4 (104.4-131.1)
Rest of Latrobe Valley			
Churchill	34.6 (25.9-51.8)	60.5	30.2 (13.0-41.0)
Moe - Newborough	95.1 (77.1-112.4)	106.8	130.6 (93.5-149.8)
Traralgon	60.1 (45.9-70.9)	48.4	61.4 (56.7-71.6)
Yallourn North - Glengarry	44.0 (22.0-66.9)	88.1	44.0 (27.5-44.0)
Surrounding areas			
Drouin	57.3 (39.5-68.0)	20.0	59.2 (53.0-65.7)
Foster	69.7 (47.8-93.6)	115.9	80.6 (43.3-100.9)
Korumburra	54.6 (33.8-81.7)	99.3	55.0 (54.9-63.3)
Leongatha	73.7 (63.3-93.3)	54.6	90.9 (84.0-111.5)
Mount Baw Baw Region	33.1 (32.9-66.1)	65.9	32.9 (16.5-61.7)
Rosedale	21.8 (21.1-43.2)	42.2	31.6 (5.3-42.2)
Trafalgar (Vic.)	52.5 (39.3-69.8)	66.9	46.5 (30.0-63.3)
Warragul	57.0 (39.3-81.0)	56.0	80.5 (57.1-91.7)
Bunyip - Garfield	36.1 (24.1-59.2)	69.2	63.2 (57.6-68.9)
All areas combined	64.4 (59.4-71.7)	64.6	73.9 (69.1-74.8)

* Between July 2009 and June 2015

† Between 11 March 2014 and 11 September 2014

Table 3 shows crude mortality rates by broad and specific cause of death categories using underlying cause of death, and both underlying and associated causes, in fire impacted areas. This analysis indicated that the number of mortality records were too few for most of the specific cause of death categories to yield reliable statistical inference. Hence, the main analyses using time series models were performed for broader death categories, including 'all respiratory', 'all cardiovascular', 'all mental health' and 'all injuries' as well as IHD as this was a major cause of death in the areas of interest.

As the mortality rates across broad cause of death categories were also low when only underlying cause of death data were used, the main analyses used both underlying and associated causes. The analyses using only underlying causes are presented in the Appendix (Section 10) as a part of the sensitivity analysis.

Table 3 Crude monthly mortality rate by cause of death categories per 100,000 population for all mine fire-impacted SA2s combined

	Underlying and associated causes of death			Underlying cause of death		
	Entire analysis period*	Mine fire period	6 months post the mine fire†	Entire analysis period*	Mine fire period	6 months post the mine fire†
Categories	Median rate (IQR)	Rate	Median rate (IQR)	Median rate (IQR)	Rate	Median rate (IQR)
All Cardiovascular	36.0 (33.3-40.1)	33.9	43.9 (40.7-45.2)	19.8 (16.8-22.4)	17.2	24.9 (24.5-25.6)
Ischaemic heart disease	18.0 (16.1-20.3)	15.4	20.3 (19.8-22.1)	9.6 (7.5-10.4)	8.0	11.3 (10.6-12.6)
Cerebrovascular disease	8.2 (6.4-9.7)	8.6	10.4 (10.0-11.4)	3.7 (3.0-4.9)	3.1	5.5 (4.6-6.0)
Other cardiovascular	24.5 (21.7-26.8)	19.7	29.1 (28.4-31.3)	5.8 (3.9-7.1)	5.5	7.4 (7.4-8.3)
All Respiratory	20.9 (18.0-22.7)	16.0	23.6 (22.4-23.9)	5.0 (3.7-6.8)	1.8	6.5 (5.7-7.2)
Asthma	0.6 (0.0-1.2)	0.0	0.3 (0.0-0.6)	0.0 (0.0-0.0)	0.0	0.0 (0.0-0.5)
COPD	6.8 (5.0-8.5)	2.5	8.3 (6.6-8.6)	3.1 (1.9-3.8)	0.6	4.3 (2.9-4.3)
Pneumonia and acute bronchitis	9.9 (7.5-11.6)	11.1	11.7 (11.1-12.7)	0.6 (0.6-1.3)	0.6	1.5 (0.8-2.3)
Other respiratory diseases	7.1 (5.6-8.9)	4.3	8.9 (8.1-9.7)	0.6 (0.6-1.3)	0.6	1.8 (0.8-2.5)
All Mental Health	3.2 (2.5-4.9)	4.3	4.3 (2.9-4.3)	0.0 (0.0-0.6)	0.0	0.0 (0.0-0.0)
Anxiety	0.0 (0.0-0.6)	0.6	0.6 (0.2-0.6)	0.0 (0.0-0.6)	0.0	0.0 (0.0-0.0)
Depression	0.7 (0.6-1.3)	1.2	1.5 (1.2-1.8)	0.0 (0.0-0.6)	0.0	0.0 (0.0-0.0)
Other mental health	2.6 (1.9-3.7)	4.3	3.1 (2.6-3.5)	0.0 (0.0-0.6)	0.0	0.0 (0.0-0.0)
All Injuries	6.2 (5.0-8.3)	12.3	7.7 (6.3-9.1)	3.2 (2.4-4.4)	9.2	3.7 (3.2-6.0)
Falls	1.3 (0.6-2.4)	4.9	1.8 (1.8-3.2)	1.3 (0.6-1.8)	4.9	1.8 (1.4-3.2)
Self-harm	1.2 (0.6-1.8)	2.5	0.9 (0.2-1.7)	1.2 (0.6-1.3)	2.5	0.9 (0.2-1.7)
Overdose/Accidental poisoning	1.2 (0.0-1.3)	0.6	1.2 (0.8-1.7)	0.6 (0.0-0.6)	0.6	0.6 (0.6-1.1)
Other injuries	4.5 (3.8-6.1)	8.0	6.1 (5.2-6.6)	1.3 (0.6-1.9)	3.7	1.5 (0.8-2.3)

* Between July 2009 and June 2015

† Between 11 March 2014 and 11 September 2014

The weekly time series plots for overall deaths, and deaths from conditions of interest, display the underlying seasonality and temporal trends (Figure 3). A clear seasonal trend is particularly noticeable in the respiratory conditions data across the analysis period. There was some evidence of an increase in deaths from injuries during the mine fire. For overall deaths there was no apparent trend over time.

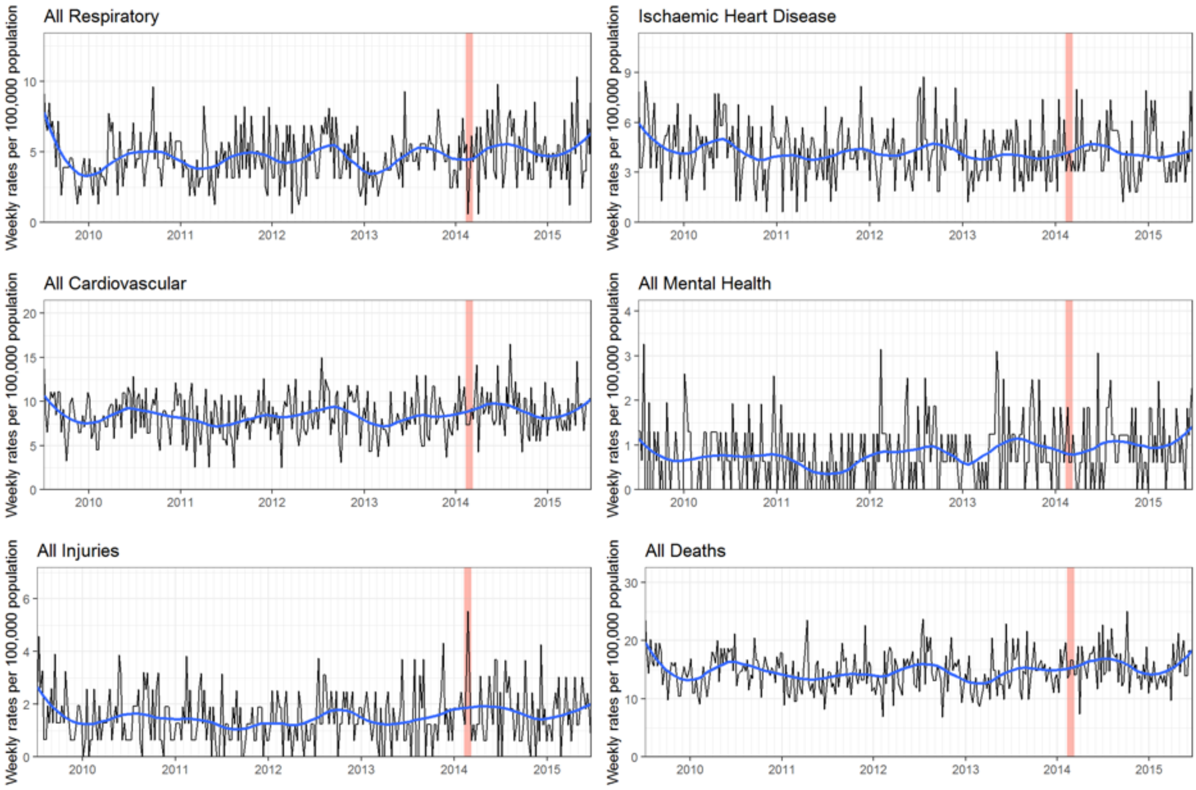


Figure 3 Unadjusted weekly time series of death rates for all fire impacted SA2s, 1 July 2009 to 30 June 2015

Note: Red bars indicate the mine fire period and the superimposed blue line is the LOESS smoothed curve

6.2 Time series analysis for the mine fire period and six months post mine fire

Figure 4A shows the relative risks for mortality overall, and by cause of death categories, during the mine fire period and during the six months after the mine fire period, compared to the remainder of the analysis period in two locations; in all of the Latrobe Valley (including Morwell) and in the surrounding smoke impacted areas. In the Latrobe Valley and in the surrounding areas, when cause of death category was not considered, the overall risks of death during the mine fire period, and during the six months after the mine fire period, were similar to those expected.

When causes of death categories were analysed separately, the results varied. During the 30 day mine fire period compared to the remainder of the analysis period, the risk of death from injuries was more than double in the Latrobe Valley (RR 2.65, 95%CI 1.42-4.96, equating to an estimated 165% increase in risk). An increased risk of death from unintentional injuries (excluding self-harm) in the Latrobe Valley during the mine fire was also observed, with a 146% increase in risk (RR 2.46, 95%CI: 1.28 to 4.73; results not shown). This suggested that the estimated increased risk of death from injuries in the Latrobe Valley was largely due to unintentional injuries. There was also some evidence of an increased risk of death from injuries in the areas surrounding the Latrobe Valley during the mine fire (RR 1.98, 95%CI 1.01-3.90).

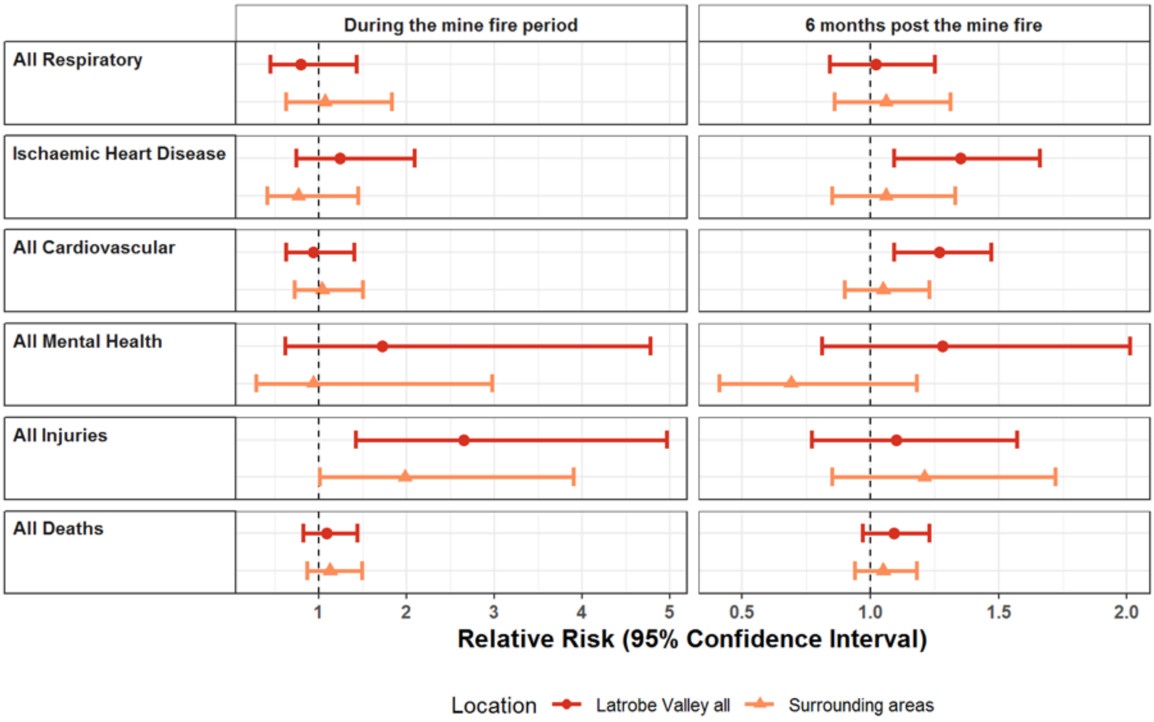
In the six months after the mine fire, there was an estimated 27% increase in risk of death from cardiovascular conditions (RR 1.27, 95%CI 1.09-1.47) in the Latrobe Valley, particularly deaths with underlying IHD where a 35% increase was observed (RR 1.35, 95%CI 1.09-1.66). However, there was no increase in cardiovascular-related deaths in the areas surrounding the Latrobe Valley in that six month period.

Figure 4B demonstrates the relative risks for mortality overall, and by cause of death categories, during the mine fire period and during the six months after the mine fire compared to the remainder of the analysis period in three location groups; in Morwell alone, in the rest of the Latrobe Valley and in the surrounding areas. The overall risks of death during the 30 day mine fire period (when cause of death categories were not considered), in all three location groups, were similar to those expected. However, in the six months after the mine fire, in Morwell but not in the other two locations, the overall risk of death was increased by 29% (RR 1.29, 95%CI 1.04-1.59).

During the 30 day mine fire period, there was a 325% increase in risk of death from injuries in Morwell (RR 4.25, 95%CI 1.53-11.78) and weaker evidence of an increased risk of death from injuries in the rest of the Latrobe Valley (RR 2.19, 95%CI 1.01-4.73) and in the surrounding areas (RR 1.98, 95%CI 1.01-3.90). During the 30 day mine fire period, there were no other causes of death found to be increased in Morwell, in the rest of the Latrobe Valley or in surrounding areas.

In the six months after the mine fire, and in Morwell, there was a 62% increase in risk of death from cardiovascular conditions (RR 1.62, 95%CI 1.25-2.10), and an 88% increase in risk of death from IHD (RR 1.88, 95%CI 1.32-2.67). No increased risk was observed in the rest of the Latrobe Valley (which excluded Morwell) or in the surrounding areas. As the increased risk of death from cardiovascular conditions remained when Morwell was analysed separately from the rest of the Latrobe Valley, this suggested that the effect observed in the Latrobe Valley (Figure 4A) was mostly driven by cardiovascular-related deaths in Morwell. There were no increases observed for respiratory-related deaths in any of the time periods or any of the locations.

A



B

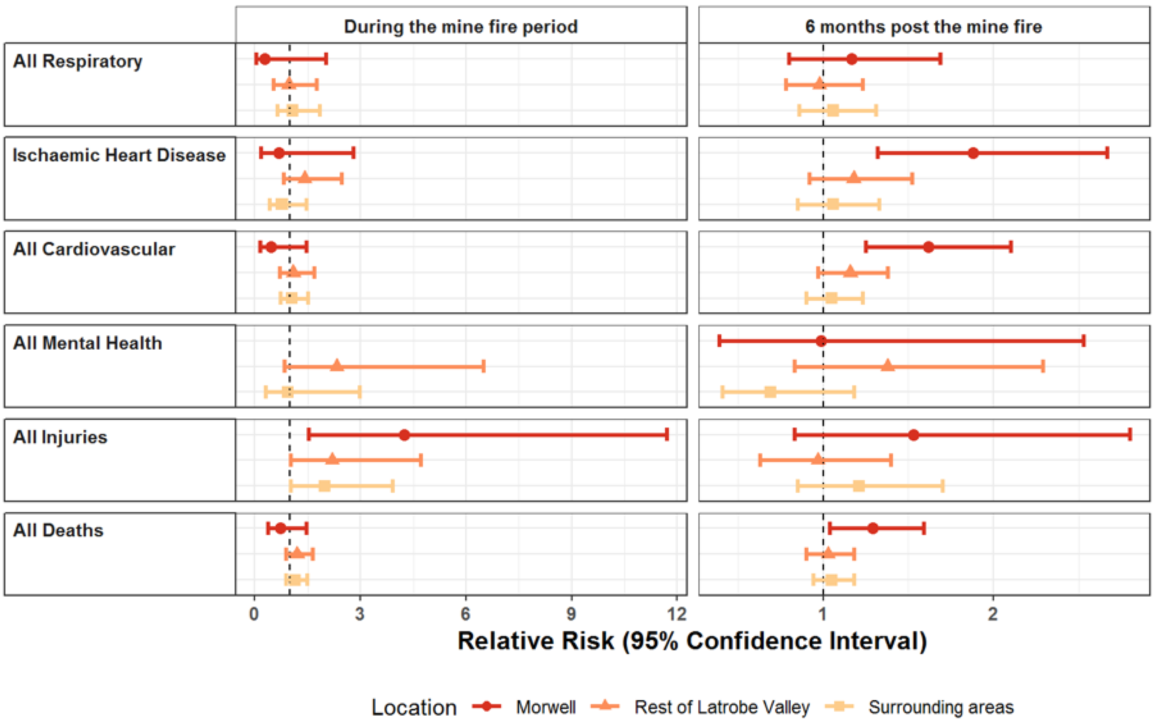


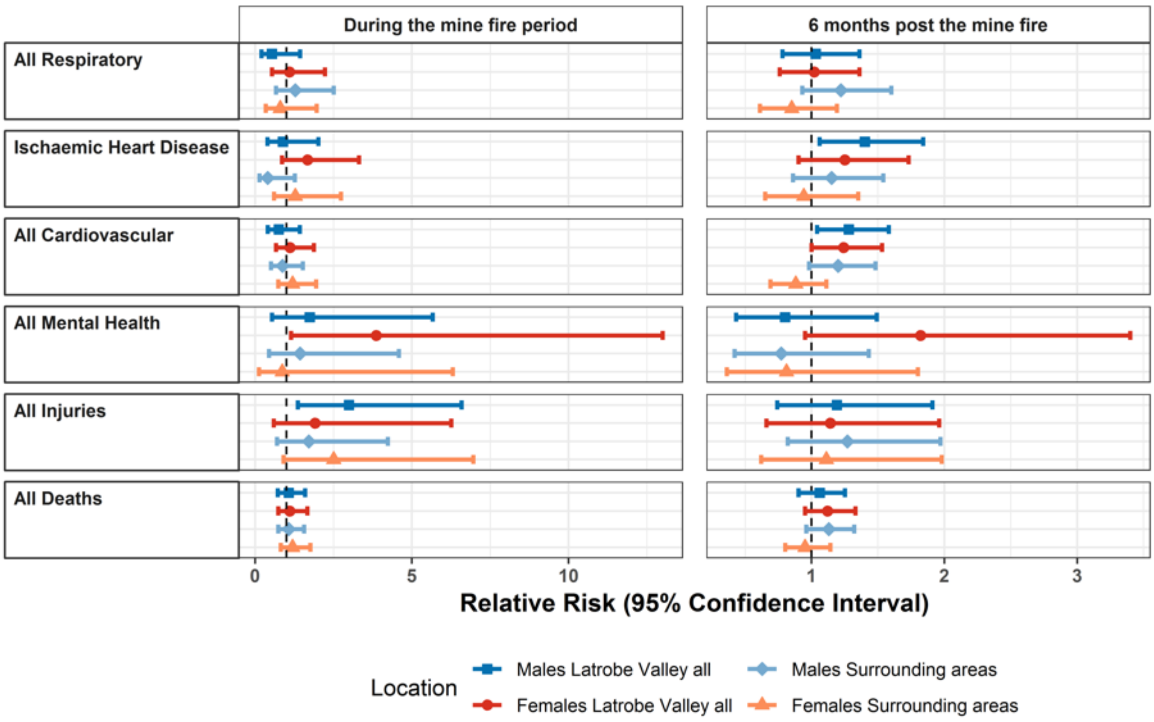
Figure 4 RRs for daily mortality rate overall, and by cause of death categories, during the mine fire period, and 6 months post mine fire compared with the remainder of the analysis period: (A) by two location groups where Morwell is included in the Latrobe Valley (B) by three location groups

Note: Relative risks (RR) were adjusted for seasonality, public holidays, day of the week, daily maximum temperature, long-term temporal trends and fraction of population aged 80 and over. RR for All Mental Health-related deaths in Morwell during the mine fire period could not be estimated due to small numbers.

Figure 5A shows the results of the analyses stratified by gender. The relative risks of mortality overall, and by cause of death categories, during the mine fire period and six months post the mine fire period, were estimated for all of the Latrobe Valley (including Morwell) and for the surrounding areas, for each gender. During the mine fire, and six months post the mine fire, the overall risks of death for both males and females in the Latrobe Valley and in the surrounding areas were similar to those expected. For males there was an increased risk of death from injuries in the Latrobe Valley during the mine fire period. Amongst females there was some evidence of a small increase in risk of death from mental health conditions in the Latrobe Valley during the mine fire period. Further investigation showed these to have mental health as an associated cause of death and not an underlying cause of death. There was some evidence of an increased risk of death from cardiovascular conditions for both males and females in the Latrobe Valley in the six months post the mine fire. Males had a 40% (95%CI: 6% to 84%) greater risk of death from IHD in the Latrobe Valley in the six months post the mine fire. In the surrounding areas, for both males and females, during the mine fire and for six months post the mine fire, no increased risks were observed for any of the cause of death categories.

Similarly, Figure 5B shows the results of the stratified analyses by age groups (80 and above and below 80 years). The overall risk of mortality in the Latrobe Valley and surrounding areas for both age groups were similar to those expected when compared to the remainder of the analysis period. In the Latrobe Valley, during the mine fire, there was an increased risk of death from injuries in residents aged 80 and above, and some evidence of an increased risk of death from injuries in residents aged below. Residents in the Latrobe Valley aged 80 and above, were at greater risk of death from cardiovascular conditions, particularly IHD, in the six months post the mine fire when compared to the remainder of the analysis period.

A



B

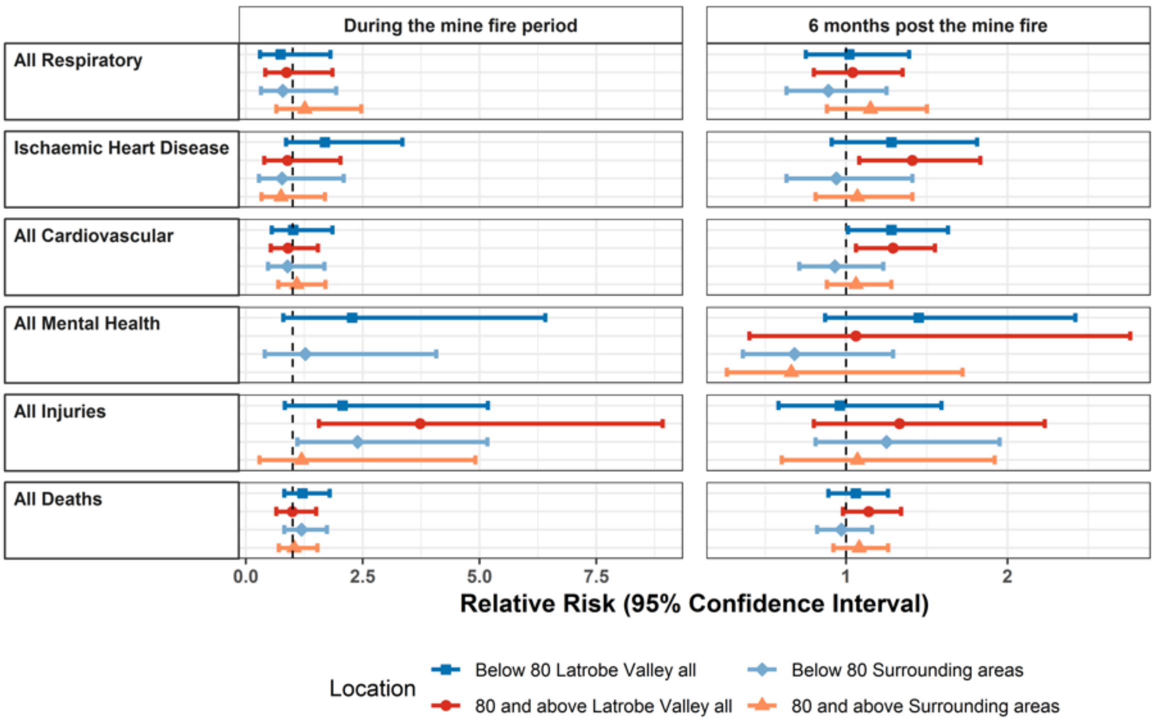


Figure 5 RRs for daily mortality rate overall and by cause of death categories during the mine fire period and six months post mine fire compared with the remainder of the analysis period: (A) by location groups and gender (B) by location group and age group.

Note: Relative risks (RR) were adjusted for seasonality, public holidays, day of the week, daily maximum temperature, long-term temporal trends, fraction of population aged 85 and over (for the 80 and above group) and fraction of population aged between 70-79 for the below 80 group.

An overview of the findings from Figures 4 and 5 is shown in Table 4.

Table 4 Summary of associations between time period, location and risk of death

Cause of death	From Figures 4A, 5A and 5B	From Figure 4B	
	In all of the Latrobe Valley (incl Morwell)	In Morwell	In the rest of the Latrobe Valley (excl Morwell)
During the 30 day mine fire period			
Overall deaths	As expected	As expected	As expected
All injuries	Increased, particularly unintentional injuries, and in men and residents aged 80+	Increased (may account for most of the increase in all Latrobe Valley)	Increased (weak)*
All cardiovascular	As expected	As expected	As expected
Ischaemic Heart Disease	As expected	As expected	As expected
All mental health	As expected in the total population, but a small increase in risk among women	Too few cases to estimate	As expected
Respiratory-related	As expected	As expected	As expected
In the 6 months after the mine fire			
Overall deaths	As expected	Increased	As expected
All injuries	As expected	As expected	As expected
All cardiovascular	Increased, particularly in men and in residents aged 80+ (weaker evidence in residents aged <80)	Increased	As expected
Ischaemic Heart Disease	Increased, particularly in men and in residents aged 80+	Increased (may account for most of the increase in all cardiovascular)	As expected
All mental health	As expected	As expected	As expected
Respiratory-related	As expected	As expected	As expected

* There was also a weak increase in injury-related deaths during the 30 day mine fire period in the smoke impacted areas surrounding the Latrobe Valley (see Figure 4B). There was no other evidence of increased mortality in the areas surrounding the Latrobe Valley.

Table 5 Mean attributable fractions and total attributable counts for Morwell, the rest of the Latrobe Valley and for surrounding areas during the mine fire and 6 months after the mine fire.

		During the mine fire period		6 months post the mine fire	
Cause of death	**Location**	**Mean attributable fraction (95% CI)**	**Total attributable counts (95% CI)**	**Mean attributable fraction (95% CI)**	**Total attributable counts (95% CI)**
All Respiratory	Morwell	-2.54 (-24.30, 0.50)	-3 (-24, 1)	0.14 (-0.24, 0.41)	5 (-8, 13)
	Rest of Latrobe Valley	-0.04 (-0.91, 0.43)	0 (-10, 5)	-0.02 (-0.29, 0.18)	-2 (-25, 16)
	Surrounding areas	0.07 (-0.59, 0.45)	1 (-8, 6)	0.06 (-0.16, 0.24)	6 (-17, 26)
Ischaemic Heart Disease	Morwell	-0.44 (-4.83, 0.64)	-1 (-10, 1)	**0.47 (0.24, 0.63)**	**17 (9, 23)**
	Rest of Latrobe Valley	0.29 (-0.24, 0.59)	4 (-3, 8)	0.15 (-0.08, 0.34)	12 (-6, 26)
	Surrounding areas	-0.29 (-1.43, 0.31)	-3 (-14, 3)	0.06 (-0.18, 0.25)	5 (-17, 23)
All Cardiovascular	Morwell	-1.15 (-5.71, 0.31)	-3 (-17, 1)	**0.38 (0.20, 0.52)**	**26 (13, 35)**
	Rest of Latrobe Valley	0.08 (-0.41, 0.40)	2 (-9, 9)	0.14 (-0.03, 0.28)	21 (-4, 42)
	Surrounding areas	0.04 (-0.39, 0.33)	1 (-12, 10)	0.05 (-0.11, 0.18)	10 (-22, 37)
All Mental Health	Morwell	-	-	-0.01 (-1.57, 0.60)	0 (-8, 3)
	Rest of Latrobe Valley	0.57 (-0.20, 0.85)	2 (-1, 3)	0.28 (-0.20, 0.56)	5 (-4, 11)
	Surrounding areas	-0.07 (-2.40, 0.66)	0 (-7, 2)	-0.45 (-1.46, 0.15)	-7 (-23, 2)
All Injuries	Morwell	**0.76 (0.35, 0.92)**	**3 (1, 4)**	0.35 (-0.21, 0.65)	4 (-2, 8)
	Rest of Latrobe Valley	**0.54 (0.01, 0.79)**	**4 (0, 6)**	-0.03 (-0.58, 0.33)	-1 (-15, 8)
	Surrounding areas	**0.49 (0.01, 0.74)**	**4 (0, 7)**	0.17 (-0.18, 0.42)	7 (-7, 16)
All Deaths	Morwell	-0.38 (-1.78, 0.31)	-3 (-14, 3)	**0.22 (0.04, 0.37)**	**22 (4, 36)**
	Rest of Latrobe Valley	0.17 (-0.14, 0.39)	7 (-6, 16)	0.03 (-0.11, 0.15)	8 (-27, 39)
	Surrounding areas	0.12 (-0.16, 0.33)	7 (-9, 18)	0.05 (-0.07, 0.16)	18 (-23, 55)

Note: Attributable fractions and counts were adjusted for seasonality, public holidays, day of the week, daily maximum temperature, long-term temporal trends and fraction of population aged 80 and over. Attributable fractions and counts for All Mental Health-related deaths in Morwell during the mine fire period could not be estimated due to small numbers.

Table 5 shows that, during the 30 day mine fire period, there were an estimated 11 injury-related deaths in the Latrobe Valley and surrounding areas combined that were "attributable to the mine fire"; meaning that they were additional to those expected and not explained by the variables included as possible confounders in the analysis model. Three of these attributable deaths were in Morwell. Morwell had a higher mean attributable fraction of injury-related deaths (0.76, 95%CI 0.35 - 0.92) than the rest of the Latrobe Valley (0.54, 95%CI 0.01 - 0.79) and surrounding areas (0.49, 95%CI 0.01 - 0.74), indicating a stronger relationship between the mine fire and injury-related deaths in Morwell than in the rest of the Latrobe Valley and surrounding areas.

In the six months after the mine fire, the analysis estimated that there were 26 cardiovascular-related deaths in Morwell attributed to the mine fire (95%CI 13-35), including 17 ischemic heart disease deaths (95%CI 9-23). When 'all deaths' were analysed, irrespective of cause of death, there were 22 attributable deaths in Morwell during the six months after the mine fire event (95%CI 4-36).

6.3 Time series analysis for mine fire-related $PM_{2.5}$

The relative risks over the lag period (cumulative RR) for mortality overall, and by cause of death categories, associated with each 10 µg/m^3 increase in mine fire-related $PM_{2.5}$, are shown in Table 6.

When assuming the lag effect lasted for three days, each 10 µg/m^3 increase in fire-related $PM_{2.5}$ on day zero was associated with a 59% (95%CI: 2 to 146%) increased risk of death from injuries. Similarly, there was an 80% (95%CI: 24 to 163%) increased risk when assuming the lag effect lasted for 5 days, a 78% (95%CI: 20 to 164%) increase for up to 7 days, a 92% (95%CI: 24 to 197%) increase for up to 14 days, and a 113% (95%CI: 14 to 297%) for up to 21 days. No other associations were found between mine fire-related $PM_{2.5}$ and overall mortality, or mortality caused by conditions of interest for any of the lag periods specified. In the stratified analysis the associations between exposure and injury were only identified in males and residents aged 80 and above (results not shown), which is consistent with the time series analysis for the mine fire period.

Table 6 Cumulative RRs for daily rates of mortality overall, and by cause of death categories, associated with each 10 μg/m^3 increase in fire-related $PM_{2.5}$ for different lag periods in all fire impacted SA2s

Condition	Specified lag days for $PM_{2.5}$	Cumulative RR*	95% CI	p-value
All Respiratory	0-3	0.88	0.52 - 1.50	0.64
	0-5	0.58	0.24 - 1.43	0.24
	0-7	0.34	0.08 - 1.39	0.13
	0-14	0.21	0.04 - 1.08	0.06
	0-21	0.25	0.05 - 1.18	0.08
Ischaemic Heart Disease	0-3	0.90	0.52 - 1.57	0.72
	0-5	0.84	0.46 - 1.54	0.58
	0-7	0.83	0.44 - 1.55	0.55
	0-14	1.04	0.61 - 1.79	0.88
	0-21	1.00	0.53 - 1.87	1.00
All Cardiovascular	0-3	0.78	0.50 - 1.22	0.27
	0-5	0.79	0.52 - 1.22	0.30
	0-7	0.77	0.49 - 1.21	0.26
	0-14	0.79	0.49 - 1.27	0.33
	0-21	0.83	0.50 - 1.37	0.46
All Mental Health	0-3	0.50	0.05 - 5.14	0.56
	0-5	0.33	0.02 - 5.56	0.44
	0-7	0.88	0.24 - 3.27	0.85
	0-14	0.94	0.26 - 3.39	0.92
	0-21	0.62	0.10 - 4.03	0.62
All Injuries	**0-3**	**1.59**	**1.02 - 2.46**	**0.04**
	0-5	**1.80**	**1.24 - 2.63**	**0.002**
	0-7	**1.78**	**1.20 - 2.64**	**0.004**
	0-14	**1.92**	**1.24 - 2.97**	**0.003**
	0-21	**2.13**	**1.14 - 3.97**	**0.02**
All deaths	0-3	1.05	0.84 - 1.31	0.69
	0-5	0.98	0.76 - 1.27	0.87
	0-7	0.97	0.74 - 1.26	0.80
	0-14	0.94	0.69 - 1.27	0.68
	0-21	0.96	0.69 - 1.33	0.80

* Cumulative RRs were adjusted for seasonality, public holidays, day of the week, daily maximum temperature, long-term temporal trends and their associated 95% confidence intervals (CIs).

6.4 Sensitivity analysis

Sensitivity analyses using only the underlying cause of death data (as opposed to both underlying and associated causes) suggested similar results to those shown above using underlying and associated cause of death data (see Appendix, Section 10).

7 Discussion

7.1 Summary of main findings

The 30 day mine fire period (from 9 February - 10 March 2014 when daily modelled $PM_{2.5}$ concentrations exceeded 1 µg/m^3) was associated with an increased risk of death from injury in Morwell and, to a lesser degree, in the broader Latrobe Valley. These were largely due to deaths from unintentional injuries. In total 11 injury-related deaths during this 30 day period, in the Latrobe Valley and surrounding areas, were "attributed" to the mine fire; meaning they were additional to those expected and not explained by other known factors. Males and residents aged 80 years and older in the Latrobe Valley were at greatest excess risk of death from injury during the mine fire. Acute increases in mine fire related $PM_{2.5}$ were associated with increased risk of death from injuries in the following days, but not with increased risk of deaths from other cause of death categories of interest. Some evidence of an increased risk of mental health-related death in females was also observed in the Latrobe Valley during the mine fire. In the 30 day mine fire period, when cause of death was not considered, the overall death rate in the Latrobe Valley looked similar to that expected.

In the six months after the mine fire, there was an increased risk of death from cardiovascular conditions, particularly IHD, for residents in Morwell and in the broader Latrobe Valley. In total for this six month period, there were an additional 26 cardiovascular-related deaths in Morwell attributed to the mine fire, which included 17 IHD deaths. The 26 cardiovascular related deaths represented 38% of all cardiovascular deaths in Morwell for that time. Males and residents aged 80 and above in the Latrobe Valley were at an increased risk of death from IHD in the six months after the mine fire. There was some evidence of an increased overall death rate (when cause of death was not considered) in Morwell in the six months after the mine fire.

For the rest of the Latrobe Valley and surrounding areas, the overall risks of death during the mine fire and six months post the mine fire were similar to those expected.

7.2 Relationship to the Hazelwood Mine Fire Inquiry investigation into deaths

The Hazelwood Mine Fire Inquiry Report 2015/2016, Volume II Investigation into 2009-2014 deaths [17] reported several preliminary analyses of death data. Associate Professor Adrian Barnett from the Queensland University of Technology analysed monthly numbers of deaths across six postcodes in the Latrobe Valley over the period 2009-2014 for the months January to June. In the second of two reports, the latter accounting for monthly temperatures which were excluded from the first report, the analysis estimated a 10% increase in risk of death during the two months (February and March) of the mine fire, with the likely number of additional deaths for the two months being 9.6.

Separate analyses undertaken by Dr Louisa Flander and Professor Dallas English at the University of Melbourne found weak evidence of additional deaths in Morwell in the year 2014 compared with 2009-2013, but fewer deaths in February-March than in previous years. However, the numbers of deaths in Morwell were too small to be conclusive. In the broader Latrobe Valley, there were an estimated nine additional monthly deaths for February-March 2014 compared with February-March 2009-2013, however these results were also inconclusive with wide confidence intervals. In a further report, Dr Flander and others concluded that there was no statistical evidence of associations between the mine fire and deaths in the Latrobe Valley [17].

Compared to those investigations, our analyses comprised additional data and methods which gave us greater confidence in our results. We were able to draw on NMD death data for the period 1 July 2009 to 30 June 2015, which included both underlying and associated causes of death. We also had daily maximum temperature data collected from the Australian Bureau of Meteorology. Our analyses controlled for factors likely to influence mortality rates including seasonality, public holidays, day of the week, daily maximum temperature, long-term temporal trends and change of population age-structure. With the addition of average 24-hourly $PM_{2.5}$ concentrations for Morwell and surrounding SA2s, which had been modelled by CSIRO, we were able to investigate any dose-response relationship between air pollution concentration levels and mortality outcomes.

7.3 Relationship to previous published scientific research

There are very few studies that have explored the association between air pollution and injury outcomes (neither mortality nor morbidity), particularly no study of coal mine fire-related air pollution. To the best of our knowledge, there is only one study examining the relationship between air pollution and unintentional injury mortality from Korea using nationally representative data [18]. This study found that there was a significant association between exposure to air pollution (PM_{10}, CO, NO_2, SO_2, and O_3) and risk of death due to unintentional injury.

The potential mechanism between air pollution and injury might be explained by the significant impact of exposure to environmental pollutants on neurological and behavioural effects, such as poor cognitive judgment, anxiety and depression [19-22] and self-harm [23]. Because of the small sample size, our study was not able to sub-categorise injury into more detailed injury types. It was also not possible to infer what activities or behaviours led to the injury-related deaths. Further research may assist with interpretation.

We also found some evidence of an increased risk of death where mental health conditions were an associated cause. Our previous research shows associations between the mine fire event and increases in symptoms of psychological distress [24, 25], dispensation of mental health medications [26] and mental health consultations [27]. Growing literature has shown associations between air pollutants and a range of mental health outcomes including depression [28, 29], anxiety [30, 31], psychosis [32] and cognitive development [33].

It was not surprising that the elderly (aged 80 years and above) were most affected by coal mine fire smoke [34-36]. Many studies have shown that older people are more sensitive to air pollution than the young [37-39]. The elderly generally have weaker immune systems, or undiagnosed respiratory or cardiovascular conditions, making them particularly susceptible to air pollution. As people age, their bodies are less able to compensate for the effects of environmental hazards.

The impact of coal mine fire on cardiovascular-related mortality was not immediate during the fire period, but appeared in the following six months. This indicates a longer term association between coal mine fire and mortality from cardiovascular conditions. Previous studies found that air pollution not only had short-term impacts [40, 41] but also long-term impacts on cardiovascular mortality [42, 43]. The reason for an absence of a significant short-term effect on cardiovascular mortality in our study might be explained by people with cardiovascular diseases consciously protecting themselves with preventive medications as shown in our previous research [26].

There are a number of possible mechanisms by which fine particles are thought to have cardio-pulmonary effects, including by inducing pulmonary oxidative stress and inflammation, and by translocation of particles into the systemic circulation [44]. It is also known that stress and anxiety contribute to cardiovascular mortality, as has been observed after disasters including the Great East Japan Earthquake [45] and the World Trade Centre Disaster [46]. Stress increases the vasomotor reflex response and stimulation of the sympathetic nervous system, leading to increases in blood pressure and heart rate [45].

A 2016 review of studies on wildfire smoke exposure and health showed consistent evidence of associations between smoke and general respiratory health effects, specifically asthma and chronic obstructive pulmonary disease, but not between smoke and respiratory-related mortality [47]. Whilst we also observed no association between the mine fire smoke and respiratory-related mortality, this should not be interpreted as meaning that the smoke posed no threat to people with respiratory illnesses. Instead, it is likely that vulnerable people with respiratory illnesses took preventive action including leaving the smoke impacted areas, wearing protective masks and/or increasing their use of preventive medications. Previous Hazelwood Health Study research has shown that the mine fire was associated not only with increased respiratory symptoms [48], respiratory-related ambulance call outs [49], emergency presentations and hospital admissions [50], but also increased dispensing of medications for respiratory conditions [26].

7.4 Strengths & weaknesses

These Hazelinks analyses have several strengths:

- This research provides the first known report of deaths from specific causes after a medium duration brown-coal open cut mine fire event, providing direct evidence regarding the impact of prolonged coal mine fire smoke on mortality.

- The use of a distributed nonlinear lag model to examine the potential delayed effects aids in understanding which days of exposure were associated with estimated increases in mortality. A major benefit of using these statistical models is that they are able to account for the delayed and nonlinear effects of ambient maximum temperature and pollutants to provide cumulative risk estimates for health outcomes along with lag specific ones. We were able to identify a lagged impact of $PM_{2.5}$ across a number of days and establish where the significant lagged effects lay. The flexibility of this type of modelling technique lies in the ability to set the number of degrees of freedom, number of lags and type of smoothing spline used.

- The analyses controlled for the potential confounding effects of maximum daily ambient temperature, long-term trend, public holidays, day of the week, seasonality and population age structure.

- The use of a high spatial resolution air exposure model allowed $PM_{2.5}$ smoke concentrations, arising from the coal mine fire, to be estimated for geographic areas where air quality monitor measurements were not available.

However, these analyses also have some limitations:

- The numbers of deaths from specific causes were few in the fire impacted areas due to low population density, hence the analyses were based on small numbers and should be interpreted with caution.
- This study design was ecological and, therefore, it was not possible to examine associations at an individual level. Time series models were established at SA2 level resolution (townships), due to small number of records at the SA1 level (smallest geographical unit for the release of census data). Hence the heterogeneity of exposure levels within each SA2, particularly within Morwell, was not considered. Therefore, it is possible that the impact of the mine fire has been underestimated for the most highly exposed residents. Information on other risk factors was also not available (e.g. cigarette smoking and alcohol consumption).
- Our analyses only investigated the impact of coal mine fire-related $PM_{2.5}$ and did not include other criterion pollutants such as carbon monoxide (CO), ozone, nitrogen dioxide or sulphur dioxide. However apart from CO on the first day, levels of these pollutants remained below National Environment Protection Measures.
- The use of modelled $PM_{2.5}$ concentrations in lieu of individual level measurements may have introduced exposure misclassification. This would bias effect estimates towards the null, reducing the likelihood of detecting an association.
- The datasets used in these analyses were collected for administrative purposes and, therefore, presented some limitations. One limitation relates to the difficulty of identifying the true underlying cause of death.
- Increased risk estimates and attributable counts and fractions which are statistically associated with the mine fire don’t necessarily imply a direct causal relationship between the smoke levels and mortality. It is possible that there were factors, other than those included in our models, that contributed to increased mortality during and after the mine fire event. Examples might include an economic downturn during and after the fire, increased demand on health services, or a change in the age structure of the local population with people moving out of the area.

8 Conclusions

This analysis shows clear evidence that there were increased numbers of deaths from injury during the coal mine fire, and increased deaths from cardiovascular causes in the six months after the fire. Acute increases in coal mine fire related $PM_{2.5}$ were associated with increases in injury deaths. These findings contribute to filling the knowledge gap which existed regarding the health impacts of open cut brown coal mine fire smoke exposure. Such research is important to improve health impact assessment of at-risk groups, and to improve targeted health advice and emergency health services. The findings should be helpful to develop and implement effective and more timely adaptive strategies and health planning to respond to and mitigate health risks due to future coal mine fire derived air pollution exposures in the community.

9 References

1. Brunekreef, B. and S.T. Holgate, *Air pollution and health.* Lancet, 2002. **360**(9341): p. 1233-42.
2. Beelen, R., et al., *Effects of long-term exposure to air pollution on natural-cause mortality: an analysis of 22 European cohorts within the multicentre ESCAPE project.* Lancet, 2014. **383**(9919): p. 785-95.
3. Haikerwal, A., et al., *Fine particulate matter (PM2.5) exposure during a prolonged wildfire period and emergency department visits for asthma.* Respirology, 2016. **21**(1): p. 88-94.
4. Strickland, M.J., et al., *Short-term associations between ambient air pollutants and pediatric asthma emergency department visits.* Am J Respir Crit Care Med, 2010. **182**(3): p. 307-16.
5. Faustini, A., et al., *Short-term effects of air pollution in a cohort of patients with chronic obstructive pulmonary disease.* Epidemiology, 2012. **23**(6): p. 861-79.
6. Dennekamp, M., et al., *Outdoor Air Pollution as a Trigger for Out-of-hospital Cardiac Arrests.* Epidemiology, 2010. **21**(4): p. 494-500.
7. Colais, P., et al., *Particulate air pollution and hospital admissions for cardiac diseases in potentially sensitive subgroups.* Epidemiology, 2012. **23**(3): p. 473-81.
8. Pope, C.A., 3rd, et al., *Ischemic heart disease events triggered by short-term exposure to fine particulate air pollution.* Circulation, 2006. **114**(23): p. 2443-8.
9. Haikerwal, A., et al., *Impact of Fine Particulate Matter (PM2.5) Exposure During Wildfires on Cardiovascular Health Outcomes.* J Am Heart Assoc, 2015. **4**(7).
10. Johnston, F., et al., *Extreme air pollution events from bushfires and dust storms and their association with mortality in Sydney, Australia 1994–2007.* Environmental Research, 2011. **111**(6): p. 811-816.
11. Atkinson, R.W., et al., *Epidemiological time series studies of PM2.5 and daily mortality and hospital admissions: a systematic review and meta-analysis.* Thorax, 2014.
12. Melody, S.M. and F.H. Johnston, *Coal mine fires and human health: What do we know?* International Journal of Coal Geology, 2015. **152, Part B**: p. 1-14.
13. Emmerson, K., et al., *Air quality modelling of smoke exposure from the Hazelwood mine fire*. 2016, CSIRO: Australia.
14. Guo, Y., et al., *Global variation in the effects of ambient temperature on mortality: A systematic evaluation.* Epidemiology, 2014. **25**(6): p. 781-789.
15. Guo, Y., et al., *Heat Wave and Mortality: A Multicountry, Multicommunity Study.* Environmental health perspectives, 2017. **125**(8): p. 087006.
16. Bhaskaran, K., et al., *Time series regression studies in environmental epidemiology.* International Journal of Epidemiology, 2013. **42**(4): p. 1187-1195.
17. Hazelwood Mine Fire Inquiry. *Hazelwood Mine Fire Inquiry Report 2015/2016 Volume II - Investigation into 2009-2014 deaths*. 2015; Available from: http://hazelwoodinquiry.vic.gov.au/wp-content/uploads/2015/12/Hazelwood-Mine-Fire-Inquiry-Report-2015-16-Volume-II.pdf.
18. Ha, K.H., et al., *Air pollution and unintentional injury deaths in South Korea.* Environ Sci Pollut Res Int, 2015. **22**(10): p. 7873-81.
19. Calderón-Garcidueñas, L., et al., *Air pollution, cognitive deficits and brain abnormalities: a pilot study with children and dogs.* Brain and cognition, 2008. **68**(2): p. 117-127.

20. Cho, J., et al., *Air pollution as a risk factor for depressive episode in patients with cardiovascular disease, diabetes mellitus, or asthma.* Journal of affective disorders, 2014. **157**: p. 45-51.

21. Freire, C., et al., *Association of traffic-related air pollution with cognitive development in children.* Journal of Epidemiology & Community Health, 2010. **64**(3): p. 223-228.

22. Weuve, J., et al., *Exposure to particulate air pollution and cognitive decline in older women.* Archives of internal medicine, 2012. **172**(3): p. 219-227.

23. Bakian, A.V., et al., *Acute air pollution exposure and risk of suicide completion.* American journal of epidemiology, 2015. **181**(5): p. 295-303.

24. Jones, R., et al., *Experiences of a prolonged coal-mine fire.* Disaster Prevention and Management, 2018. **27**(5): p. 534-545.

25. Maybery, D., et al., *Psychological outcomes following the Hazelwood mine fire: A mixed methods study*. 2019.

26. Johnson, A.L., et al., *Fine particulate matter exposure and medication dispensing during and after a coal mine fire: A time series analysis from the Hazelwood Health Study.* Environ Pollut, 2019. **246**: p. 1027-1035.

27. Johnson, A.L., et al., *Coal-mine fire-related fine particulate matter and medical-service utilization in Australia: a time-series analysis from the Hazelwood Health Study.* International Journal of Epidemiology, 2019.

28. Lim, Y.-H., et al., *Air pollution and symptoms of depression in elderly adults.* Environmental health perspectives, 2012. **120**(7): p. 1023-1028.

29. Szyszkowicz, M., B. Rowe, and I. Colman, *Air pollution and daily emergency department visits for depression.* International journal of occupational medicine and environmental health, 2009. **22**(4): p. 355-362.

30. Power, M.C., et al., *The relation between past exposure to fine particulate air pollution and prevalent anxiety: observational cohort study.* bmj, 2015. **350**: p. h1111.

31. Pun, V.C., J. Manjourides, and H. Suh, *Association of ambient air pollution with depressive and anxiety symptoms in older adults: results from the NSHAP study.* Environmental health perspectives, 2016. **125**(3): p. 342-348.

32. Attademo, L., et al., *Environmental pollution and risk of psychotic disorders: A review of the science to date.* Schizophrenia research, 2017. **181**: p. 55-59.

33. Clifford, A., et al., *Exposure to air pollution and cognitive functioning across the life course–a systematic literature review.* Environmental research, 2016. **147**: p. 383-398.

34. Di, Q., et al., *Association of short-term exposure to air pollution with mortality in older adults.* Jama, 2017. **318**(24): p. 2446-2456.

35. Saldiva, P.H., et al., *Air pollution and mortality in elderly people: a time-series study in Sao Paulo, Brazil.* Archives of Environmental Health: An International Journal, 1995. **50**(2): p. 159-163.

36. Devlin, R., et al., *Elderly humans exposed to concentrated air pollution particles have decreased heart rate variability.* European Respiratory Journal, 2003. **21**(40 suppl): p. 76s-80s.

37. Guo, Y., et al., *The burden of air pollution on years of life lost in Beijing, China, 2004-08: retrospective regression analysis of daily deaths.* Bmj, 2013. **347**: p. f7139.

38. Kan, H., et al., *Season, sex, age, and education as modifiers of the effects of outdoor air pollution on daily mortality in Shanghai, China: The Public Health and Air Pollution in Asia (PAPA) Study.* Environmental health perspectives, 2008. **116**(9): p. 1183-1188.

39. Chen, R., et al., *Short-term exposure to sulfur dioxide and daily mortality in 17 Chinese cities: the China air pollution and health effects study (CAPES).* Environmental research, 2012. **118**: p. 101-106.

40. Analitis, A., et al., *Short-term effects of ambient particles on cardiovascular and respiratory mortality.* Epidemiology, 2006. **17**(2): p. 230-233.

41. Guo, Y., et al., *The short-term effect of air pollution on cardiovascular mortality in Tianjin, China: Comparison of time series and case–crossover analyses.* Science of the Total Environment, 2010. **409**(2): p. 300-306.

42. Pope, C.A., et al., *Cardiovascular mortality and long-term exposure to particulate air pollution: epidemiological evidence of general pathophysiological pathways of disease.* Circulation, 2004. **109**(1): p. 71-77.

43. Pope, C.A., et al., *Lung cancer and cardiovascular disease mortality associated with ambient air pollution and cigarette smoke: shape of the exposure–response relationships.* Environmental health perspectives, 2011. **119**(11): p. 1616-1621.

44. Knol, A.B., et al., *Expert elicitation on ultrafine particles: likelihood of health effects and causal pathways.* Particle and Fibre Toxicology, 2009. **6**(1): p. 19.

45. Takiguchi, M., et al., *Trends in the Incidence of Sudden Deaths and Heart Diseases in Fukushima After the Great East Japan Earthquake.* International Heart Journal, 2019. **60**(6): p. 1253-1258.

46. Cohen, H.W., et al., *Long-term Cardiovascular Disease Risk Among Firefighters After the World Trade Center Disaster.* JAMA Network Open, 2019. **2**(9): p. e199775-e199775.

47. Reid, C., et al., *Critical review of health impacts of wildfire smoke exposure.* Environ Health Perspect, 2016. **124**: p. 1334–1343.

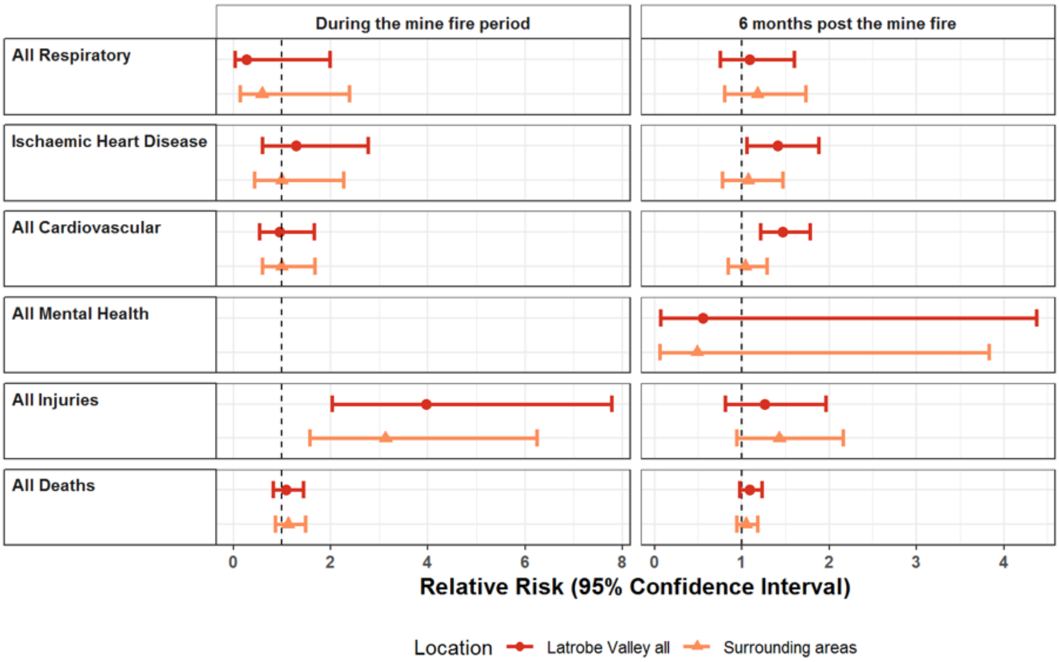
48. Johnson, A., et al., *Associations between respiratory health outcomes and coal mine fire* $PM_{2.5}$ *smoke exposure: a cross-sectional study.* Environment International, 2019. **submitted**.

49. Guo, Y., et al., *Hazelwood Health Study Hazelinks Ambulance Victoria Data: Time Series Analyses (First Data Extraction)*. 2017.

50. Dennekamp, M., et al. *Hazelinks – Emergency presentations and hospital admissions analysis (First Data Extraction) v 1.2*. 2017 18/02/2020]; Available from: https://hazelwoodhealthstudy.org.au/__data/assets/pdf_file/0004/1636483/2017-08-30-hospital-analysis-extract-1-technical-report.ver1_.1.pdf.

10 Appendix

A



B

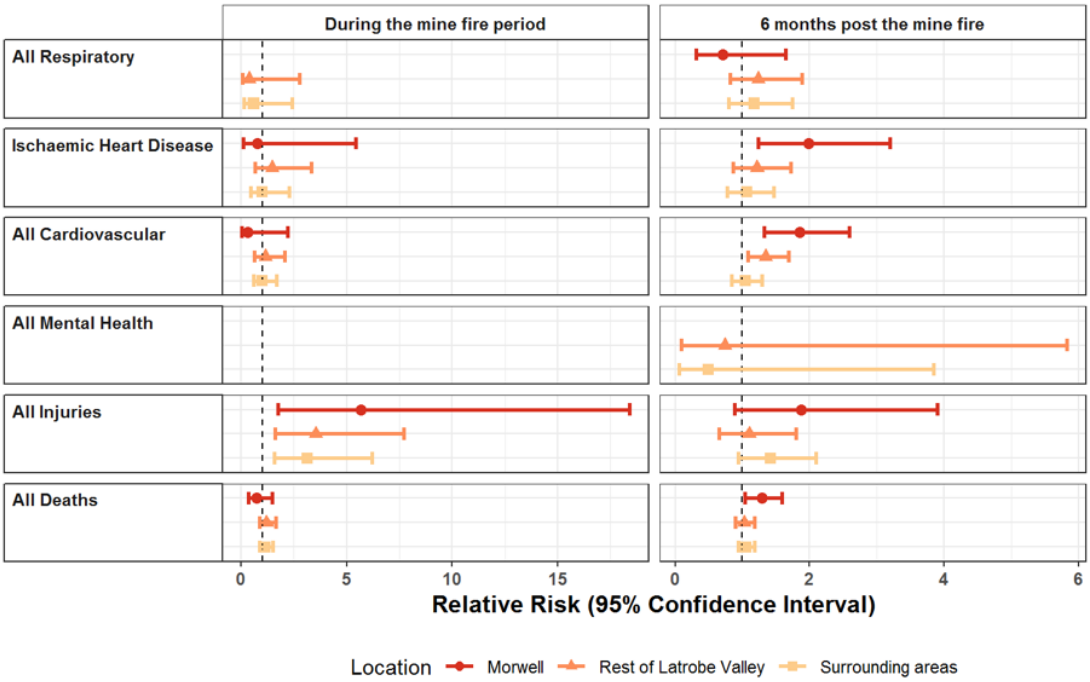


Figure A1 RRs for daily mortality rate overall and by underlying cause of death categories (not including associated causes) during the mine fire period and six months post mine fire compared with the remainder of the analysis period: (A) by two location groups where Morwell is included in the Latrobe Valley (B) by three location groups

Note: RR were adjusted for seasonality, public holidays, day of the week, and daily maximum temperature, long-term temporal trends and fraction of population over age 80 and over.

Table A1 Cumulative RRs for daily rates of mortality overall, and by underlying cause of death categories (not including associated causes), associated with each 10 μg/m³ increase in fire-related $PM_{2.5}$ for different lag periods in all fire impacted SA2s

Condition	Specified lag days for $PM_{2.5}$	Cumulative RR*	95% CI	p-value
All Respiratory†	0-3	-	-	-
	0-5	-	-	-
	0-7	-	-	-
	0-14	-	-	-
	0-21	-	-	-
Ischaemic Heart Disease	0-3	1.00	0.48 - 2.09	1.0
	0-5	0.87	0.36 - 2.10	0.76
	0-7	0.84	0.34 - 2.09	0.71
	0-14	1.17	0.58 - 2.37	0.67
	0-21	1.17	0.50 - 2.70	0.72
All Cardiovascular	0-3	0.83	0.47 - 1.46	0.52
	0-5	0.78	0.42 - 1.45	0.43
	0-7	0.77	0.41 - 1.45	0.42
	0-14	0.82	0.43 - 1.54	0.53
	0-21	0.87	0.44 - 1.72	0.69
All Mental Health	0-3^	-	-	-
	0-5^	-	-	-
	0-7^	-	-	-
	0-14	1.15	0.14 - 9.53	0.90
	0-21	1.91	0.25 - 14.65	0.54
All Injuries	**0-3**	**1.74**	**1.06 - 2.85**	**0.03**
	0-5	**2.02**	**1.33 - 3.06**	**0.001**
	0-7	**1.89**	**1.17 - 3.03**	**0.01**
	0-14	**2.03**	**1.19 - 3.44**	**0.01**
	0-21	**2.38**	**1.14 - 4.99**	**0.02**
All deaths	0-3	1.05	0.84 - 1.31	0.69
	0-5	0.98	0.76 - 1.27	0.87
	0-7	0.97	0.74 - 1.26	0.80
	0-14	0.94	0.69 - 1.27	0.68
	0-21	0.96	0.69 - 1.33	0.80

* Cumulative RRs were adjusted for seasonality, public holidays, day of the week, daily maximum temperature, long-term temporal trends and their associated 95% confidence intervals (CIs).

† Numbers too small to estimate the effect of exposure.

11 Document History

Version number	Date approved	Approved by	Brief description
1.0	19 Nov 2019	Senior Project Manager	Submitted to DHHS
1.1	21 Feb 2020	Senior Project Manager	Revised to include attributable counts and more detailed discussion. Resubmitted to DHHS
1.2	19 Oct 2020	Senior Project Manager	Report title and contact details revised. Broken link corrected on p 19.