Impacts of coal mine fire-related PM_{2.5} on the utilisation of ambulance and hospital services for mental health conditions

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Abstract

Climate change and an increase in the number of major fire events occurring around the world have drawn attention to the importance of understanding the association between air pollution events and mental health. In 2014, the Morwell open-cut brown coal mine adjacent to the Hazelwood power station in the Latrobe Valley region of Victoria, Australia, caught fire as a result of nearby wildfires, and exposed the local community to a prolonged period of deteriorated air quality. The aim of this study was to examine how exposure to coal mine fire-related fine particulate matter (PM_{2.5}) during the event affected the utilisation of local health services for mental health conditions (ambulance attendances; emergency department (ED) presentations; hospital admissions). A time-series analysis indicated that mine fire-related PM_{2.5} exposure was associated with short-term increases in ambulance attendances and ED presentations but not hospital admissions. To allow for delays between exposure and changes in service utilisation, different lag periods were assessed. The most prominent effects were observed over a 5-day lag period where, for each 10µg/m³ increase in daily mean mine fire-related PM_{2.5}, the risk of an ambulance attendance for anxiety increased by 38% (95%CI: 13% to 69%) and the risk of an ED presentation for depression increased by 36% (95%CI: 3% to 79%). Accordingly, ambulance and hospital services should expect to encounter an increase in the number of people seeking assistance for mental health conditions during extreme air pollution events and mechanisms need to be in place to ensure that surges in demand for mental health care during these circumstances can be accommodated.

Keywords: Emergency health services; Health service data linkage; Mental health; PM_{2.5} exposure; Coal mine fire; Time-series analysis.

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1. Introduction

Coal mines are highly vulnerable to fire events, either through spontaneous ignition or from external sources such as wildfires (Onifade & Genc, 2019). Because they are challenging to extinguish, coal mine fires have the capacity to become protracted events which can have extensive environmental, health, economic, and social consequences (Walker, 1999). Air-borne pollutants generated by coal combustion are broadly categorised as gases, volatile organic compounds and trace elements, and particulate matter with a median aerodynamic diameter less than 10 μ m or 2.5 μ m (PM₁₀ or PM_{2.5}) (Melody & Johnston, 2015; Munawer, 2018). A considerable body of evidence is available detailing the risks to physical health posed by exposure to smoke emanating from wild fires or from domestic coal combustion, including cardiovascular diseases and respiratory diseases, however, there has been very little research to date regarding the health impacts of coal mine fires (Melody & Johnston, 2015). In particular, there is a need for research that details what implications exposure to coal mine fire smoke has for mental health.

Association between air quality and mental health is an emerging topic in pollution research (Buoli et al., 2018) and is of importance given the growing risk of fire events occurring in the context of climate change (van Oldenborgh et al., 2021; Xu et al., 2020). At present, there is some evidence indicating that emergency presentations and hospital admissions are more frequently accessed for mental health problems in times when air quality deteriorates. For instance, elevation in ambient air pollution, including the concentration of PM_{2.5}, has been associated with increases in the number of presentations at emergency departments (ED) or hospital admissions for depression (Szyszkowicz et al., 2009; Wang et al., 2018), suicide attempts (Szyszkowicz et al., 2010), and substance abuse issues (Szyszkowicz et al., 2018). However, these studies are focused on changes in service utilisation associated with fluctuations in ambient air quality, rather than within the context a major pollution event caused by a bushfire or a coal mine fire.

On 9 February 2014, the Morwell open-cut brown coal mine adjacent to the Hazelwood power station in the Latrobe Valley region of Victoria, Australia, caught fire as a result of nearby wildfires, causing neighbouring areas to be covered in plumes of smoke and ash over a six-week period (Teague et al., 2014). The mine fire did not directly result in fatalities or significant loss of property; however, air quality monitoring indicated that PM_{2.5} levels during the event greatly exceeded accepted national safety standards, with concentrations in the residential area bordering the mine breaching the threshold considered safe on 23 days during the event (Luhar et al., 2020). The prolonged period of poor air quality due to the heavy distribution of smoke generated considerable concern in the local community. Many people living in Morwell, the major town of approximately 13,000 residents situated nearest to the mine, expressed concern about potential immediate and longer-term health consequences of exposure to the smoke (Jones et al., 2018; Macnamara, 2015; Yell et al., 2019). These concerns were a catalyst for the Victorian Department of Health commissioning a comprehensive study of the impacts of the mine fire on health and wellbeing (the Hazelwood Health Study; HHS).

HHS studies to date have found evidence indicating long-term mental health impacts of the Hazelwood mine fire in the affected community, including heightened levels of self-reported distress, increased use of mental health-related general practice and specialist services, and increased prescription of psychiatric medications (Broder et al., 2020; Johnson et al., 2019; Johnson et al., 2020; Maybery et al., 2020). However, it is also important to consider ambulance attendances, hospital ED presentations, and hospital admissions, as people often seek assistance through these services in response to episodes of mental health crisis (Murphy et al., 2015). Accordingly, to more comprehensively understand the mental health impacts of the mine fire and associated changes in mental health (MH) service demands, the aim of this analysis was to examine how exposure to PM_{2.5} during the mine fire period affected the utilisation of each of these services for mental health conditions.

2. Methods

2.1 Air pollution estimation

Due to incomplete ground-level air pollution monitoring at the time of the mine fire (Fisher et al., 2015; Reisen et al., 2017), CSIRO Oceans & Atmosphere used The Air Pollution Model (TAPM) v4.0.5 combined with a chemical transport model (Hurley, 2002; Hurley et al., 2008) to simulate the spatial-temporal distribution of mine fire smoke and to retrospectively estimate daily total PM_{2.5} concentrations during the event. The TAPM modelling also factored in PM_{2.5} concentrations in the region attributable to sources other than the mine fire. The modelled total PM_{2.5} concentrations were validated against local ground-level monitoring data collected during the later stages of the mine fire period and were found to be consistent. A parallel model was also generated to estimate expected PM_{2.5} concentrations (background PM_{2.5}) if the mine fire had not occurred. The mean daily background PM_{2.5} concentration was estimated to be 5 µg/m³ over the mine fire period (which is in line with meteorological data during non-fire periods). This background PM_{2.5} was subtracted from the estimated total PM_{2.5} to calculate PM_{2.5} concentration attributable to the mine fire smoke (mine fire-related PM_{2.5}). The modelling was mapped to Statistical Areas Level 2 (SA2) (Australian Bureau of Statistics, 2011) to generate daily estimates of mine fire-related PM_{2.5} concentrations according to locality across the Latrobe Valley and surrounding areas. A comprehensive description of the modelling approach has been published by Luhar et al. (2020).

SA2s were considered to have been exposed to the mine fire if the modelled daily average mine fire-related PM_{2.5} concentration in the area reached 1 µg/m³ for at least one day. The modelling indicated that daily mine fire-related PM_{2.5} concentrations, averaged across the Latrobe Valley, were greater than 1 µg/m³ from 9 February to 10 March 2014. After this time, mine fire-related PM_{2.5} concentrations in the region quickly returned to regular background levels. Accordingly, this 30-day stretch was used to define the mine fire period for the purpose of this

study. The 24-hourly average PM_{2.5} concentrations, and the peak mine fire-related PM_{2.5} concentrations, for each of the 13 impacted SA2s during the mine fire period are presented in Figure 1 and further detail can be found in Figure S1.

2.2 Source data

2.2.1 Ambulance attendance data

Ambulance attendance data for the period 1 July 2010 to 31 March 2015 were collected from the Ambulance Victoria Data Warehouse, which maintains electronic Patient Care Records (PCRs) created by paramedics at the point of care along with other operational data. Records include complex clinical and operational information such as event location, patient details, paramedic diagnosis, and attendance outcome. Data between 26 September 2014 and 31 December 2014 were unavailable due to the impact of industrial action on data collection by paramedics.

2.2.2 ED presentation data

ED presentation data for the period 1 July 2010 to 31 March 2015 were collected from the Victorian Emergency Minimum Dataset (VEMD) maintained by the Department of Health (DH). The dataset contained de-identified demographic, administrative, and clinical information about ED presentations at all public hospitals and a selection of private hospitals in the state of Victoria (Department of Health and Human Services, 2017).

2.2.3 Hospital admissions data

Hospital admissions data for the period 1 July 2010 to 31 March 2015 were obtained from the Victorian Admitted Episodes Dataset (VAED) also maintained by the DH. The data comprised demographic, clinical, and administrative information for all admitted episodes of care occurring in Victorian hospitals, rehabilitation centres, extended care facilities, and day procedure centres (Department of Health and Human Services, 2016).

2.2.4 Estimated residential population data

Estimated residential population data between 2005 and 2015 for each impacted SA2 area were obtained from the Australian Bureau of Statistics (<http://www.abs.gov.au/AUSSTATS/abs@.nsf/DetailsPage/3218.02014-15?OpenDocument>).

2.2.5 Daily maximum temperatures

Daily maximum temperatures between 2005 and 2015 for each impacted SA2 area were collected from the Australian Bureau of Meteorology (<http://www.bom.gov.au/climate/data-services/station-data.shtml>).

2.2.6 Mental health conditions

The ICD-10 principal diagnosis in ED and hospital admission data, and the final primary diagnosis in ambulance data, were used to categorise outcomes as “Anxiety”, “Depression” and “Other Mental Health conditions”. “All Mental Health conditions” represented these three categories combined. Final primary diagnosis was used in ambulance data. The assignment of diagnoses and ICD-10 codes to each of the MH condition categories are presented in the Supplementary Information (see Table S1).

2.3 Statistical analyses

Each unit record in the three datasets was supplied with an SA2 code based on either the residential address detailed for the patient in the ED presentations and hospital admissions data, or the attendance address detailed in the ambulance data. Monthly population rates (crude rates per 10,000 population) of service utilisation were first compared between (1) the period prior to the mine fire (calendar months from 1 July 2010 to 31 January 2014 inclusive), (2) during the peak exposure period (9 February 2014 to 10 March 2014 inclusive), and (3) the post-mine fire period (calendar months from 1 April 2014 to 31 March 2015 inclusive) in all smoke-exposed areas as well as in Morwell specifically. Time-series plots of monthly service utilisation rates were generated to visualise potential time-dependent patterns, such as long-term trends and seasonality.

Time-series analyses (generalised additive models; GAMs) were used to assess the impact of 24-hour mean mine-fire related PM_{2.5} on each service. Quasi-Poisson models were used to allow for over-dispersion of daily counts. For many environmental health factors, including air pollution, there is typically a delay in the ensuing presentation of consequent effects on health and mortality, commonly known as a lagged effect. The non-linear lag effect of PM_{2.5} was modelled using a distributed lag model (Gasparrini, 2011). We allowed for lags of 3, 5, 7, 14, and 30 days using a natural cubic spline with degrees of freedom varying from 2 to 5.

Our modelling also controlled for seasonality (modelled using a natural cubic spline with 4 degrees of freedom for day of the year), long-term trend (linear, modelled as year of the event), day of the week (a 7-category variable), daily maximum ambient temperature (characterised using a distributed lag model with non-linear exposure relationship and lags of up to 7 days), and public holidays (a binary variable: “yes” or “no”). Random intercepts for SA2 areas were included in the GAM to adjust for inherent spatial variations in service utilisation. The relative risks (RR) on each lag day were combined into a cumulative RR to estimate the overall effect of PM_{2.5} exposure over the modelled lag time. The cumulative RR per 10µg/m³ increase in mine fire-related PM_{2.5} is reported to facilitate direct comparisons with results reported in previously published literature.

Sensitivity analyses were performed to ascertain the robustness of findings. Models specifying different degrees of freedom in spline terms (3-5 lag days for air pollution; 3-6 for temperature; 5-9 for seasonality) and different lag days (3-20 for temperature) were tested.

All analyses were conducted using the software package R (Version 4.0.3) (R Core Team, 2016), with GAMs conducted using the package “mgcv” (Wood, 2004), and distributed lag non-linear structures conducted using the package “dlnm” (Gasparrini, 2011).

2.4 Ethics approval

This study protocol was approved by Monash University Human Research Ethics Committee (Project numbers 6066 and 25680). The datasets used in these analyses were collected primarily for administrative purposes and identifying information was removed from the data by the providers prior to being made accessible. Accordingly, individual informed consent was not required to conduct this study.

3. Results

Figure 1 illustrates that Morwell was exposed to a higher level of mine fire-related PM_{2.5} compared with the other nearby SA2s. However, several towns situated nearby were also exposed to elevated PM_{2.5} levels during the event. The distribution of modelled daily average PM_{2.5} concentrations for areas exposed to smoke during the mine fire is given in the Supplementary Information (Figure S1). Crude monthly rates of service utilisation were compared between the pre-, during-, and post-mine fire periods in all impacted areas (Table 1), and in Morwell specifically (Table 2). Monthly crude rates of service utilisation were higher during the mine fire period across all three services in the impacted area, and rates of MH-related ambulance attendances and ED presentations were almost doubled in Morwell compared with the average pre-and post-mine fire rates. Increased service utilisation rates were also found in the rest of the Latrobe Valley, and in surrounding areas (Table S2). During the mine fire period, ambulance attendance rates were highest for the most exposed SA2s. The volume of ED presentations was also highest in the SA2s most exposed during the event; however, increases in ED presentation rates were observed in other SA2s that were less exposed as well. Increases in hospital admissions were mainly evident in SA2s with lower exposure. Long-term trends in MH-related service utilisation rates (crude monthly rates) are provided in Figure 2. The rates of MH-related ambulance attendances and ED presentations remained relatively stable over the study period; however, rates of MH-related hospital admission increased gradually.

Figure 1

Geographical location of the SA2s impacted by smoke during the mine fire are colour-differentiated by (A) the mean 24-hour mine fire-related $PM_{2.5}$ exposure during the first 30 days of the mine-fire and (B) peak 24-hour mine fire-related $PM_{2.5}$ exposure

	Pre-mine fire period ^a Median rate (IQR) ^d	Mine fire period ^b Rate	Post-mine fire period ^c Median rate (IQR)
Ambulance attendances^e			
Anxiety	2.2 (1.9-2.5)	3.6	2.3 (2.0-2.6)
Depression	0.9 (0.8-1.2)	1.3	0.9 (0.8-1.0)
Other mental health	3.3 (3.0-3.6)	4.7	3.7 (2.9-4.5)
All mental health	6.5 (5.7-7.0)	9.7	6.7 (6.3-7.4)
ED presentations			
Anxiety	2.3 (1.9-2.5)	3.5	2.4 (2.1-2.6)
Depression	1.5 (1.3-1.8)	2.1	1.4 (1.3-1.6)
Other mental health	3.3 (3.0-3.6)	5.5	3.8 (3.5-4.3)
All mental health	7.1 (6.5-7.7)	11.0	7.8 (7.2-8.1)
Hospital admissions			
Anxiety	1.0 (0.8-1.1)	1.1	1.2 (1.0-1.5)
Depression	3.0 (2.5-3.8)	5.8	3.3 (3.1-3.7)
Other mental health	4.0 (3.4-4.6)	5.6	5.1 (4.7-5.3)
All mental health	7.8 (7.1-9.1)	12.6	10.4 (9.3-10.7)

^a Calendar month pre-mine fire = 1/7/2010 to 31/1/2014 (inclusive).

^b 30 day mine period = 9/2/2014 to 10/3/2014 (inclusive).

^c Calendar month post-mine fire = 1/4/2014 to 31/3/2015 (inclusive).

^d IQR = Interquartile range: 25th to 75th percentile.

^e Data between September and December 2014 were excluded due to the impact of industrial action on paramedic data collection.

Table 1

Comparison of monthly rates of MH-related ambulance and emergency service utilisation per 10,000 population for the periods (1) pre-mine fire, (2) during the mine fire, and (3) post-mine fire, for all 13 SA2s impacted by smoke from the mine fire combined. Utilisation rates are given by service type and mental health condition

	Pre-mine fire period ^a Median rate (IQR) ^d	Mine fire period ^b Rate	Post-mine fire period ^c Median rate (IQR)
Ambulance attendances^e			
Anxiety	4.2 (3.5-6.3)	9.2	4.3 (3.4-5.0)
Depression	1.4 (1.4-2.8)	2.1	1.4 (1.2-1.8)
Other mental health	7.0 (5.2-8.1)	12.1	10.3 (8.2-12.4)
All mental health	13.3 (11.2-15.4)	23.4	16.3 (14.8-19.2)
ED presentations			
Anxiety	4.9 (3.5-5.3)	6.4	4.3 (3.5-6.8)
Depression	2.8 (2.1-3.9)	5.0	2.8 (1.4-3.5)
Other mental health	6.3 (4.9-8.4)	12.8	7.8 (6.8-8.2)
All mental health	13.3 (12.6-15.6)	24.1	17.2 (13.8-18.2)
Hospital admissions			
Anxiety	1.4 (0.7-2.1)	0.7	2.1 (1.4-2.8)
Depression	2.8 (2.1-3.5)	5.0	5.7 (4.6-7.5)
Other mental health	6.3 (5.6-9.1)	7.8	8.6 (7.1-10.3)
All mental health	12.0 (8.7-14.1)	13.5	17.9 (13.9-20.2)

^a Calendar month pre-mine fire = 1/7/2010 to 31/1/2014 (inclusive).

^b 30 day mine period = 9/2/2014 to 10/3/2014 (inclusive).

^c Calendar month post-mine fire = 1/4/2014 to 31/3/2015 (inclusive).

^d IQR = Interquartile range: 25th to 75th percentile.

^e Data between September and December 2014 were excluded due to the impact of industrial action on paramedic data collection.

Table 2

Comparison of monthly rates of MH-related ambulance and emergency service utilisation

per 10,000 population for the periods (1) pre-mine fire, (2) during the mine fire, and (3) post-mine fire, for Morwell. Utilisation rates are given by service type and mental health condition

Figure 2

Monthly time-series for MH-related ambulance and emergency service utilisation for all SA2s exposed to $PM_{2.5}$ during the mine fire period. Note: Ambulance data between 25 September 2014 and 31 December 2014 were excluded from analyses due to the impact of industrial action on paramedic data collection

Figure 3 summarises the cumulative RRs for MH-related service utilisation associated with each 10 $\mu\text{g}/\text{m}^3$ increase in mine fire-related $\text{PM}_{2.5}$, with separate estimations for lag effects of 3, 5, 7, 14, and 30 days. After adjusting for confounders, short-term increases in anxiety-related ambulance attendances and depression-related ED presentations were found to be associated with increases in mine fire-related $\text{PM}_{2.5}$ exposure, suggesting a dose-response relationship. There was no evidence that MH-related hospital admission rates were associated with increases in mine fire-related $\text{PM}_{2.5}$ exposure. When the lag effect was assumed to last for 5 days, each 10 $\mu\text{g}/\text{m}^3$ increase in mine fire-related $\text{PM}_{2.5}$ exposure was associated with an estimated 38% (cumulative RR = 1.38, 95%CI: 1.13 to 1.69) increase in ambulance attendances for anxiety, and a 36% (cumulative RR = 1.36, 95% CI: 1.03 to 1.79) increase in ED presentations for depression; those being the largest estimated effect sizes among all lag models (see Figure 3). Ambulance attendances for “All MH conditions” were also found to be associated with $\text{PM}_{2.5}$ exposure in a dose-response relationship (cumulative RR = 1.17, 95%CI: 1.01 to 1.36 for a 7-day lag).

Figure 3

Results of time-series regression for the utilisation of each service type by mental health category for various lags. Note: results presented as cumulative relative risks (RR) and 95% confidence intervals associated with each 10 µg/m³ increase in mean mine-fire related PM_{2.5}

The individual RRs for different lag days, estimated from within the 7-day lag models, are displayed in Figure 4. A 7-day lag model was chosen to show how the risk of seeking health services for mental health conditions changed within the 7 days after mine fire-related PM_{2.5} exposure. The elevations in risk for anxiety-related ambulance attendances and depression-related ED presentations were found to begin from the first day after PM_{2.5} exposure (lag day 1) and to last for about 5 days. There was also evidence that PM_{2.5} exposure was associated with increased risk of ED presentations and hospital admissions at lag days 3 to 5 for “All MH conditions”, and for the “Other MH conditions” category specifically. However, due to a reduction in the RR estimated on the exposure day (lag 0), and after a week (lag day 7), there was no strong evidence for a cumulative effect.

(A) Ambulance attendances

(B) ED presentations

(C) Hospital admissions

Figure 4

Exposure-lag relationships for 10 $\mu\text{g}/\text{m}^3$ increases in mean fire-related $\text{PM}_{2.5}$, estimated using a 7-day lag model with (A) ambulance attendance data, (B) ED presentation data, and (C) Hospital admission data

4. Discussion

This study presents the first known analysis demonstrating how exposure to high levels of PM_{2.5} resulting from a prolonged brown coal mine fire affects rates of ambulance attendances, hospital ED presentations, and hospital admissions for mental health conditions in affected communities. The results of the study show that greater exposure to PM_{2.5} during the 2014 Hazelwood mine fire was associated with increased ambulance attendances for anxiety and increased ED presentations for depression, in dose-response relationships.

The adjusted time-series regression analysis indicated that, over a 5-day lag period, for every 10µg/m³ increase in mean mine fire-related PM_{2.5} the risk of an ambulance attendance for anxiety increased by 38% (95%CI: 13% to 69%) and the risk of an ED presentation for depression increased by 36% (95%CI: 3% to 79%). These increases in ambulance attendances and ED presentations are well above estimates from previous large scale ambient pollution studies, where similar 10µg/m³ increases in PM_{2.5} were associated with more modest increases of 1.5% for ambulance attendances (Phung et al., 2018) and 0.13% for ED presentations (Liu et al., 2019) for mental health conditions. It is evident that a severe pollution event involving a sudden, steep, and protracted increase in PM_{2.5} concentrations has considerably greater repercussions for mental health and the level of demand for ambulance attendances and ED presentations among those exposed, than the same 10µg/m³ increase in exposure resulting from changes in ambient pollution.

There are multiple mechanisms that could trigger a psychiatric episode in response to a large-scale smoke event, including stress or worry in relation to perceived threat posed by the fire itself, or respiratory distress due to exposure to pollutants in the atmosphere. Broder et al. (2020) identified several risk factors that predicted increased distress in

response to exposure to the Hazelwood mine fire, including younger age, unemployment, prior exposure to traumas, pre-existing mental health diagnosis, and pre-existing chronic illness. There is considerable evidence that respiratory and psychological health are interconnected, including a separate finding from the Hazelwood Health Study that increased distress was strongly associated with increased respiratory symptoms, regardless of level of exposure to mine fire-related PM_{2.5} (Samuel et al., in press). There is evidence that the link between respiratory and psychological symptoms is complex, with a meta-analysis by Grassi et al. (2013) concluding that hyperventilation may not be simply caused by anxiety but also by other respiratory factors.

While anxiety is one of the most common mental health conditions prompting an ambulance call out, attendances for depression are far less prevalent (Roggenkamp et al., 2018). This could be because anxiety may manifest as a physical concern, which generates a perception of urgency that increases the likelihood of an emergency call and an ambulance being dispatched (Coster et al., 2017; Roggenkamp et al., 2018). On the other hand, it may be that symptoms of depression are perceived as being somewhat less urgent in comparison with symptoms of anxiety, allowing time for the person to present to ED on their own, or to be brought there by other people. Alternatively, depression may be more readily identifiable as a mental health concern by the call centre triage system and, hence, prompt referral to alternative care pathways, such as General Practitioners and counselling services, rather than an ambulance dispatch (Roggenkamp et al., 2018).

The absence of a relationship between PM_{2.5} exposure during the mine fire period and hospital admissions should not be interpreted as indicating that mental health outcomes were transitory and not requiring of further support. It is likely that most of the MH-related ambulance attendances and ED presentations were subsequently treated in

non-hospital settings such as general practices and psychology practices (Wainberg et al., 2017). This is supported by other HHS findings showing that greater PM_{2.5} exposure was associated with increased use of MH-related general practice and specialist services, and the prescription of psychiatric medications (Johnson et al., 2019; Johnson et al., 2020). In addition, it has been reported that there was a shortage of MH-related beds in the region around the time of the mine fire, which may have further increased the likelihood that cases were referred to services outside the hospital (Office of the Public Advocate, 2013, 2014).

4.1 Implications for ambulance and hospital services

The current analysis demonstrates that ambulance and hospital services should expect to encounter an increase in the numbers of people seeking care for mental health-related issues during extreme air pollution events. In light of the increasing environmental volatility associated with climate change, major disaster and pollution events similar to the 2014 Hazelwood mine fire and the 2020 Australian Black Summer bushfires are becoming more common (Davey & Sarre, 2020; Vardoulakis et al., 2020). Hence, it is imperative that services be suitably resourced to meet mental health needs in response to such events. This issue of suitable resourcing is particularly urgent considering that rural areas are more susceptible to adverse environmental events related to climate-change (Hughes et al., 2016), but also typically subject to mental health workforce shortages and barriers that inhibit service access and uptake (State Government of Victoria, 2020). Pre-emptively increasing ambulance and hospital service response capacity during peak bushfire seasons might be a way to improve resourcing. The establishment of services and resources that can be mobilised swiftly to augment existing local services, such as embedding mental health professionals in emergency call centres or in ambulances, or setting up specially targeted mobile mental health response teams (Roggenkamp et al., 2018) may also be useful. As

demonstrated in the Australian responses to the Black Summer bushfires and subsequently the COVID-19 pandemic, there is also considerable potential in increasing the provision and accessibility of mental health care via telehealth, including access to free or subsidised services. This in turn may help to alleviate strains that are placed on ambulance and hospital services during fire or other pollution events (Berger & Reupert, 2020; Kendrick & Isaac, 2020).

4.2 Strengths and limitations of the study

A key strength of this study is that the distributed lag time-series regression model made it possible to account for potential delayed effects and determine which time-points were most critical, across mental health conditions and health service-types. Furthermore, our evaluation of the associations across multiple lag-effect lengths supported the robustness of model results. The model also made it possible to control for the potential confounding effects of maximum daily ambient temperature, long-term trend, public holidays, and day of the week. Another strength of the research method implemented in this study is the utilisation of objective, rather than self-report, outcome data.

This study does, however, also have limitations. The use of modelled PM_{2.5} concentrations at an SA2 level instead of an SA1 or individual level measurement introduces the possibility of exposure misclassification due to heterogeneity of PM_{2.5} exposure levels in the population. In theory, this would bias effect estimates towards the null and reduce the likelihood of detecting an association. Additionally, 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, ozone, nitrogen dioxide or sulphur dioxide, however these are likely to have been collinear with PM_{2.5}.

The datasets used in these analyses were collected primarily for administrative purposes and, accordingly, had associated limitations. One important limitation relates to the level of diagnostic precision that can be expected in each service. There are inherent difficulties in making rapid clinical judgements in emergency situations where formal mental health assessments are impractical and rarely administered. For instance, research by Taggart et al. (2006) concluded that anxiety disorders are poorly identified in the ED during routine assessment. Accordingly, it is possible that the relationship between PM_{2.5} exposure and utilising health services for MH-related concerns may be stronger than reported here.

4.3 Conclusion

This study demonstrates that a large-scale mine fire event causing a protracted period of poor air quality, including high concentrations of PM_{2.5}, was associated with increases in ambulance attendances for anxiety and emergency department presentations for depression in those areas exposed to greater levels of mine fire-related PM_{2.5}. Given the growing likelihood of future fire events due to climate change, there is a need to ensure that the health system is prepared to respond to periods of increased demand for mental health services and, in particular, mental health crisis support.

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6. Supplementary Information

Category	Final Principal Diagnosis for Ambulance attendances	Principal diagnoses for hospital admissions and ED presentations (ICD10 code)
Anxiety	Anxiety; panic attack	F40-44
Depression	Depression	F32-33
Other mental health	Emotional distress; eating disorder; psychiatric episode; self-harm ideation; sleep disorder; suicidal Ideation	F4-99 (excluding F40-44 and F32-33)
All mental health	Includes all of the above	Includes all of the above

Table S1

Assignment of health service diagnosis codes to mental health condition categories

	Pre-mine fire period ^a (Median rates, IQR) ^d	Mine fire period ^b (Rate)	Post-mine fire period ^c (Median rates, IQR)
Ambulance attendances^e			
Morwell	13.3 (11.2-15.4)	23.4	16.3 (14.8-19.2)
Churchill	4.3 (3.4-6.9)	9.3	3.4 (3.2-5.9)
Moe-Newborough	11.3 (9.2-12.5)	12.8	10.1 (8.4-12.2)
Traralgon	6.0 (5.3-7.1)	11.2	7.8 (7.5-9.4)
Yallourn North-Glengarry	2.2 (0.0-4.5)	0.0	2.2 (0.0-5.1)
Drouin	5.0 (3.8-6.8)	6.0	5.6 (4.5-6.0)
Foster	2.4 (1.2-4.8)	4.9	3.0 (2.1-3.7)
Korumburra	3.4 (2.2-4.5)	4.5	3.3 (1.1-5.9)
Leongatha	3.7 (2.8-5.5)	7.3	5.5 (4.8-7.4)
Mount Baw Baw Region	1.7 (0.8-3.3)	5.0	1.7 (1.7-4.2)
Rosedale	4.3 (2.1-8.6)	6.4	4.2 (2.1-4.8)
Trafalgar	2.8 (1.4-4.3)	10.8	2.7 (1.0-5.4)
Warragul	6.4 (4.1-8.1)	7.4	6.5 (5.0-7.2)
ED presentations			
Morwell	13.3 (12.6-15.6)	24.1	17.2 (13.8-18.2)
Churchill	6.1 (4.7-7.8)	6.8	5.9 (3.8-7.6)
Moe-Newborough	9.0 (7.1-10.5)	15.8	10.5 (8.9-11.3)
Traralgon	7.5 (6.2-8.6)	10.5	9.0 (8.6-9.9)
Yallourn North-Glengarry	4.5 (2.2-4.5)	11.2	2.2 (2.2-3.4)
Drouin	9.5 (7.7-10.2)	12.0	6.7 (6.2-8.4)
Foster	1.2 (1.2-3.0)	3.6	2.4 (1.2-4.3)
Korumburra	2.3 (1.2-3.4)	2.2	4.4 (3.3-5.6)
Leongatha	1.9 (0.9-2.8)	3.7	1.8 (0.9-2.3)
Mount Baw Baw Region	3.3 (1.7-6.6)	10.0	5.0 (3.3-5.1)
Rosedale	6.4 (2.1-9.7)	10.6	6.4 (4.2-6.4)
Trafalgar	4.3 (2.8-6.9)	13.6	4.1 (2.7-7.4)
Warragul	8.1 (6.8-10.5)	10.8	8.9 (7.6-10.2)
Hospital admissions			
Morwell	12.0 (8.7-14.1)	13.5	17.9 (13.9-20.2)
Churchill	6.1 (3.9-7.7)	11.9	9.3 (6.8-12.3)
Moe-Newborough	7.7 (6.0-9.7)	10.4	9.8 (9.5-10.4)
Traralgon	7.2 (5.7-11.5)	15.0	10.5 (9.9-11.8)
Yallourn North - Glengarry	2.2 (0.0-2.2)	6.7	4.5 (3.4-9.0)
Drouin	5.7 (3.9-7.7)	12.0	6.7 (5.3-8.1)
Foster	7.2 (4.8-9.6)	13.3	8.5 (5.5-11.6)
Korumburra	6.7 (3.9-7.9)	7.8	6.7 (5.0-9.5)
Leongatha	9.5 (6.6-13.0)	11.0	10.1 (8.3-11.5)
Mount Baw Baw Region	3.3 (1.7-5.0)	6.7	3.4 (3.3-5.9)
Rosedale	4.2 (2.1-7.5)	12.7	4.2 (2.1-4.2)
Trafalgar	6.8 (4.1-9.0)	5.4	5.4 (3.3-10.7)
Warragul	10.6 (7.9-12.5)	21.0	15.0 (12.7-16.4)

^a Calendar month pre-mine fire = 1/7/2010 to 31/1/2014 (inclusive).

^b 30 day mine period = 9/2/2014 to 10/3/2014 (inclusive).

^c Calendar month post-mine fire = 1/4/2014 to 31/3/2015 (inclusive).

^d IQR = Interquartile range: 25th to 75th percentile.

^e Data between September and December 2014 were excluded due to the impact of industrial action on paramedic data collection

Table S2

Comparison of monthly MH-related ambulance and emergency service utilisation rates per 10,000 population in each SA2 impacted by smoke during the mine fire

Figure S1

Violin probability density plots of modelled daily average mine fire-related $PM_{2.5}$ concentrations during the 30-day mine fire period for areas exposed to smoke

The boxplot inserts indicate the 25th and 75th percentiles. The horizontal line indicates the median. Whiskers indicate lowest and highest values, excluding outliers. Dots indicate outliers. The violin shapes surrounding the boxplots are rotated kernel density estimations indicating the full distribution of PM_{2.5} concentrations. There are two identical distributions per box plot; one mirrored either side. Thicker sections of the violin shape represent higher frequencies.