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Research proceedings from the Bushfire and Natural Hazards CRC Research Forum (peer reviewed)

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Dr John Bates, Bushfire and Natural Hazards CRC

As emergencies and disasters caused by natural hazards increase in frequency and severity across the globe, it is more important than ever to provide decision-makers with the evidence, information and tools that they can use to make the necessary critical decisions.

Research is supporting our emergency services, government and community organisations as they work to prevent, prepare for, respond to and recover from natural hazards.

The Bushfire and Natural Hazards CRC's Research Forum, held as part of the AFAC19 conference powered by INTERSCHUTZ in Melbourne in August, showcased the latest natural hazards science and explored how outcomes can be further integrated into policy and practice to contribute to disaster risk reduction and to make our communities more disaster resilient.

This *Australian Journal of Emergency Management Monograph* special edition from the Research Forum provides a snapshot of current peer-reviewed research happening right around Australia: including fire behaviour, predictive services and modelling; severe weather and climate; risk; capability, resilience and wellbeing; and, communications.

Khalid Moinuddin

Image: Bushfire and Natural Hazards CRC

As our demographics change, we expand our cities further into the bush and increase our dependence on technology, our exposure to risk intensifies. The economic, social and environmental costs are forecasted to rise in a way that is unprecedented and unsustainable. These challenges are complex, and we should be wary of quick fix solutions. These research papers are a small contribution to the larger discussion.

This monograph is complemented by a companion monograph (Monograph 5), which includes extended research abstracts from the Research Forum, and I encourage you to take some time to read both of these Monographs.

Dr John Bates

Research Director
Bushfire and Natural Hazards CRC

Editor in Chief
Australian Journal of Emergency Management

Peer-reviewed article

A new decision support tool for prescribed burning risk assessment

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ABSTRACT

In most Australian jurisdictions, the use of prescribed fire is promoted on the basis of its efficacy in mitigation of risk. Despite this, formal attempts to evaluate effects on risk to people, property and environmental values across different jurisdictions are generally lacking. In particular, there is no basis for assessing the generality of attempts to predict risk in response to any particular strategy for use of prescribed fire (e.g. the 5 per cent target recommended by the 2009 Victorian Bushfires Royal Commission). General principles therefore need to be developed about how to apply a risk-based approach across widely varying environments, human communities and combinations of key management values.

In this Bushfire and Natural Hazards Cooperative Research Centre project, researchers from the University of Wollongong, Western Sydney University and the University of Melbourne have come together with end users across southern Australia to design a project to systematically investigate how risk to any particular management value will respond to variations in the spatial location and rates of treatment. Project outputs are currently being moulded for utilisation by end users in a dedicated tool, the Prescribed Fire Atlas, which will guide the implementation of 'tailor-made' prescribed burning strategies to suit the biophysical, climatic and human context of all bioregions across southern Australia.

Introduction

Fire managers and scientists are working together to develop new ways to assess the risks associated with wildfire. In Victoria there has been a transition to a risk reduction target, which uses modelling and analysis to compare the different management scenarios with a maximum risk baseline (Victorian Government 2015a). The approach explicitly refers to residual risk, the percentage of maximum bushfire risk that remains in the landscape following a particular fire management scenario. Similar risk assessment methods have been employed in Tasmania (State Fire Management Council 2014). Cost trade-offs have been analysed for future fire management approaches in the Australian Capital Territory, to determine which are most cost-effective and provide the greatest reduction in risk (Penman and Cirulis 2019). There are many other examples in Australia and abroad of risk assessment for fire management, both at an integrated level (e.g. Alcasena et al. 2019, Finney et al. 2011) as well as for particular issues such as forestry (Ager et al. 2019), biodiversity conservation (Bentley and Penman 2017) and suppression (Penman et al. 2011).

Prescribed burning is the main fire risk reduction tool currently available and is therefore a major focus for risk assessment. The clarity of its rationale – to reduce the risks from wildfire by modifying fuel properties through the application of fire under moderate weather conditions – stands in stark contrast to the complexity of its application. Although it is not yet required of most fire managers, the aforementioned risk assessments suggest the possibility of eventually providing a comprehensive, quantitative accounts of all the costs and benefits of prescribed burning, as well as the trade-offs between multiple management objectives. These analyses could include the influence of prescribed burning on the risks posed by wildfires (e.g. to human settlements and environmental values) as well the risks of planned burns themselves (e.g. smoke impacts on human health and amenity, environmental values).

In this context, there is a need for standardised approaches for comparing and contrasting risk across multiple assets that can be readily communicated within agencies and to the community. Such tools are best developed in collaborative projects of researchers and end users, such as in our project supported by the Bushfire and Natural Hazards Cooperative Research Centre (BNHCRC). The express purpose of our research is to support the delivery of effective, 'tailor-made' prescribed burning solutions across southern Australian ecosystems by providing a quantitative trajectory of risk reduction for multiple values in response to differing prescribed burning strategies. The project is divided into two phases: fire behaviour accounting and risk accounting.

Fire behaviour accounting

At the heart of the project is predictive modelling of the effect of prescribed burning on the incidence and behaviour of unplanned fires. Simulation modelling involves the coding and scaling up of fire behaviour models to predict spatial patterns of fire spread and extent at landscape scales. These simulators are provided with certain inputs (e.g. the terrain, vegetation type and weather conditions in a case study landscape), in order to produce estimates of wildfire properties such as rate of spread, flame height and intensity. Simulation modelling has played a key role in advancing risk techniques (for recent examples see Connell et al. 2019, Guillaume et al. 2019 and Furlaud et al. 2018). The key advantage of simulation modelling is the ability to run large numbers of experiments representing scenarios of spatial scale, treatment rate, patterns, asset configurations and weather conditions that would be impossible to explore in empirical field experiments. While simulators have a range of limitations, such as their computational expense and inaccuracies in the representation of key processes and elements (or their omission altogether), it is reasonable to expect performance to improve as existing models are validated, improved and new models are developed (Sa et al. 17, Faggian et al. 17, Duff et al. 18).

Choice and experimental design of fire behaviour simulator

Simulation models are widely used in Australian fire management, and in South Australia and the eastern states the primary tool is PHOENIX RapidFire (Tolhurst et al. 2008). PHOENIX is used by fire agencies in these states for incident prediction, risk assessment and strategic planning. For example, it was used in the development of statewide and regional risk profiles in Victoria (Victorian Government 2015b). We therefore decided in conjunction with end users to make PHOENIX the simulation model in our project, although our approach is compatible with other simulators (e.g. Johnston et al. 2008, Tymstra et al. 2010) and simulation frameworks (e.g. Hilton et al. 2015). PHOENIX and other similar simulators are spatially explicit and hence have many inputs that are spatially explicit, such as fuel mapping, asset locations and fire history. With the exception of wind, weather is assumed to be spatially uniform i.e. orographic effects on temperature and relative humidity. Here we sketch the key aspects of our experimental design; for full details see Cirulis et al. (2019).

There are several key inputs to the simulation process.

- Ignition locations are selected using a spatial likelihood model (Clarke et al. 2019).
- Fuel type and arrangement is based on data and advice from fire management agencies.
- Weather is drawn from Bureau of Meteorology data and samples from the full range of possible conditions at each case study location, including fire danger index classes and different drivers of high fire danger (temperature-driven, wind-driven, wind change-driven).
- Fire history includes wildfire as well as variable combinations of edge and landscape treatments, applied to burn blocks derived from agency data or generated using an algorithm.

The above combination of inputs results in thousands of simulations, whose key outputs are predictions of fire size, fire intensity, flame height and the presence of embers for given weather conditions, treatment rates and treatment locations. Vulnerability models are used to relate fire properties to impacts on individual assets or management values, based on peer reviewed literature. We have initially used a core set of house loss, life loss, length of road damaged, length of powerline damaged and area burnt below minimum tolerable fire interval. These values were identified as priorities for end users and we are currently working with them to develop further values and associated vulnerability models. Key improvements to existing simulation modelling studies are the use of ignition likelihood and a representative distribution of local weather, the consideration of an increased number of assets and the exploration of a greater diversity of potential treatment futures supported by improved computing power.

Risk accounting

We use Bayesian decision networks to estimate the level of risk mitigation available through different prescribed burning treatments (Marcot et al. 2006). Bayesian decision networks are mathematical models presented graphically, allowing for the interaction and influence of many factors on an outcome of interest. They are able to propagate the probability distributions (and associated uncertainty) of multiple variables, as well as selections from a range of candidate options for one or more decisions, through to an overall likelihood. These features make them ideal tools for wildfire risk assessment (Penman et al. 2011):

- Their graphical nature makes them easy to understand
- Their ability to integrate multiple factors makes them suitable for holistic analyses that support decisions around one or more management options
- Their ability to handle probability distributions means they are able to provide true estimates of risk, while making transparent key sources of uncertainty in overall outcomes.

In our approach, the model learns probability distributions of fire weather conditions and wildfire incidence for combinations of discrete rates of prescribed burning in edge and landscape blocks, and generates estimates of residual risk at each treatment level. The use of data from fire behaviour simulations (e.g. probability distributions of area burnt) is an integral part of the process. By incorporating the entire range and probability of local conditions, this process produces 'full' estimates of risk that can be compared between case study landscapes. It is thus possible to not only investigate the trajectory of risk reduction for different values in a given region, but also ask how such trajectories differ between regions, both in absolute as well as relative terms (e.g. compared to zero treatment). These trajectories can also be used as input into trade-off analyses (e.g. Driscoll et al. 2010), highlighting the ramifications of optimising for particular values or sets of values. Identifying effective risk reduction options is a key objective for fire managers that will use this tool.

At the request of end users we incorporated cost into the Bayesian decision network. The impacts of wildfire can be wide-ranging, including to livelihoods, human health, infrastructure, primary production and ecosystem services (Bowman and Johnston 2014; Stephenson et al. 2013). Estimates of the cost of wildfire are therefore substantial, although they vary considerably depending on scope and method e.g. at least $4b for the 2009 Black Saturday fires (Teague et al. 2010) and average annual costs for 2007-2016 of $1.1b (ABR DRSC 2017). In the U.S., the 2017 fire season was the most expensive ever, with costs exceeding $US 2.4b (US Forest Service, 2019). We have initially included two classes of cost: treatment costs (separate cost for edge and landscape) and impact costs (e.g. cost of house loss, powerline damage). The local trajectories of cost for given treatment rates and locations can then be tracked and compared between regions, allowing identification of the most cost-effective prescribed burning strategies, either overall or for a given management value.

Using project outputs

The research team has worked with end users to develop an interface for exploring and interrogating the multifaceted outputs from the project. This interface, called the Prescribed Fire Atlas, is a decision support tool, not a decision making tool. The aim is to present outputs clearly, engagingly and with appropriate guidance material, to enable end users to make their own decisions. Feedback from end users has so far identified a number of issues and priorities for inclusion in the Atlas:

- There is value in both relative and absolute measures. This enables end users to not only identify individual and aggregate risks/costs, but also compare them with alternatives such as business as usual scenarios, solutions in other jurisdictions and risk reduction targets.
- There is value in bottom up and top down approaches to interrogation of outputs i.e. entering current or potential strategies in order to determine their risk and cost, and specifying desired risk levels or available budgets in order to assess available options within these constraints.
- Given that the Atlas joins a long list of decision support tools and web interfaces available to fire managers, there is a need to ensure its design maximises complementarity and compatibility with these other tools.
- The Atlas may have value as a tool to support internal and external communications and education, aside from its core role in strategic planning and risk assessment. Project outputs could be used to educate stakeholders and overcome misunderstandings about the relationships between biophysical drivers, planned and unplanned fire.

Conclusion and future challenges

We have described here a tool for systematically comparing prescribed burning effects on risk mitigation across multiple landscapes and management values. The tool has been designed to provide a credible means by which fire agencies can respond to demands for transparent accounting of the costs and benefits of their activities. It does this by combining methodologies for assessing the effects of prescribed burning on fire behaviour and risk to management values including costs. While the project represents an important step forward in wildfire risk management research, a number of challenges remain to maximise its value. The treatment of values is essentially modular, meaning that the addition of new values (e.g. agricultural impacts, human health impacts from smoke) or modifications of existing ones is not just desirable, but possible. The project can equally easily incorporate new costs associated with prescribed burning, suppression and wildfire impacts as they are made available. It will also be important to test the sensitivity of results to choice of simulator and fire behaviour model (e.g. Zylstra et al. 2016). Hosting, maintenance, evaluation and monitoring of the Prescribed Fire Atlas are important issues, particularly in light of funding for the BNHCRC ending in 2021. Finally, as our understanding of wildfire risk and the effects of wildfire management improves, it may be possible to transition from cost effectiveness analyses to a cost benefit analysis, moving from an appraisal of costs of different management options to an assessment of their net benefit to society (NSW Treasury 2017).

Acknowledgements

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Peer-reviewed article

Fire danger ratings inform the community and fire managing agencies of fire risk. Fire danger ratings are currently primarily based on fire danger indices (FDIs) calculated using methods that were developed many decades ago. The challenges and issues with these methods are well documented. We aimed to develop a more objective and observation-based approach to fire danger assessment that considers spatial data on the occurrence of actual fires as well as on fire factors that are already routinely produced every day for Australia. A preliminary assessment suggested a very good potential of the methodology to formally and objectively incorporate any new fire danger predictors. The method can be combined with forecasted rather than observed weather and fuel conditions to produce forward predictions of expected FDI.

Towards comprehensive characterisation of flammability and fire danger

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Introduction

Fire danger ratings are used to prepare the community and fire management agencies for the relative likelihood of fire occurrence, and the likely rate of spread and difficulty of suppressing fires once they occur. They can trigger fire bans and operational fire preparations, and affect activities such as prescribed burning. Fire danger ratings are currently primarily based on fire danger indices (FDIs) calculated using methods that were developed many decades ago, such as the McArthur Forest and Grassland Fire Danger Meters (McArthur 1966; 1967) and algorithms since fitted to those meters (Noble et al. 1980) to routinely calculate Forest and Grassland FDIs (FFDI and GFDI, respectively). The issues with the McArthur approach have been well-documented over the years and are manifold. Most limiting, perhaps, is that much-improved data are now available on weather and fuel variables that affect fire danger, such as the moisture content of the soil, litter and live fuel. However, there is no straightforward way to retrofit the McArthur framework to these new observations (Holgate et al. 2017). Further issues are that the FFDI and GFDI were developed from a small database of fires in a narrow range of vegetation types, and are not representative for the full range of weather types and fuel types and condition encountered across Australia. Unfortunately, beyond the personal experience of users who have applied the indices more broadly, there is no generic and formal possibility to consider such variations and adapt to them.

This research was motivated by the desire to develop a more objective approach to fire danger assessment, considering spatial data on the occurrence of fires as well as on fire danger factors – weather and fuel factors that influence fire occurrence and behaviour - that are now routinely produced every day. We do not propose that the methodology developed here can meet all requirements of the new Australian Fire Danger Rating System that is currently in development. However, the approach developed here may contribute to those developments by demonstrating how multiple data sources can be combined in a statistical prediction framework. Our general approach is predicated on the use of satellite-based fire detections as an observational data set of fire occurrence. We considered a set of eight predictor variables relating to fire weather and fuel condition that are derived daily from satellite remote sensing, station data interpolation or modelling. For each Australian Fire Weather Area, for each of three broad land cover types (‘forest’,’grass’ and ‘shrub’), and for each predictor variable, we calculated the conditional probability of fire occurrence at different predictor values. We fit a statistical distribution function to these probabilities and combine the eight factor-probability predictions into a single combined Fire Danger Index.

Data

Fire occurrence data are available for 2003 onwards from the Geoscience Australia Sentinel Hotspots fire detection system (Geoscience Australia 2014). The fire detections are based on detecting anomalously high surface temperatures in thermal imagery obtained by multiple satellite instruments, dominated by the two MODIS instruments in the first part of the record.

Several caveats apply to the observations: the MODIS thermal sensor footprint and accuracy is ca. 2.5 km, which means that small and low-intensity fires may not be detected and that the exact location may not always be known. The two MODIS instruments cover the surface approximately four times each day, and therefore, there is a possibility that fires are not detected. Conversely, detected fires do not only include unplanned bushfires but also planned burns (e.g., savanna, crop residue and fuel control burning and gas flares).

A list of detected fires and their inferred temperature is downloaded annually and resampled to daily grids at 0.025° (~2.5 km) resolution as part of ANU’s Australia’s Environment report. The data are made available for visualization or download through Australia’s Environment Explorer (www.ausenv.online). Here, the maximum daily fire intensity for each pixel was transformed to binary data on fire occurrence by assuming any fire with a temperature of >80 °C could be considered a fire event.

GIS data on the location of 134 Fire Weather Areas (FWAs) across Australia was combined with data on fuel type from the Australian Flammability Monitoring System (AFMS, www.anuwald.science/afms), where three broad fuel types are distinguished: ‘grass’, ‘shrub’, and ‘forest’. This classification was developed by Yebra et al. (2018) in deriving satellite-based Live Fuel Moisture Content (LFMC) estimates available in the AFMS, based on an amalgamation of classes in NASA’s MODIS land cover product (Friedl et al., 2010). The stratification by FWA and fuel type was done to account for regional differences in fire regime, fuel type and other fire factors. Any alternative definition of regions would be possible, however (e.g., fire climate classification).

The eight predictor variables include the LFMC data, as well as indicators of soil moisture availability that correlate with live fuel and dead litter fuel, and fire weather variables (temperature, wind speed and humidity). The LFMC (in % water mass / dry leaf mass) from the AFMS is derived from MODIS satellite instrument observations and updated every four days at 500-m resolution (Yebra et al. 2018). As indicators of soil moisture, we used the daily updated 0.05° (~5-km) resolution outputs from the Bureau of Meteorology’s Australian Landscape Water Balance website (www.bom.gov.au/water/landscape). The Australian Water Resources Assessment model (Frost et al. 2016; Van Dijk 2010) that underpins this data service produces estimates of the relative moisture availability (0–1, scaled to a fraction of plant available water) in the topsoil (w0, 0–10 cm), shallow soil (ws, 0.1–1m) and deep soil (wd, 1–6m). While these are simulated separately for shallow- and deep-rooted vegetation, we used the publicly available grid-cell average values here. The fire weather variables were also derived from gridded data provided by the Bureau of Meteorology, including 0.05° (~5-km) daily climate grids of maximum daily temperature (Tmax, °C) and 3pm vapour pressure (VP15, hPa) and mean daily wind speed (Uavg, m/s) that are based on interpolation of station data (Jones et al., 2007). The VP15 values were not used directly but combined with Tmax and an assumed standard surface pressure to calculate relative humidity (RH, %) and vapour pressure deficit (VPD, Pa) using standard methods. All eight predictors (LFMC, w0, ws, wd, Tmax, Uavg, RH, and VPD) were resampled from their original resolution to the 0.025° and daily resolution of the fire observations. The analysis period was 2003-2017, where the start year is limited by the fire observations, and the end year by the readily available wind speed data. However, all data are updated daily, and therefore, a repeat of the methodology in future can rely on an extended dataset.

Methods

The steps to predict the composite Fire Danger Index from the eight predictor variables are detailed below.

1) Extraction x-y data pairs: First, all occurrences of a predictor variable x (e.g., LFMC) over time for each grid cell corresponding to an FWA region and a fuel type of interest were recorded. In addition, it was also recorded whether a fire event occurred on that grid cell and day. Only 0.025° grid cells dominated by one fuel type (>80% cover fraction) were considered. For cases where the total number of fire events was <30, the sample was considered too small, and no further processing was undertaken.

2) Calculate conditional probabilities P(Y|X>xi): The calculation is explained here for the case where fire danger is expected negatively related to x (where it expected positively related, the same logic was applied). For each value xi in a series with small intervals, the total number of records (N) and the number of fire events (Ne) corresponding to x>xi was calculated. From these, the conditional probability of fire was calculated as P(Y|X>xi)=Ne/N. The resulting values were rescaled by dividing by the marginal (or ‘unconditional’) fire probability P(Y). An example is shown in Figure 1. Note that while not a desirable feature, rescaled probabilities for intermediate x values can exceed unity, if the frequency of fires in the sample exceeds the frequency for the entire population.

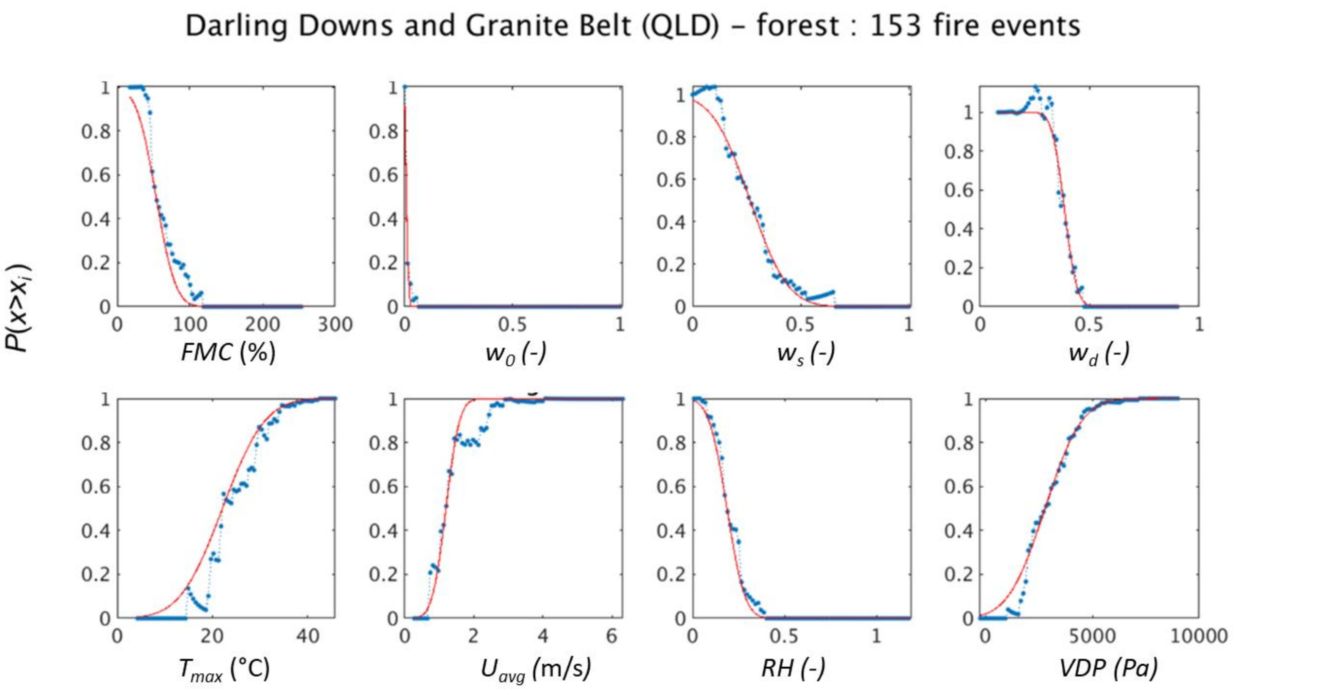

Figure 1. Example of empirical and fitted cumulative probability, rescaled to between zero and unity, for the eight fire risk predictors (see text for explanation of symbols).

3) *Fit cumulative distribution function.* A simple Gaussian Cumulative Distribution Function (CDF) was fitted to the resulting probability function (Fig. 1). The distribution requires estimation of a mean (μ) and standard deviation (σ). The mean can be interpreted as a fire danger threshold, in that fire probability increases most rapidly at this value of *x*, whereas σ defines the sharpness of the transition between low and high fire occurrence probabilities. For a Gaussian distribution, μ is equal to the *x* for which rescaled probability *P* exceeds 0.5 $x(P=0.5)$, whereas σ can be calculated from the inter-quartile range $IQR=|x(P=0.75) - x(P=0.25)|$ as $\sigma=IQR/1.349$.

4) *Calculate the Fire Danger Index.* For each of the eight predictors, the respective fitted CDF function (for the respective FWA and land cover type) was applied to the predictor time series. The result might be termed the The resulting FDI can be calculated for each 500-m grid cell and each day.

However, by visually comparing the predicted fire danger time series with actual fire frequency across the region and fuel type for each day, the specificity of the estimates can be interpreted, that is, the ability of the method to accurately distinguish high and low fire danger conditions Factor Component FDI (*FCF*) and represents the fire danger expected when only considering one factor. An overall composite FDI was calculated by multiplying each of the eight FCFs and raising the result to the power 1/8.

5) *Evaluation*. The entire time series of fire observations were used to calculate probabilities to maximize sample size. This precludes an independent verification.

Results

For all FWA and vegetation type combinations for which a sufficiently large number of detected fires (N>30), the parameters μ and σ of the Gaussian CDF were fitted. Generally, this produced parameter values that were near-uniform across the continent or showed a gradual transition, but local anomalies did occur (Fig. 2). Preliminary investigation of these anomalies suggests that they were often associated with a relatively small sample size (see inset in Fig. 2), suggesting that the chosen sample threshold may have been too small. Inspection of the calculated FCF and overall FDI time series indicated that the key variables that appear to control fire occurrence varied between fuel type and FWA (representing different fire regimes). For example, the predictive value of LFMC was quite strong for grasses and shrublands, as well as for open forests in (seasonally) drier FWAs, but less so for forests in humid regions (Fig. 3). All variables except deep soil moisture (w_d) appeared to provide information on fire danger, but the inclusion of such non-informative variables does not deteriorate the overall FDI predictions, as their FCF is always (near-) unity. A visual comparison between FDI and actual fire frequency generally shows good correspondence. Fires do not always occur during high FDI conditions, as may be expected, given ignition is required. Formal verification statistics have not yet been calculated, but visually, the results show a low 'false negative' rate for most FWAs.

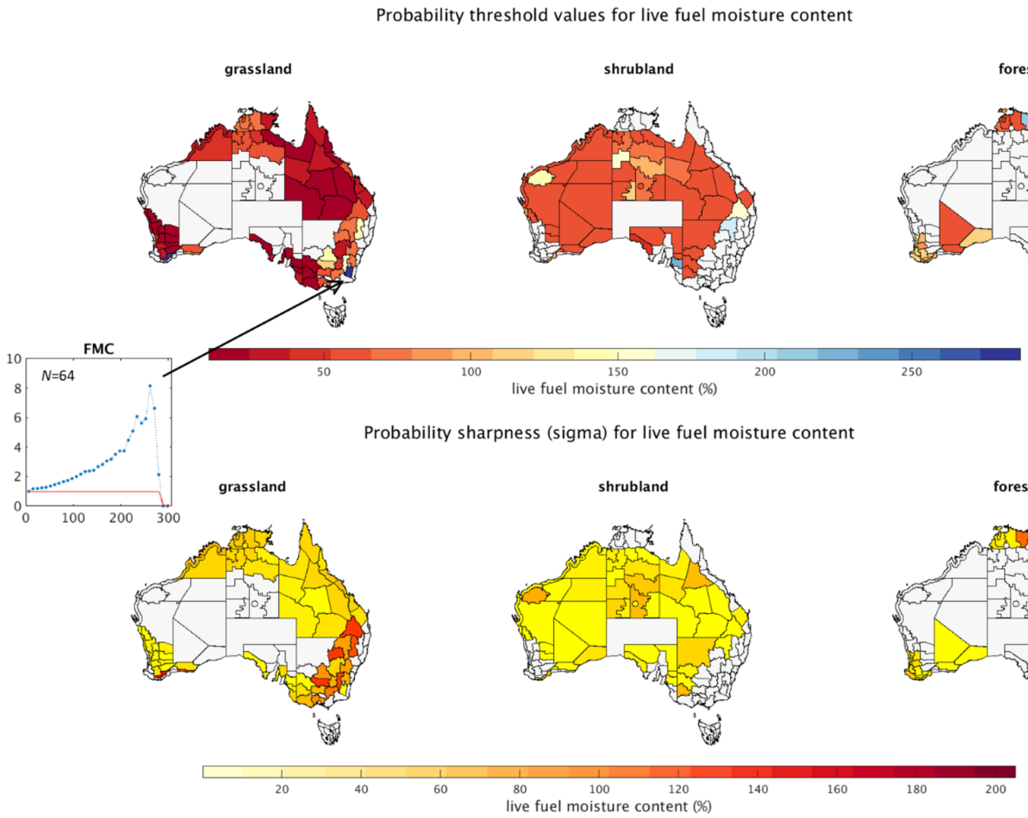

Figure 2: Regional differences in (top) threshold (μ) and (bottom) sharpness (σ) of the fitted CDF function between rescaled fire frequency and one of the eight variables (LFMC). The inset shows an example of an anomalous CDF (note the small sample size and high FMC values).

Conclusions

From these preliminary research results, we conclude that it is possible to at least partially replace the traditional McArthur FDI with an FDI that has a stronger basis in observations. We used readily available, daily updated spatial data on fire danger predictors (fuel condition and weather) to develop an FDI that translates these predictors into a combined FDI based on a database of fires detected by the satellite-based Sentinel Hotspots system. A preliminary assessment suggested a very good potential of the methodology to formally and objectively incorporate any new fire danger predictors. It is noted that the MacArthur method is used to assess the risk of fire occurrence but also fire behaviour and suppression difficulty. Further research or trials would be required to determine whether the FDI developed here has merit for that application.

are well-constrained by fire observations and the temporal variability in component factor FDIs is a strong indication of their predictive value. Further research would also be beneficial to test the merit of alternative statistical approaches (e.g., more flexible CDFs and formal joint-probability approaches) or, possibly, machine-learning approaches.

We did not attempt verification against independent observations or the McArthur FDIs, and also did not undertake formal verification analysis yet; this will be the subject of further research. Nonetheless, the predictions

FDI forecasts would be of greater value than the retrospective analyses provided here, and can be produced by replacing the daily climate analysis grids with forecasts of temperature, humidity and wind speed and soil moisture from numerical weather predictions (e.g., the Bureau of Meteorology's ACCESS system and the AWRA forecasting system currently in the testing phase). Any systematic biases between the two data sources would need to be accounted for in this process. The resulting composite FDI could be produced daily as forecast at a resolution of 500m nationally and disseminated as an experimental service as part of the AFMS. In time, this could make a useful contribution to a new Australian Fire Danger Rating System.

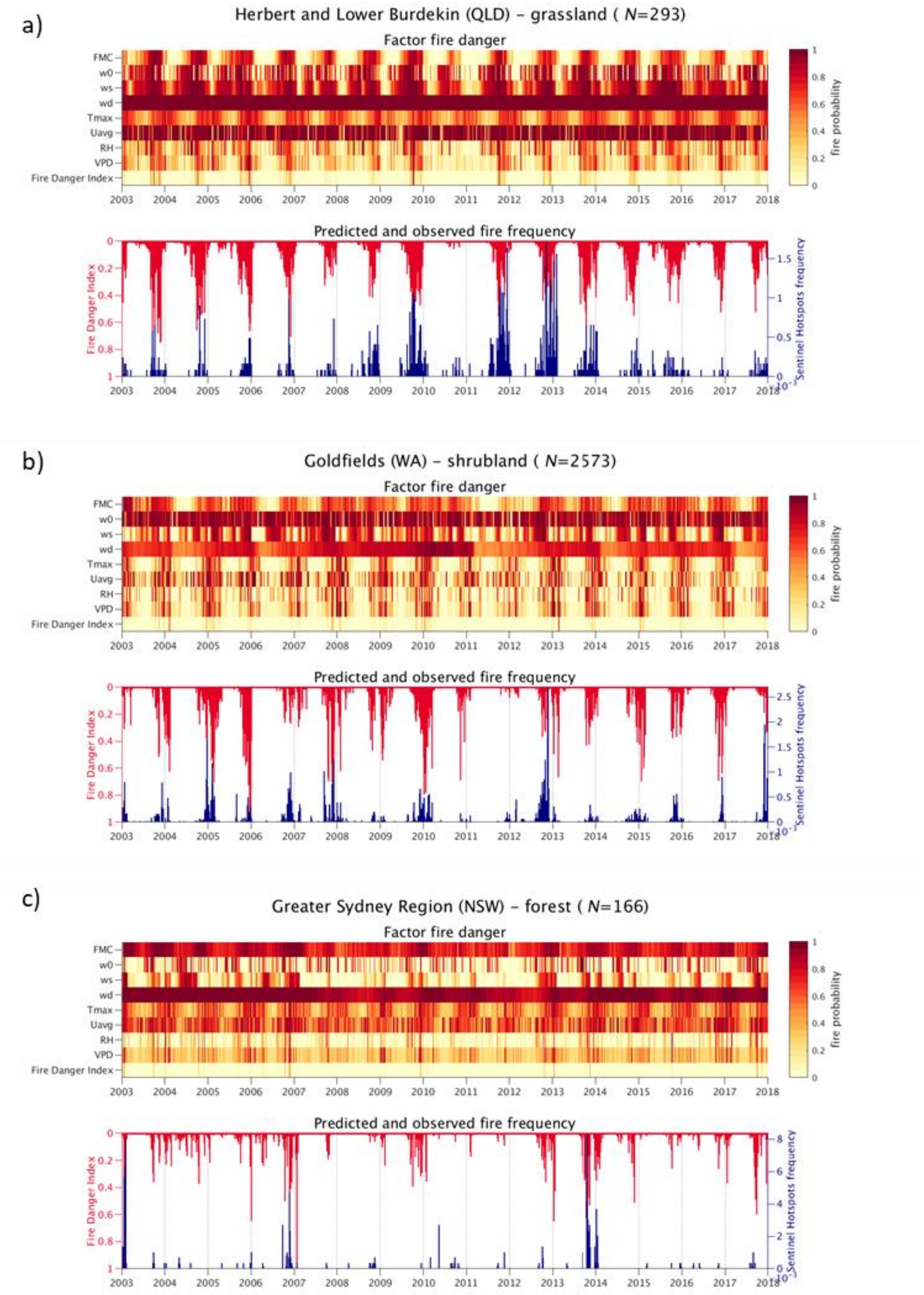

Figure 3: Example time series of (top panels) Factor Component and overall FDI for three FWAs with contrasting fire climate and fuel types, and (bottom panels) comparison of overall FDI and observed fire frequency. Time series are all calculated as averages across the vegetation type and FWA.

Acknowledgements

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Doctor **Marta Yebra** is a remote sensing scientist and leads development of the Australian Flammability Monitoring System.

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Peer-reviewed article

Science in operations: QFES response to the 2018 Queensland fires

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ABSTRACT

In late November 2018, Queensland experienced an unprecedented fire event, with more than 1,000 bushfires burning across the state. Fire weather conditions peaked on Wednesday 28 November, with 'Catastrophic' fire danger observed at Rockhampton Airport for over three hours. Over 1 million hectares of land were burnt, 479 post-fire damage assessments were completed, with nine homes destroyed and a further eight damaged.

Queensland Fire and Emergency Services (QFES) requested national resources to support both tactical firefighting and operational roles. In anticipation of forecast conditions on 28 November, QFES Manager of Predictive Services, Fire Behaviour Analyst (FBAN) Andrew Sturgess requested Bureau of Meteorologist (BoM) meteorologist and Bushfire and Natural Hazards Cooperative Research Centre (CRC) researcher Mika Peace provide support to the State Operations Centre FBAN team. In this paper, we share our personal experiences and reflections as well as those of the FBAN team.

In summary, we consider how the Queensland learnings may inform future events. Challenges include resourcing to develop teams with the appropriate capabilities and the ability to identify extreme conditions in advance.

Introduction

The demand for meteorological information during the November 2018 Queensland bushfires was prodigious, particularly for real-time interpretation relating to fire behaviour. The BoM Embedded Met provided high-level briefings at the synoptic scale, while Mika as FBAN support provided weather intelligence relevant to fires at a meso- and micro-meteorology scale.

Inter-agency collaboration showed the benefits of multidisciplinary teams, as FBANs and meteorologists discussed specific weather impacts on fire behaviour at individual fires. These included variable wind conditions and potential plume development given consideration of vertical stability and available fuel. Inputs to Phoenix simulations were objectively assessed and adjusted to examine alternate scenarios and risks, including potential credible worst-case impacts to communities.

Frequent, detailed briefings were provided to the Queensland Disaster Management Committee chaired by the Premier, QFES Commissioner and Executive, the State Disaster Coordinator, Deputy Commissioner Queensland Police Service and Regional Operational Centres. These communications linked meteorology and fire behaviour, underpinned by scientific interpretation of real-time data, which was extremely valuable in informing operational decision making.

The fire and weather situation

Preceding the November fires, conditions across Queensland had been hotter and drier than normal, with below average rainfall for several months, and above average temperatures for several years. This led to lower than average soil moisture and dry fuels, resulting in climatological conditions favourable for high intensity fires. The 'Northern Australian Seasonal Bushfire Outlook' identified above normal fire potential for the Central Coast, Whitsundays and the Capricornia parts of Queensland.

In late November there was an unprecedented extreme heatwave over northern Queensland coastal areas, with several locations breaking long-standing temperature records by a considerable margin. The heat, in combination with wind, elevated the fire danger well above climatological expectations. Several hundred fires burned across Queensland over two to three weeks during November and December.

On Wednesday 28 November 'catastrophic' fire danger was observed at Rockhampton, driven by westerly winds with a maximum of 51.8 km/h at 1500

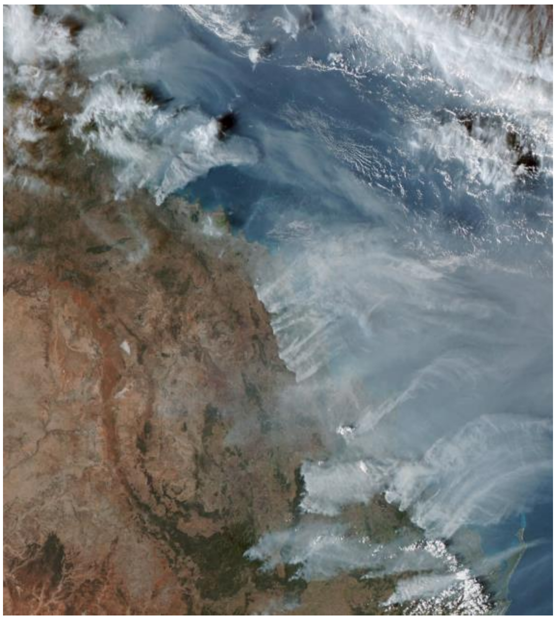

Figure 1: Himawari satellite image showing smoke plumes from fires across Queensland on Friday 30 November 2018. Courtesy Bureau of Meteorology satellite team.

hours. The winds circulated a low pressure system that was unusually intense for Queensland latitudes and the strong, dry, offshore winds were favourable for rapid fire spread across the dry landscape. Wednesday 28 November was the worst day in a protracted period of a campaign fire-fighting effort; the Gracemere fire, which had the potential to impact Rockhampton was just one of the fires of concern. Fortunately, no lives were lost; however several homes and a number of buildings were destroyed.

Interagency collaboration and multidisciplinary teams

Detailed briefings and elevated emergency response started on Sunday evening 25 November. On Monday evening, Andrew contacted Mika to request assistance and on Tuesday evening she arrived in QLD to support QFES operations on Wednesday morning.

Over the following three days, Mika provided broadscale, mesoscale and microscale meteorological information, with direct interpretation on likely fire behaviour. Fire behaviour elements discussed included plume depth, organisation, structure and development. Spotting potential and direction were assessed, along with wind speed and direction and timing and variability of changes to wind fields. Other considerations included fuel moisture, topographic and coastal wind and fire interactions and potential risks to ground crews.

QFES FBANs used the Phoenix simulation software on the fires of most concern across the state. Mika worked with the FBANs, providing meteorological information, suggesting modifications to fuel moisture content and testing alternative 'credible worst-case scenarios' for wind speed and direction for the highest priority fires with regard to local assets and communities. Australian Digital Forecast Database grids were verified in real time against observations and the results were used to modify subsequent Phoenix simulations. Alternative scenarios based on local topographic effects and plume entrainment processes were tested. Phoenix perimeter outputs were verified against linescan imagery when available and this identified fire perimeter that were most likely to grow under changing wind conditions.

The information was relayed to firegrounds through mechanisms considered appropriate by the State Operations Centre (SOC) representatives, mostly through phone and video calls. Interpretive briefings were provided on request to all and sundry, including the SOC, Premier, Deputy Premier, Police Commissioner and QFES Commissioner.

The demand for meteorological information, tailored and repeat briefings, and interpretative assistance was prodigious.

Andrew's reflections: the importance of relationships

Mika and I provided expert advice to a group that had had limited exposure to a fire event of this magnitude. Contemporary disaster management is inclusive of political leaders. Politicians routinely rely on briefings to assist them with their preparedness from people they know and trust. This event involved extreme pressure with minimal time to build relationships. QFES staff, politicians and the State Disaster Managers needed to rapidly determine who they would trust to provide expert advice to assist them making time critical, high consequence decisions. We played a key role in turning this team of experts into an *expert team. Mika and I provided complementary strengths as well as the requisite skills, knowledge, temperament and experience to support managers making these critical decisions. Communication underpins successful operations. I requested Mika's support because I was confident in her ability to communicate the fire science concisely to the executive managers and provide expert input to assist our FBAN team to make the most robust predictions possible. Our relationship in turn engendered trust from our FBANs. So, although they had never met Mika, they very quickly accepted her as part of the predictive team.*

Mika's reflections: the role of science

My main focus was to support the FBAN team and provide meteorological interpretation, with the primary objective of 'no surprises'. Much of my research over the last decade has been on identifying the ingredients that led to unexpected extreme fire behaviour. We knew the fires were going to be extreme, the challenge was anticipating their behaviour in advance, and ensuring all the ground crews and emergency management teams were briefed as to what fire activity was possible before it happened, so people were as prepared as possible for the impending conditions. How would the weather drive the fire behaviour and, of the hundreds of fires in the landscape, which ones did we need to focus on? I worked closely with the FBAN team to address these questions and shared information through them and with Andrew, who initiated a cascade of further briefings.

I had a head full of science, with the primary method of sharing it being verbal communication through discussions and briefings (I didn't even have PowerPoint presentations). Everything I shared was evidence-based science drawn from a wide research and operational knowledge and communicated in context against the decisions and challenges in predicting the fire activity and appropriate response. It isn't necessary for science to be published or pretty to be useful, it just needs to be applied through clear communication and in context. It was very rewarding to be part of the response team and to use the science when it really mattered.

Meteorological support during extreme events

The Bureau of Meteorology has 'Embedded Mets' in most states and territories (Victoria, NSW, WA, SA and QLD but currently not Tasmania or Northern Territory). The Embedded Mets typically work at fire and/or emergency services headquarters, with a primary role of providing weather briefings and interpretation during routine and high impact events, including media on request. The Embedded Mets are all highly qualified meteorologists with excellent communications skills. However, their training is not multi-disciplinary and fire science or fire behaviour knowledge is not required. The distinction between the Embedded Met briefings; which describe synoptic and mesoscale weather patterns, interpretation of observations (i.e. of radar and satellite) and timely relay of warning information and forecast uncertainty; and the support provided by Mika, was the shift in focus to mesoscale and microscale meteorology with a strong focus on how the weather was likely to affect fire behaviour.

The roles and skill set of meteorologists is evolving as the Bureau transitions to a new service model, with a stronger focus on customer engagement and understanding and responding to the needs of clients. In future this will mean stronger partnerships, deep customer insights, high impact services and briefings that are tailored according to specific requirements. This model will require a high level of training in order to develop the depth and breadth of knowledge required to perform in a multidisciplinary space at Incident Management Teams and the Bureau looks to input from partners on how best to provide the optimal customer-focused experience.

Measuring the value: testimonials

In such events, the benefits are somewhat intangible and therefore difficult to measure, but in this case the positive feedback was considerable, including an article prepared by the Bushfire and Natural Hazards Cooperative Research Centre (Fire Australia 2019).

The testimonials below are from the QFES FBANs, Rusty, Kent and Ben, who worked on Andrew's team preparing the fire predictions using Phoenix. Their comments show firstly; the importance of communication in distilling complex information into an understandable and highly relevant message, where context and prioritisation was critical in real time delivery of products and secondly; meteorology and fire behaviour are two quite separate fields of expertise; the value was in Andrew's decision to assemble a team with complimentary skills and the ability to work cohesively. Together, we had a deep appreciation of the complexity of the situation and the skills and insight to add value where it was of most benefit and then communicate the key messages to the SOC.

Mika was all about the communication of a complex topic into a language that I can understand. I am not a Meteorologist and Mika was talented in providing only what I needed to know at the time in a format that I could understand. I appreciated that I could feel safe enough to ask potentially over simple or perceivably dumb questions of Senior Specialist Meteorologist, who could then respect my level of understanding.

Russell Stephens-Peacock, QFES FBAN

Mika's experience and knowledge was of great benefit on an unprecedented fire weather day. Having a meteorologist with Mika's skill sets working side by side with us as Fire Behaviour Analysts led to more honed forecasts, better prepared prediction products and in turn, a better service to the community.

Kent Barron, QFES FBAN

The Agnes Waters and Deepwater fire was along the coastal strip. As the inland westerly weather approached the coast, the coastal sea breeze and the resulting convergence zone was very difficult to time and account for in predictions. My training in fire weather as an FBAN did not equip me to deal with such nuance. Mika was able to apply her expertise and provide personalised amendments to forecast weather data to account for this providing increased rigour and traceability in fire spread predictions.

Ben Twomey, QFES FBAN

Learnings for future events

Australia will continue to experience extreme weather events with increasing frequency and intensity and concomitant increasing impacts, due to the influence of climate change and a growing population. Our national fire and emergency management agencies will be under increasing pressure and scrutiny to provide the optimal response to support the Australian community in the face of these challenges. This will include advising decision-makers in government and policy, using the most accurate and informed and effectively communicated guidance, underpinned by world-leading, evidence-based science.

In Queensland in 2018, there were no fatalities and property loss was minimal. There is always an element of luck that sits alongside good management.

It is not possible to anticipate and plan contingencies for all possible future scenarios. It is likely that the worse-case scenario is beyond what we can imagine, and it is probable that cascading and overlapping events will present response challenges that stretch resources beyond capacity. A structure that supports organic response and enables well-connected people to call in any available assistance when faced with predicted and escalating situations is imperative to providing optimal response to emerging disasters.

Advances in Numerical Weather Prediction over the past decade means that forecasts provide sufficiently accurate guidance to be useful with a 7-10 day lead time. The burgeoning quantity of ensemble information means that the uncertainty in predictions can be assessed and operational use of ensembles is expected to reduce uncertainty in forecasts in coming years. The consequence is that extreme weather events will be forecast several days in advance with greater accuracy, with detail refined during the short lead time. This will enable mobilisation of resources days ahead of a weather event.

In Queensland, Andrew made a call on-the-spot to fly-in Mika as an additional resource. Similar actions should be encouraged and supported in response to inevitable future events. The Bureau of Meteorology recognises the opportunity to provide science and communication capacity to incident management teams and establish networks in advance. This includes identifying capabilities across research and other non-operational spaces and managing the challenges of having a surge-ready team. It is inevitable that some individuals will not be suited to transition from the slow-burn research space to the adrenalin-charged immediate-response of operations. The ability to bring current and emerging science and a new perspective to real-time decision-making will be imperative.

There are bilateral benefits as ultimately, such an approach will build stronger research utilisation links and trusted relationships and accelerate the uptake and adoption of research findings which are focussed on high impact outcomes, as well as focus research efforts toward real-world issues.

Our operational resources are becoming increasingly tight and supporting front-line responders with the science knowledge and capability held in researchers will realise the benefits of research investment in critical periods, ultimately strengthening operational decisions. Future success will require processes that enable people like Andrew to call on whomever and whatever resources they consider appropriate and to have funding flexibility and discretionary decision making to enable rapid, non-bureaucratic response.

Acknowledgements

With thanks to Bureau of Meteorology, Queensland Fire and Emergency Services, the Bushfire and Natural Hazards Cooperative Research Centre and our colleagues. Particular thanks to Bruce Gunn, who supported the initiative.

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Peer-reviewed article

Fire weather and prototype fire danger ratings for the Gell River fire, Tasmania

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ABSTRACT

We provide a preliminary analysis of the meteorology of key aspects of the Gell River fire in Tasmania during late December 2018 and early January 2019, including the lightning storm that ignited the fire, and conditions on 4 January 2019, when the fire increased substantially in size. We also briefly assess the performance of the Australian National Fire Danger Rating System (AFDRS) Research Prototype available on 4 January against observations of fire spread and routine McArthur Forest Fire Danger forecasts.

The Gell River fire occurred within a context of declining October – April rainfall in western Tasmania over the last two decades, in comparison to the average rainfall for the period since 1900 (Fig. 1, Bureau of Meteorology and CSIRO (2018)). It was one of several large fires that competed for fire management resources over an extended period during the 2018-2019 Tasmanian fire season. The fire impacted natural values including those of the Tasmanian Wilderness World Heritage Area (TWWHA) and risked spreading into parts of the iconic Mt Field National Park, as well as threatening a number of communities in the Derwent Valley, particularly Maydena. The Gell River fire also threatened major electrical transmission infrastructure connecting the large Gordon-Pedder power generation facility in the west of Tasmania to population centres in the east, and burnt approximately 500 ha of a 5,000 ha pine plantation. On 4 January, thick smoke from the fire crossed over the Greater Hobart area, sparking concern and raising awareness within the wider community about the fire activity (Fig. 2).

Contributing weather factors

Rainfall in the weeks leading to the fire ignition had been sporadic. While December rainfall had been close to average, the three months leading up to the start of January had generally seen below average rainfall in the vicinity of the ignition area (Fig. 3a, b). Rainfall of 10-15 mm had occurred in the 24 hours to 0900 EDST (Eastern Daylight Savings Time) 22 December but there was subsequent no rainfall. Fuel availability calculations indicated that moorland fuels were available to burn when ignition occurred on 27 December. While sufficient antecedent rainfall had occurred to prevent the fire from spreading freely into many wet forest areas at that time, some rainforest areas, particularly about forest margins, were drier than others and available to burn.

On 27 December, widespread lightning occurred over central Tasmania (Fig. 4) including the Gell River region, associated with a trough extending over Tasmania from Victoria (Fig. 5). The atmosphere below the unstable mid-level cloud band within which lightning was generated was dry, with a dewpoint depression of 20 to 35°C between 950 and 700 hPa, resulting in minimal thunderstorm precipitation reaching the ground. This combination of weather factors permitted some lightning ignitions to become established fires. Over ensuing days, the Gell River fire was able to remain alight, before it grew progressively under the influence of dry, warm weather during the first few days of January. The fire made a major run during 4 January, increasing from approximately 5 700 ha to 14 000 ha, in hot, windy conditions ahead of a significant cold front that crossed Tasmania during the day but which did not deliver any rainfall. The atmosphere was dry and unstable ahead of the cold front. The instability, together with mechanical turbulence generated by the movement of the airmass over the Tasmanian topography, allowed the mixing of dry, high-momentum air from the upper atmosphere to the land surface during the day, especially in regions away from the west and north coasts and including the Gell River area. The fire burnt through mostly buttongrass moorland in the Vale of Rasselas on 4 January, but impinged on some forested areas, particularly forest edges. The post-frontal airmass was cooler, but substantially. dry, inhibiting the normal diurnal uptake of moisture by fuels overnight in the wake of the frontal passage and permitting the fire to continue growing, albeit more slowly than on 4 January.

Australian Fire Danger Rating System

The AFDRS has been developed in recent years following agreement by Senior Fire Officers and Ministers that the current system of fire danger ratings, developed in the 1960's, has significant shortcomings, and that a new system was required.

The AFDRS incorporates recent fire science and is designed to be modular and have the capacity for continual improvement.

AFRDS forecasts have been generated daily using this system since October 2017 with the Research Prototype being made available to land managers across Australia for evaluation and testing (Matthews et al., 2018). It was initially planned that prototype fire dangers would be calculated across Australia during the period October 2017 through to March 2018, with an evaluation period to follow. The prototype was felt to be sufficiently useful, however, that the project was extended to include the northern Australian fire season during 2018 and a second southern season 2018-2019, during which period the Gell River fire occurred. This extension has permitted further evaluation and the additional benefit of increased familiarity of the system on the part of fire managers.

With a commitment by Australian fire and government agencies to implement the AFDRS operationally across Australia over the next three years, AFDRS calculations and data continue to be generated daily to allow further increased familiarity and use by fire managers.

As part of the evaluation, over 400 fire danger forecasts were compared against current methods of forecasting fire danger, across eight primary fuel types and around Australia. The evaluations were carried out by fire managers and by the AFRDS project team, with results suggesting that the AFDRS Research Prototype performance was better than that of the current system (Grootemaat et al. 2019). In particular, the prototype was better than the current system in identifying severe fire behaviour conditions, which are relatively uncommon (Matthews et al. 2018).

Key underpinning components of the system include a national, consistent fuel grid together with clearly defined descriptions of expected fire behaviour, suppression and containments implications and potential consequences. The fuel grid is linked to fire behaviour models specific to the eight major fuel types within the AFDRS. This enables a greater discrimination of potential fire activity within the varying vegetation types than the McArthur fire danger rating system.

Fire Danger associated with the Gell River fire on 4 January

Operational fire weather forecasts for 4 January indicated Very High fire danger for eastern parts of the West Coast district and Severe fire danger in adjacent areas of the Upper Derwent Valley for forested areas (Fig. 6a) and Very High fire danger in moorlands. These values were calculated using the McArthur Mark V forest fire danger index and rating system (McArthur, 1967; Noble et al., 1980) and the Buttongrass Moorland fire danger rating system (Marsden-Smedley et al., 1999), and results suggested that fire could run freely through either vegetation type on this day. A map of forecast forest fire danger index is routinely generated by the Bureau of Meteorology, and distributed to fire agencies. However, areas of moorland (or other vegetation types) are not separately identified within those maps.

On the other hand, integrated maps of daily maximum fire danger rating are published daily within the AFDRS that incorporate all vegetation types within the mapped region. Category 5 (extremely rapid fire growth, very difficult to control) fire danger was forecast by the AFDRS within the buttongrass moorland-dominated Vale of Rasselas, identified by the red ellipse in Fig. 6b, but only Category 1 to 2 (very low or self-extinguishing) fire danger was flagged for the bounding wet forests.

Under the prevailing conditions, the fire was observed to run extensively through the moorland fuel types but had limited penetration into the adjacent areas of wet forest

Discussion

As suggested in Fig. 1, western Tasmania has become increasingly vulnerable to fire in recent decades. While fires have regularly occurred in western Tasmania since European settlement (e.g. "Black Friday" 1934, 2 February 1939, Zeehan fires 1981; State Emergency Service (1990), Australian Bureau of Statistics (2000)) and through prehistory (e.g. Bowdler (2010)), in the last twenty years, they have become more widespread and more frequent with drying conditions during the warmer months (Thackway et al. (2008), Marsden-Smedley (2014), Australasian Fire and Emergency Services Authorities Council (2016), French et al. (2016), Press (2016)). Tools to better manage such fires therefore have considerable value not only in Tasmania but across Australia.

The Australian Fire Danger Rating System integrates recent, operationally ready, fire science and presents a way to improve the suitability of fire danger forecasts in an increased number of fuel types using clearly defined descriptions of expected fire behaviour, suppression and containment implications and potential consequences. In environments such as those in western Tasmania which feature a complex mosaic of different vegetation types, the AFDRS promises to be a valuable tool to improve the accuracy of fire danger prediction, while making forecasts more specific and targeted. The Gell River fire provided a good example of such application and broad suitability of the AFDRS forecasts on 4 January 2019.

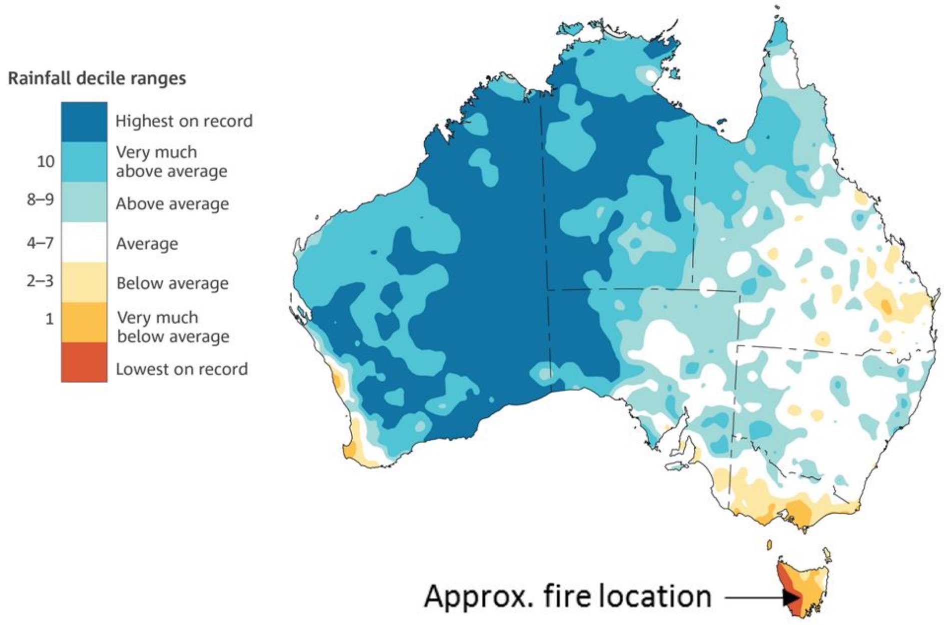

Figure 1: Deciles of Oct-Apr rainfall 1998-2018, cf. the same period since 1900 (from State of the Climate, BoM/CSIRO 2018).

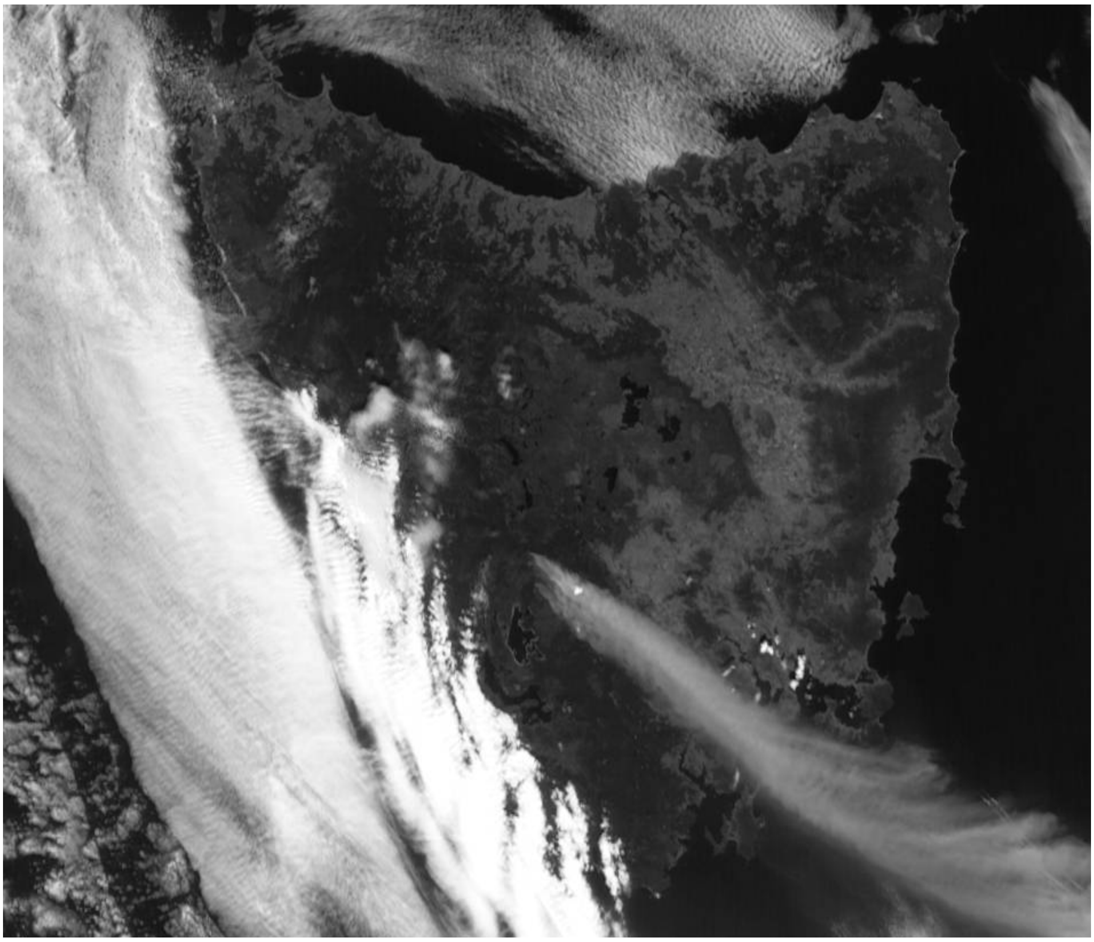

Figure 1: Visible wavelength Himawari-8 image showing the smoke plume from the Gell River fire extending over southeast Tasmania.

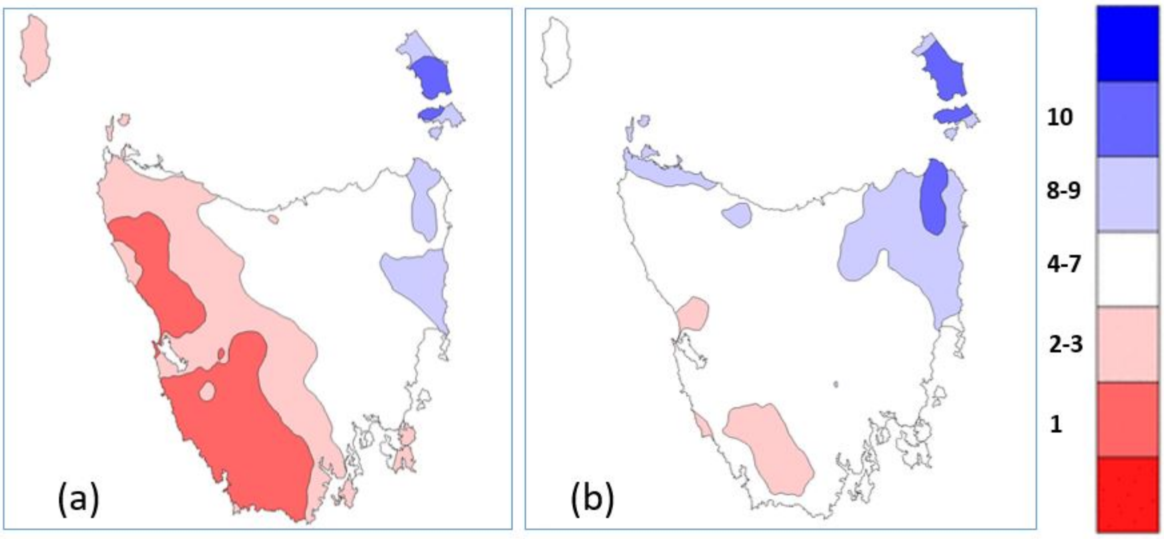

Figure 3: Tasmanian rainfall deciles for (a) Oct-Dec 2018 and (b) Dec 2018. Legend at right indicates decile ranges.

A further consideration is that current operational fire danger forecasts do not distinguish between wet and dry forest types which have different fuel moisture profiles (see e.g. Duff et al. (2018), Cawson et al. (2018) for discussion of the impact of fuel moisture on flammability). The tertiary classification of vegetation in the fuel mapping that underpins the AFDRS permits a substantially greater degree of resolution of fuel characteristics than is possible with fire danger systems currently in use operationally within Australia. On the other hand, models of fuel availability in wet forests require further development to be reliable.

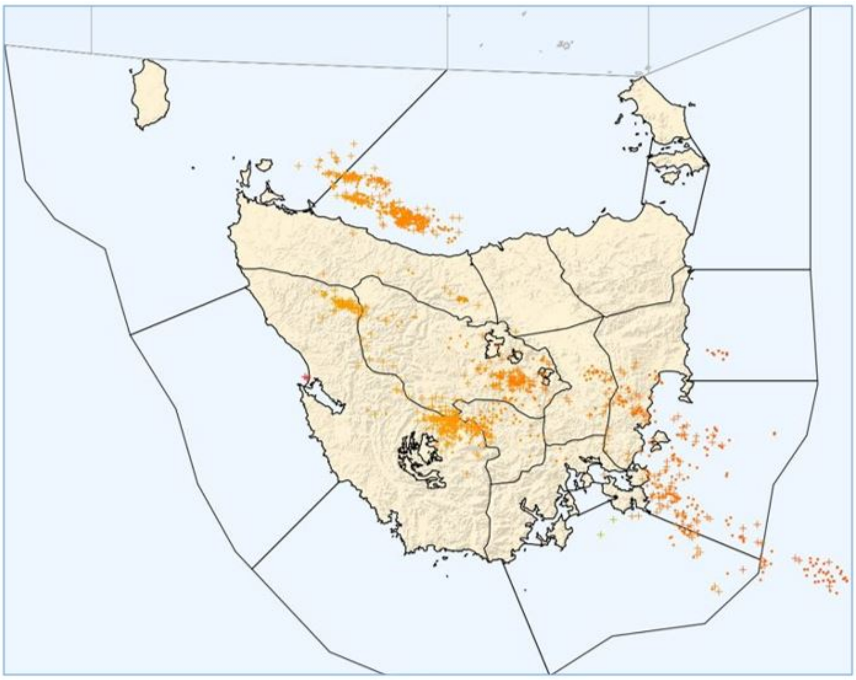

Figure 4: Lightning detections for the 24 hours to midnight Thursday 27 December 2018. Source: Global Position and Tracking Systems, TOA Systems Inc.

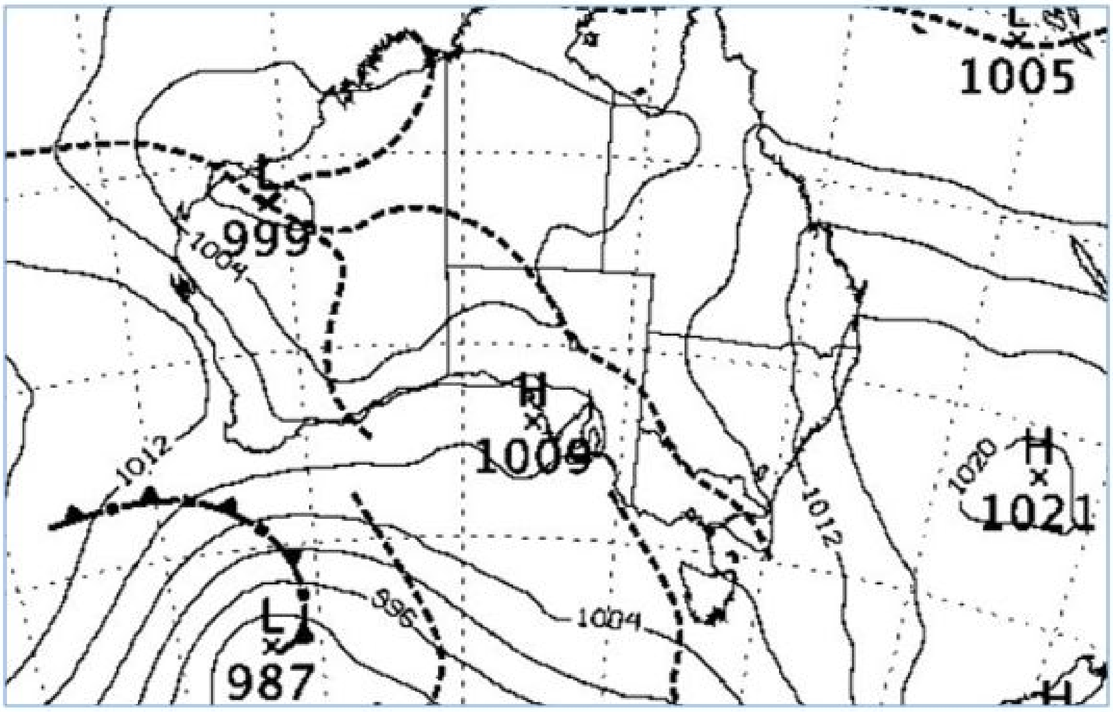

Figure 5: Mean Sea Level Pressure map for 2300 EDST Thursday 27 December 2018. Source: Bureau of Meteorology National Operations Centre.

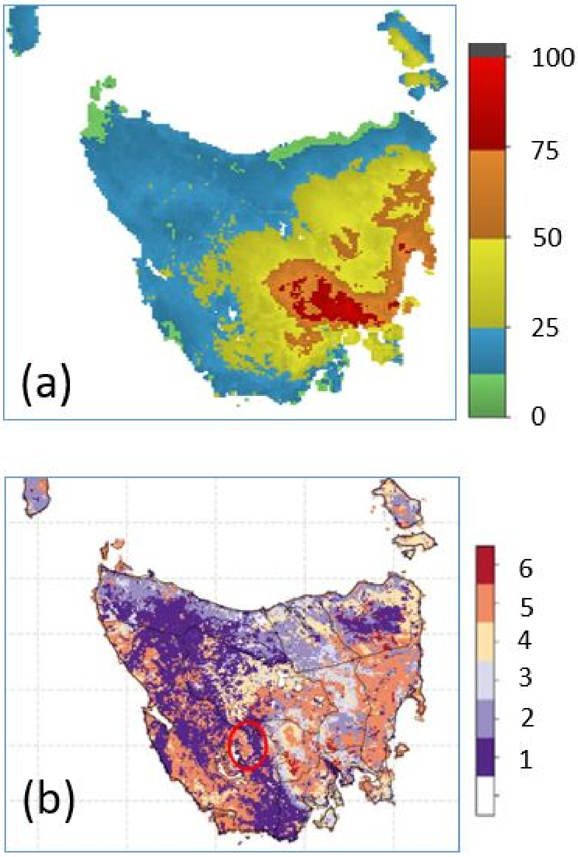

Figure 6: (a) FFDI forecast for Tasmania, based on 0500 EDST 4 January update to weather grids (b) AFDRS forecast for 4 January 2019. Location of Vale of Rasselas highlighted by red ellipse.

Despite the better representation of fuel types within the AFDRS and use of appropriate fire behaviour models for different fuels (Matthews et al. 2018, Grootemaat et al. 2019), there was good evidence that the Gell River fire burnt into some forest (W. Frey, pers. comm., Fig. 7), in spite of the low fire danger ratings assigned to the forest by the forecast system. It is likely that poor resolution of soil moisture, and therefore fuel moisture, played a part here (see e.g. Vinodkumar et al. 2019, Walsh et al. 2017, Merlin et al. 2012). Several factors would have contributed to this uncertainty in soil moisture estimation. The fire started in a remote area with very limited observational infrastructure – the nearest regular rainfall recordings are tens of kilometres away at locations including Scotts Peak, Butlers Gorge and Ouse. In a uniform environment, this may not have been problematic, if still not ideal. In the topographically diverse environment of western Tasmania, it can lead to significant inaccuracies (Walsh et al. 2017). In addition, the fire started in a region where the rainfall gradient, decreasing from over 3000 mm/year in the west to around 500 mm/year on the east coast, is at its greatest. One further difficulty still is that the deep organic soils that are common in western Tasmania are not well-represented by current soil moisture models (Press, 2016).

Some of these problems are likely to be improved with the introduction of tools under development within the Bushfire and Natural Hazards Co-Operative Research Centre, including the Australian Flammability Monitoring System (AFMS, Yebra et al. 2018) and the JASMIN Land Dryness system (Vinodkumar and Dharssi, 2019), which uses numerical weather model output to estimate soil moisture. Both of these tools employ assimilation of remotely sensed data, which helps to address the lack of surface measurements. Cloud cover can be a problem in some areas, however, particularly western Tasmania. With JASMIN in particular, recent research to downscale the system from its current 5 km horizontal resolution to 1 km resolution would be valuable in Tasmania, but this has proven to be a difficult task in forested areas (Vinodkumar et al. 2019). The inclusion of the fluxes of moisture and energy between the surface and atmosphere that are a feature of JASMIN, given its basis in the Bureau of Meteorology's numerical weather prediction system, will nonetheless assist in the refinement of soil moisture characterisation in remote areas such as Gell River.

A proposal is being co-ordinated by the Tasmanian Parks and Wildlife Service to site a soil moisture sensor within the Tasmanian Wilderness World Heritage Area near Scotts Peak, to facilitate better understanding of the flux of moisture through the organic soils of western Tasmania. If this project is implemented, the information from this sensor will also contribute to better soil moisture representation for future fires in this region, and in similar environments.

The AFDRS is designed to be modular, so that as new science is developed and tested it can be implemented within the fire danger rating system. In this way, the potential of tools such as the Australian Flammability Monitoring System and JASMIN can be realised within the AFDRS, and current research into wet forest flammability can be included in updated fuel availability functions for those forest types. At a time when fuels in western Tasmania are increasingly available to burn during the warmer months, the AFDRS will assist fire managers better prepare for and respond to fires in the rugged and fragile landscapes found in western Tasmania. The predictions of the AFDRS on 4 January were unsurprising to fire behaviour analysts tasked with predicting fire progression. The integration of fuel maps and appropriate fire models with an overarching categorisation of fire behaviour across the landscape is nonetheless a helpful tool to assist in the prediction of fire danger in a complex assemblage of vegetation types.

Conclusion

The Australian Fire Danger Rating System is being operationally implemented nationally in coming years, after successful prototyping commencing during the 2017-18 southern Australian fire season. The system draws together much recent fire science and meteorology, including topics as diverse as vegetation typing and fire behaviour models to climatologies derived from new weather reanalyses (Matthews et al. 2018). We have highlighted in a brief overview a single application of the AFDRS, providing background information on the weather and fire event sufficient to set a context for the application of system. The case of the Gell River fire progression during 4 January demonstrates the value of the AFDRS, both in integrating the output of a number of fire behaviour models and in the improvement of forecasted fire danger.

Figure 7: Vale of Rasselas following fire passage on 4 January 2019, showing areas of burnt moorland, and some areas of forest into which fire penetrated. Image courtesy Warren Frey, Tasmania Fire Service.

Acknowledgements

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Jim Richley (TFS) for fire isochrones 3-5 Jan 2019.

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Peer-reviewed article

Simulations of radiation heat flux on a structure from a fire in an idealised shrubland

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ABSTRACT

Wildland-urban interface areas are growing rapidly. Building standards are required to ensure that the structures built in fire prone areas are resilient to fire. Australian Standard AS 3959 was developed to prescribe construction requirements for houses in bushfire prone areas. The model in AS 3959 is applied to estimate the Bushfire Attack Level (BAL) that is expected on a structure during the nominally worst-case bushfire scenario that the house can experience. Once the BAL is based on the fuel and terrain near the structure, and determines the construction requirements for the structure. AS 3959 is based upon a view-factor model of radiant heat flux, which estimates the level of heat flux expected at the structure.

The view-factor model essentially estimates how much of the fire is 'seen' by the structure. The example simulation shown in Figure 1 has a schematic of the view-factor model superimposed upon it. AS 3959 assumes (among other idealisations) a straight-line fire of 100 m width with a constant flame temperature of 1090 K, and seeks to maximize the view factor by varying the flame angle. In reality, flame temperatures can exceed 1200 K (Worden et al. 1997) and the flame angle is determined by the interaction of the buoyant fire plume and the driving background wind. Flame temperature is a critical parameter because it is raised to the fourth power in the model. As an illustrative example, if the flame temperature reaches 1400 K then the expected radiative heat flux will be approximately 175 % of the value if flame temperature was 1090 K. Flame angle varies greatly depending on whether a fire is dominated by buoyancy, or by the background wind and fires can transition between the buoyancy dominated and wind dominated modes.

Wind dominated fires have long, elongated flames that are close to the ground, whereas buoyancy dominated fires have tall, vertical plume-like flames. Obviously, the flame of a buoyancy dominated fire will have a larger view-factor than a wind dominated fire. However, wind dominated fires occur when the wind speed is high (for all other conditions equal). Because AS 3959 is based on empirical models which do not account for the differences between buoyancy dominated and wind dominated fires, AS 3959 could ignore a fire that gives higher radiative heat flux at lower driving wind speed. That is, the model in AS 3959 may not correctly predict what set of weather and fuel conditions give the worst-case scenario. AS 3959 is also considerably restricted by a lack of a model for ember attack. While the AS 3959 standard prescribes numerous requirements to mitigate against the risk of embers, there is minimal guidance about what ember risk is expected for given fire conditions.

Khan et al. (2019) simulated grassfires impacting on a structure and compared the simulated heat flux with the predictions of AS 3959. AS 3959 was found to somewhat under predict the heat fluxes in the higher BAL classifications. The fires simulated in Khan et al. were 20 m in width, and the radiative heat flux received at the structure was comparable with the BAL levels expected from a 100 m wide fire.

The width restriction in the simulations was due to computational time constraints, however, the results imply that the heat flux from a 100 m wide fire will likely

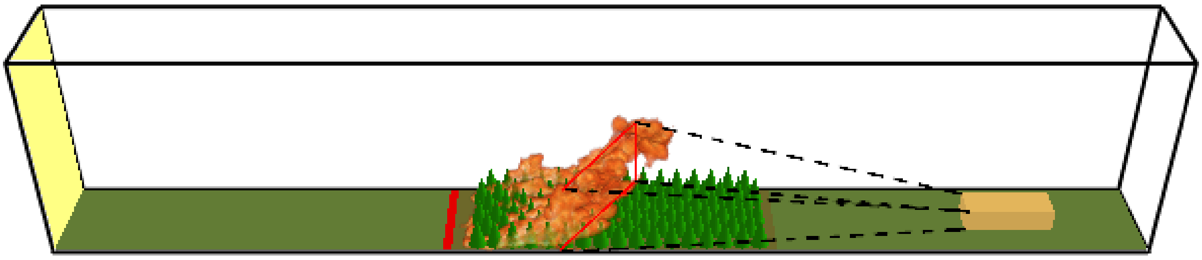

Figure 1: Rendering of the domain, with the fire at 34 s from ignition. The structure is shown as a brown rectangular prism. The trees are rendered as green cones. The flame is visualised through isosurfaces of heat release rate per unit volume (>100 kW/m3). A sketch illustrating the view factor model is imposed on the drawing. The red line indicates a modelled rectangular flame and the black dashed lines indicate how much of the radiation from the flame arrives at the receiving surface on the structure.

exceed the predicted BAL, because as the fire width increases it is reasonable to assume the radiative heat flux on the structure will also increase.

Hilton et al. (2017) simulated the heat flux on an structure from a fire using SPARK. In their model the fire was modelled using the McArthur (1967) empirical model, and the radiative heat flux was calculated using a ray-tracing algorithm. The simulations of Hilton et al. (2017) did not attempt to replicate the scenarios specified in AS 3959, but instead simulated a fire moving past a structure.

The purpose of this study is to simulate a fire from an elevated fuel source like a shrubland and measure the radiative heat flux on a nearby house-like structure. In light of the results we offer some comments on the possibility of performance-based design using simulation results.

Numerical model

Physics-based fire simulation

Wildland-Urban Fire Dynamics Simulator (WFDS) is used to simulate burning of an idealised shrubland and measure the radiation heat flux received at a house-like structure. WFDS simulations of burning single trees have been carefully validated (Mell et al. 2009). Simulations of radiation heat load on structures from prescribed forest fires have been conducted by Hostikka et al. (2008). Hostikka et al. considered a prescribed fire, that is one where the intensity is prescribed a priori rather than computed by simulating pyrolysis and combustion reactions. Here we simulate a dynamic fire with full physics.

WFDS uses a large eddy simulation (LES) approach to modelling fluid momentum. That is, the largest turbulent eddies are resolved on the grid, and smaller turbulent motions are modelled using the default Deardoff sub-grid scale model (McGrattan et al. 2013b). Solid phase pyrolysis is modelled using the linear model of Morvan and Dupuy (2004). Gas-phase combustion is simulated using a mixture-fraction combustion model. For complete details see McGrattan et al. (2013a, 2013b).

Model setup

The shrubland is comprised of pine trees, 2.25 m tall on a surface of grass. While pine trees and grass surface fuel are an unusual choice to replicate Australian shrubland, validated fuel property measurements exist (Mell et al. 2007, Mell et al. 2009) and therefore we can be confident that simulating pine trees yields realistic results for pine shrublands. Note that, unlike Khan et al. (2019), a replication of AS 3959, as close as possible, is not attempted here. To replicate AS 3959 would require a study of the fuel types, such as the shrublands considered by Anderson et al. (2015), listed in the standard. Thermo-physical and chemical properties of the fuels would have to be measured and the simulations of combustion of shrubland samples would need to be validated against experiments.

The forested area is 37 m long and starts 45 m from the domain inlet. The trees are regularly spaced in a staggered fashion in four columns. The trees are spaced 2 m apart; alternating between columns of 16 and 17 trees. The tree is modelled as a cylindrical trunk and the crowns are modelled only as pine needles with 2.2 kg/m3 bulk density in a conical shape. The overall domain is 124 m long, 12 m wide, and 25 m tall. The domain size is chosen as the largest domain studied by Moinuddin and Sutherland (2019) and can accommodate a realistic house like structure. 200 mm grid resolution was used throughout the domain; the domain size and grid resolution were shown to be sufficient to ensure numerically converged heat release rate results (Moinuddin and Sutherland 2019) which are free of errors caused by under resolving the simulations. The inlet is a power law (1/7) model of the atmospheric boundary layer (ABL) with a wind speed of 3 m/s at 2 m. The two lateral edges use a symmetry boundary condition to force the fire to remain approximately straight throughout the simulation. Constant pressure boundary conditions are used at the top and outlet of the domain. The house is modelled as a solid, but thermally inert, obstruction located 25 m downstream of the shrubland. There is no combustible fuel between the shrubland and the house. The house structure is relatively small: 10 m long, 8 m wide, and 4.5 m tall. There is no attempt to reproduce detailed features of a house. The idea is that the centre of the front wall will receive most of the radiative heating and therefore the centre of the front wall is of the most interest. The rest of the house shape is then somewhat irrelevant to these simulations. A rendering of the domain showing the fire progression is shown in Figure 1.

Results and Discussion

Fire spread results

The location of the fire front as a function of time is computed from the centerline (y=0) heat release rate (HRR) data. The HRR data is first examined over all times to measure the maximum observed HRR. HRR data that are less than 1% of the maximum observed HRR are set to zero. The remaining nonzero HRR data are set to one. This filtering process effectively yields a black and white image of the flame based on the threshold of 99% of the maximum HRR. At each output time step, the geometric centroid of the flame image is computed, and the x-component of the centroid is taken as the flame front location. The flame centroid data is slightly noisy and depending on instantaneous flame geometry, the flame centroid can move backwards between observations.

Time is measured from the ignition time and the x-distance is measured as the distance from the ignition location.

The fire front location is plotted in Figure 2. Two distinct regions of propagation are observed; from time 0 to 20 s, the fire propagates along the surface, but at time 20 s the fire enters the crowns of the trees. The total fire intensity is plotted against time in Figure 3. A quasi-steady intensity is achieved at time 30 s. The intensity decreases at time 80 s as the fire reaches the end of the burnable region. The quasi-steady region is observed between 30 and 80 s.

The flame angle is computed from threshold HRR images. Following Cobian- Iñiguez et al. (2019) an ellipse is fitted to the HRR image at every time level. The ellipse is constrained so that the second moment of the ellipse is equal to the second moment of the nonzero region of the image. This process results in the ellipse that best overlaps the irregular flame shape. The length of the major axis of the ellipse and the orientation angle of the ellipse then corresponds to the flame length and flame angle respectively.

The flame angle is plotted in Figure 4. Initially, the flame is close to vertical. As the fire transitions from the surface to the crown at around time 20 s, the flame angle varies around an average of 62 degrees. Here, 90 degrees corresponds to a vertical flame, 0 degrees corresponds to a perfectly attached flame moving in the windward direction. Negative flame angles correspond to a flame that leans into the oncoming wind. There is no angle model within AS 3959, instead the flame angle is chosen to maximize the radiant heat flux on the structure, modelling the worst-case scenario. For a structure on flat ground the worst possible flame angle would be 90 degrees.

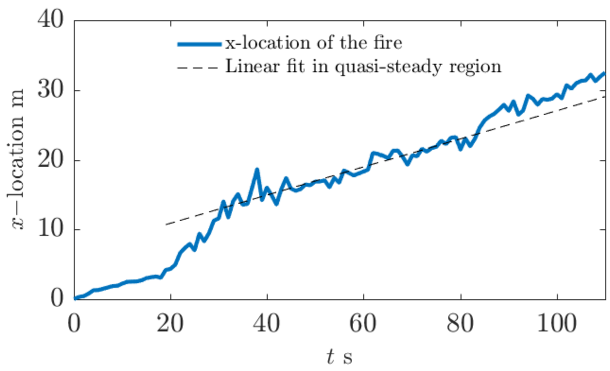

Figure 2: Fire front location as a function of time. A linear fit to determine the rate-of-spread after the crown fire developed is also shown. The rate-of-spread is 0.2 ms-1.

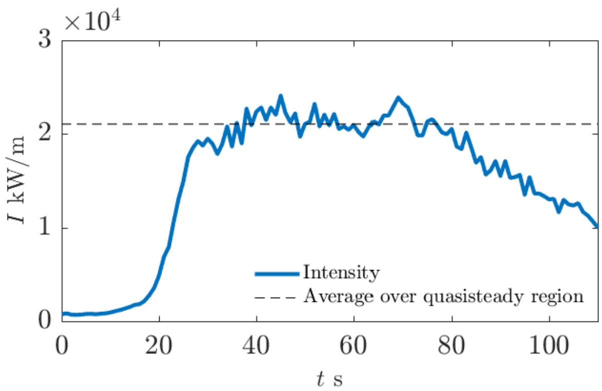

Figure 3: Fire line intensity as a function of time.

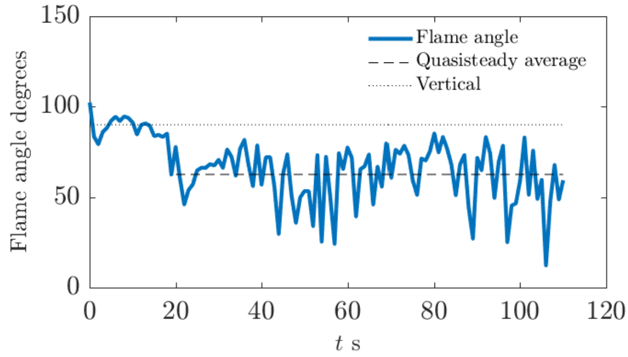

Figure 4: Flame angle in degrees as a function of time. The dotted line indicates a constant vertical flame, and the dashed line is the average flame angle in the quasi-steady region.

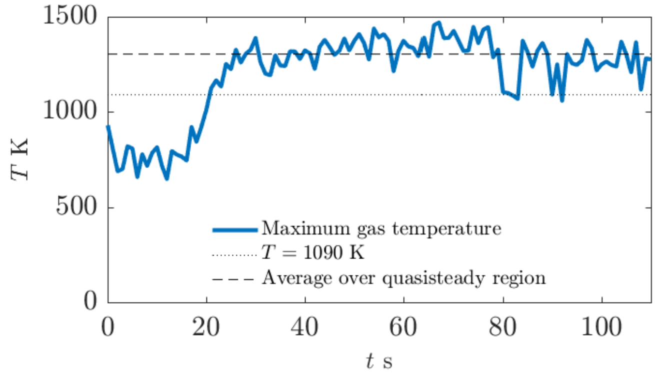

Figure 5: Maximum gas temperature as a function of time, compared to the AS 3959 assumption of 1090 K, and compared to the time-average maximum gas temperature over the quasi-steady region.

The maximum centerline gas temperature is taken as a proxy of the flame temperature. The mean flame temperature as a function of time is plotted in Figure 5. The flame temperature is found to be more than the 1090 K assumed in AS 3959 at approximately 1400 K; therefore, the radiant heat incident on the structure may be underestimated by AS 3959. Interestingly, even though the fire line intensity starts to decrease at around time 80 s, the maximum gas temperature remains approximately constant; probably because the maximum gas temperature related to the flame temperature and will largely be independent of the volume of over where the heat is released (ie. the intensity).

Heat flux at the structure

The radiative and convective heat fluxes at the structure are plotted in Figure 6 as a function of fire distance from the structure. The front face of the structure is set at $x = 0$ m and negative distance represents fire upstream of the structure. Both heat fluxes are very small, the maximum BAL level assumes 40 kW m -2. The maximum radiative heat flux received is 500 W m-2. The incident heat flux is likely insufficient to cause an ignition of a real structure. Note that there is a 25 m vegetation free zone before the house, and this distance is sufficient to ensure the radiant heat flux is small in this case. The radiant heat continues to grow as the fire approaches the structure. The magnitude of the radiant heat flux at the distances considered is of comparable size to the radiant heat flux simulated by Khan et al. (2019).

The distance between the flame and the structure is the crucial factor to consider when computing the expected heat fluxes on the structure. However, given the domain in these simulations is much narrower (12 m) than assumed by AS 3959 it is worth calculating the ratio of heat flux from the narrow and full width fires, using the AS 3959 model. Using the values and models prescribed for shrubland we find that for a 12 m wide fire, the predicted heat flux is approximately one third of the value predicted for the 100 m wide fire.

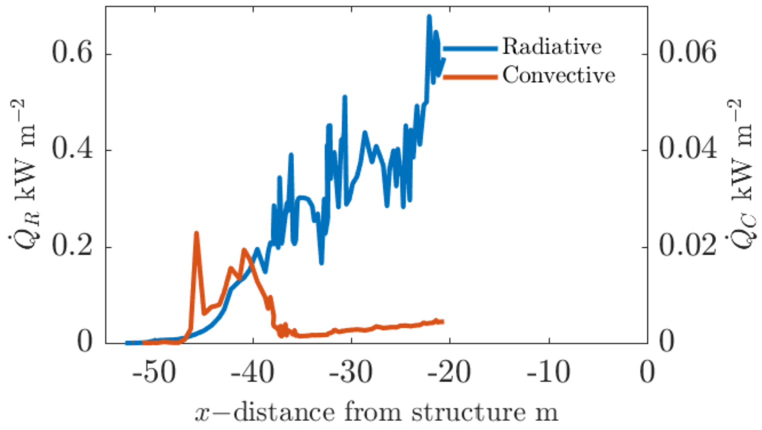

Figure 6: Radiative and convective heat fluxes received at the front face of the structure. Note that distance is measured from the centre of the fire to the front face of the structure. Negative distances represent a fire upstream of the structure. Note that the convective heat flux is shown on a scale an order of magnitude less than the scale of the radiative heat flux.

The convective heat flux on the structure is even smaller than the radiant heat flux. The flame angle is approximately 60 degrees throughout the simulation, and so the convective transport of heat will be predominantly vertical. When the flame angle is small the convective heat load is marginally higher but likely still negligible. This observation may appear at odds with Finney et al. (2015) who demonstrate that convective heat transfer is vital for the ignition of grass-like fuels. This is because the grass-like fuel is highly porous, has a large surface area, and is much closer to the flame. The plume temperature decreases rapidly away from the flame due to mixing of ambient air. The flow of the hot gasses over the house-like object is also considerably different to the flow through a porous fuel bed, resulting in a considerably lower convective heat flux on the surface of the structure.

Future work

Further work is required to model realistic Australian fuel types. Some measurements of Eucalyptus fuels have been made (Wadhwani et al. 2017) which would allow simulation of some of the fuel types specified in AS 3959. Those simulations could be used to verify or strengthen the BAL model within AS 3959.

Feasibility of performance-based design for bushfire prone areas

There is a possibility of performance-based design of structures in fire prone areas emerging as design tool in the near future. In this work, we have demonstrated that it is possible to simulate the impact of a design fire upon an idealised structure. Computational time constraints impede the simulation of larger fires on more realistic structures. Improvements to computational technology and development of refined physics based models will allow simulation of large scale fires on realistic houses. Therefore, performance-based design of structures must be considered. The simulated resilience of a structure to

fire impact can be optimized to meet certain prescribed criteria: eg the structure can withstand exposure to a wildfire for a sufficient period. Performance-based design would work on a case-by-case basis and if a structure satisfies the performance criteria, then the design is deemed suitable for construction. Two key points must be addressed before performance-based design of structures in a bushfire prone area can be adopted. (1) Design criteria, that is (at least) the intensity and duration of fire that a compliant building is expected withstand, must be determined. (2) Physics-based modelling of impact upon structures must be carefully validated against experimental or field observations to ensure that design scenarios are reasonably simulated. Importantly, firebrands must be incorporated into physics-based models. Firebrands were found to be the leading cause of house loss in the 2003 Canberra bushfires (Bianchi and Leonard, 2005). Significant advances in the simulation of ballistic firebrands (eg. Thurston et al. 2017, Wadhwani et al. 2019) have been made. However, none of these works consider the impact of firebrands on structures and none of these works consider ember showers and transport of embers that remain close to the ground.

While it seems possible that both of these points can be satisfactorily addressed, it will be some time before physics-based simulations of realistic fires impacting on proposed structures will become a routine part of the design process.

Conclusions

The radiative heat flux at the front face of a structure from a fire in a pine shrubland has been simulated using a physics-based model. In the quasi-steady spread region, the maximum flame temperature was found be approximately 1400 K, greater than the 1090 K used by the model in AS 3959. The flame angle was found to be approximately 60 degrees, which is less than the vertical flame that would be assumed under AS 3959 for flat ground. The maximum incident heat flux on the structure is low: 500 W m-2 however, that is likely due to the distance between the structure and the fire.

Khan et al. (2019) reported similar results: at 25 m from the structure the heat fluxes were negligible and well below the 12.5 kW m-2 limits prescribed by AS 3959. However, as the fire approached and overran the structure the simulated radiant heat flux in Khan et al. was commensurate or greater than the values prescribed by AS 3959. We expect that if the structure adjoined the shrubland, the structure would receive a significantly larger heat flux, at least in order-of-magnitude agreement with AS 3959.

Finally, we appraised physics-based simulations for performance-based design for construction in a bushfire prone area. Ultimately, firebrand impact upon structures will need to be included in simulations. Fire and heat flux impacting on idealised structures is currently feasible, but more research is required before performance-based design becomes routine.

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Peer-reviewed article

ACCESS-Fire: coupled fire-atmosphere modelling

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ABSTRACT

Coupled models are a class of fire prediction models that integrate a fire component with an atmospheric component, to examine how the energy released by a fire modifies the surrounding atmosphere. Coupled models can resolve complex interactions between the fire, topography and atmosphere, which subsequently manifest on fire behaviour. Results from simulations promote understanding of the driving processes in dynamic fire events. This can inform development of predictive tools that may be used to anticipate extreme fire behaviour and mitigate against the impacts of significant fires.

Globally, several coupled models have been developed; mostly by meteorological institutions for application in a research capacity. They can be broadly separated as taking either physical or empirical modelling approaches. We are running ACCESS-Fire; an empirical coupled model. It links the research version of the Australian Community Climate and Earth-System Simulator (ACCESS) Numerical Weather Prediction (NWP) to a set of empirically derived fire spread equations. In this presentation we will describe the coupled fire-atmosphere model ACCESS-Fire and report on progress on simulations of recent significant fire events.

In Australia and overseas, the imperative for accurate, flexible and timely predictions for prescribed (fuel reduction) burns and bushfires will only increase. Incorporating complex, dynamical meteorological fields is a critical component in building fire prediction systems that can resolve some of the most destructive elements of fire behaviour. Although coupled fire-atmosphere models are currently limited in producing timely operational output due to computational requirements, these restrictions will diminish as technology capabilities continue to increase.

Fire atmosphere interactions

Large bushfires release substantial amounts of energy into the surrounding atmosphere. This energy release modifies the structure of the surrounding wind, temperature and moisture profiles in space and time. The changes driven by the fire can manifest as winds that are similar in speed but opposite in direction to the prevailing winds, pyrocumulus clouds and, in extreme cases, pyro-cumulonimbus clouds. The dynamic feedback loops produced by the fire-atmosphere coupling process can have a dramatic influence on how a fire evolves. Fire-atmosphere feedbacks can also be strongly enhanced by local topographic influences due to wind flow being modified through high terrain.

In current operational fire simulation models used in Australia, simple meteorological values are provided as inputs to an algorithm for fire spread which produces a prediction of fire perimeter evolution across a two-dimensional landscape. This approach does not incorporate any three-dimensional interactions between the fire and atmosphere and, in certain cases, will provide a limited depiction of how a fire may evolve, particularly in a dynamic environment in high terrain. This project explores the ability to examine fire-atmosphere interactions through use of a coupled model.

We use the premier operational and research Australian high-resolution weather prediction model ACCESS, which has been coupled to a set of empirical fire-spread models including McArthur forest, McArthur grassland, CSIRO forest (Vesta) and Rothermel. The modelling framework allows for inclusion of any similar empirical fire model. The ACCESS model (uncoupled) has been used to examine several high impact fire events and has provided detailed insights into the meteorological processes impacting a fire environment. Coupling ACCESS to a fire model provides opportunity for future development of a coupled modelling capability in Australia, as well as potential to provide a fire prediction tool to international partners through the overarching UK Met Office Unified Model framework.

We have selected two case studies to simulate and analyse with ACCESS-Fire with the objective of better understanding and prediction of fire-atmosphere feedback processes and demonstrating the skill and usefulness of the coupled model. Fire-atmosphere feedback is important because it often reflects a transition from steady-state fire spread to rapidly fluctuating, dynamic and more intense fire activity, which is inherently more difficult to predict. Blow-up fires, extreme fire behaviour and dynamic fire behaviour are all terms that may be used to describe fire activity that is erratic and potentially dangerous to firefighters and destructive to communities. Coupled model results have been shown to assist in identifying and the triggers and ingredients that lead to non-linear fire activity. This knowledge will enable risk mitigation activities to be undertaken; both at bushfires and fuel reduction burns.

Coupled fire-atmosphere models are increasingly being used internationally in both research and operational spheres. The most progressive operational implementation is in the USA state of Colorado, where the WRF-Fire model is a component of a new capability for fire prediction in the state. Other USA work includes using the WRF-Fire model for predicting particulate trajectories in fire plumes.

A coupled fire-atmosphere model has also been used to analyse fire behaviour in Mediterranean fires. As Australia has one of the most fire-prone landscapes in the world, with critical infrastructure and homes in high risk areas, and with climate projections indicating an increase in fire risk in landscape, our requirement for developing capability in this space is unparalleled.

ACCESS-Fire model developments

Coupling a fire model to the ACCESS model was a project originally conceived in a collaboration between Melbourne and Monash universities with the objective of simulating the Black Saturday fires (Toivanen et al. 2018). The fire code that was written during the Monash project was provided to BoM and our simulations are run on NCI. The original code was configured for a single event and implemented in the now-retired UMUI ACCESS model interface. Significant effort has been invested in modifying the code to run on multiple events and in transitioning to the new, more interactive and intuitive Rose-Cylc model user interface. Ongoing development work will continue to build the model's functionality, capability and predictive skill.

A significant development challenge we have overcome is selecting the appropriate settings for the atmospheric boundary layer to ensure model stability. Because ACCESS is a global numerical weather prediction model, it was not designed to handle the energy fluxes from a large fire at resolutions of ~100 m; in particular, ACCESS was not intended or designed to resolve the turbulent mixing processes required to disperse the fire's energy through the near-surface atmospheric grids.

The settings for the boundary layer model configuration have undergone significant testing in order to determine the most appropriate options to maintain model stability.

The ACCESS-Fire model continues to be under development and further testing of the model configuration and capabilities is required. In its current form, it is a research model which can be used to explore the atmospheric processes surrounding bushfires and deliver proof-of-concept of the value of a coupled framework for simulating landscape-scale wildfires. Although a future transition to operational application is possible, it is not imminent due to the effort required to develop and test such a capability.

Case studies

In our presentation, we show initial results from two case studies that have been selected in consultation with our partners in fire and land management agencies (Fig. 1 and Fig. 2). The Waroona fire in southwest Western Australia in January 2016 is the first case study. Over a two-day period, there were four extreme fire behaviour events; two separate pyro-convective thunderstorms and two evening ember storms.

The Sir Ivan fire in NSW is the second case study. The fire occurred on a day of 'catastrophic' fire danger and produced a pyrocumulonimbus cloud when the environmental wind direction changed from northwest to southerly. An unprecedented, detailed set of observations were collected during the event by NSW RFS and these will be a valuable component in the analysis.

Waroona fire

The Waroona fire burnt over 68,000 ha and destroyed more than 160 homes in southwest Western Australia in January 2016. On the second evening of the fire, there were two fatalities when the fire made an unexpected run and produced a destructive ember storm over the town of Yarloop.

During the first two days of the fire, there were four episodes of extreme fire behaviour. Two separate pyrocumulonimbus (pyrocb) events developed; both produced anomalously fast runs in the prevailing winds and lightning from the first pyrocb was observed to ignite new fires. The second pyrocb event occurred at a time that is outside the normal diurnal timing of thunderstorms. Two evening ember storms occurred; the first impacted the town of Waroona and the second caused devastation when it devastated the town of Yarloop. The ember storms were driven by fire plumes interacting with local downslope winds; resulting in a turbulent horizontal transport mechanism conducive to lofting and transport of numerous firebrands. None of the four episodes of extreme fire behaviour matched the time of highest fire danger as measured by fire danger indices.

The first pyrocb on 6 January was triggered by the passage of a sea breeze front and developed a deep plume to higher than 14 km. Lightning from the pyrocb ignited new fires downwind and a density current outflow was observed at a nearby Automatic Weather Station (AWS). On 7 January, the second pyrocb developed during late morning, triggered by high energy release along a 20 km fire line.

On the evening of 6 January, the town of Waroona was reported to be under ember attack at around 2100 hr. The ember attack is likely to have been a result of lighting ignition of a new fire closer to the town, which was subsequently driven by a density current outflow from the pyrocb. Downslope winds provided a localised lofting, transport, and turbulent dispersion mechanism for firebrands, and produced the ember attack over Waroona. On 7 January a second evening ember storm occurred, which effectively destroyed the town of Yarloop. The ember storm over Yarloop was similarly driven by downslope winds. Heavy, long unburnt fuels to the east of the town were a significant contributing factor to the intensity of the fire as well as being a source of firebrands. Doppler radar velocity scans show significant vertical plume development and localised convergence at the time Yarloop was destroyed by the ember storm.

On both evenings, the fire was burning on the lee slopes of the Darling escarpment, consequently, local downslope winds and topographic effects played an important role in driving the fire activity and the evening ember showers.

An important aspect of the dynamics of downslope winds in driving ember showers is their highly turbulent nature, which is conducive to spotting and ember showers, particularly if local fuels are favourable for firebrand production. Slow overnight fuel moisture recovery in the hot, dry conditions would also be a contributing factor.

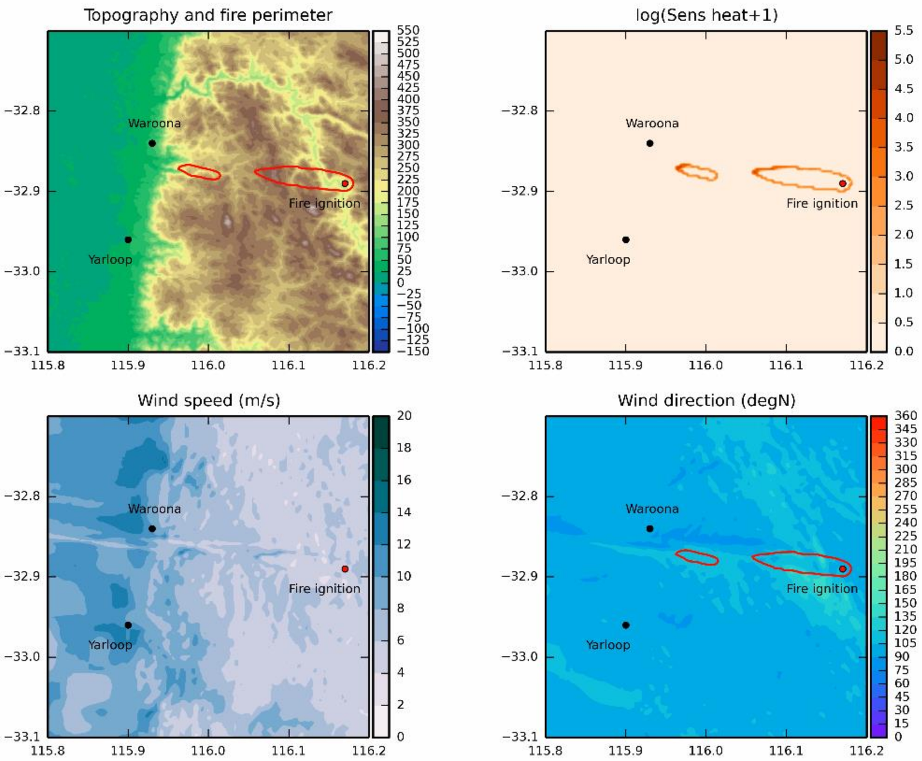

Figure 1: Simulation of the Waroona fire, shown at 2251LT Local Time 6 January 2016. Top left: topography and fire perimeter. Top right: sensible heat flux from the fire grid (logarithmic scale). Bottom left: wind speed. Bottom right: wind direction.

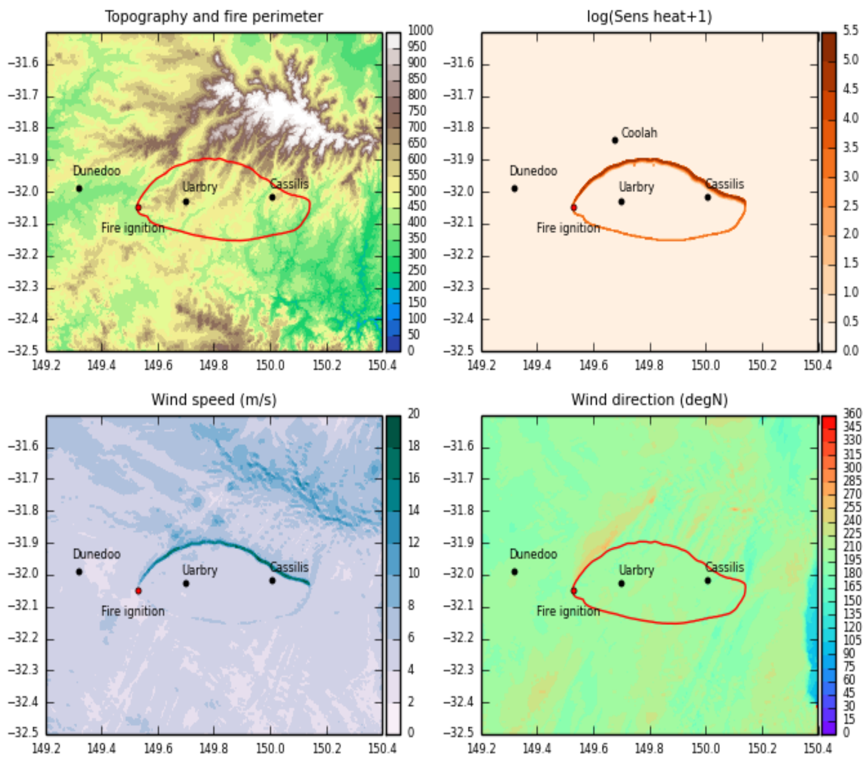

Figure 2: Simulation of the Sir Ivan fire, shown at 2116 LT, Sunday 12 February 2017. Top left: topography and fire perimeter. Top right: sensible heat flux from the fire grid (logarithmic scale). Bottom left: wind speed. Bottom right: wind direction.

Sir Ivan fire

The Sir Ivan fire burnt 55,000 ha in NSW on Sunday 12 February 2017, on a day when temperature records were broken during the worst fire weather conditions recorded in that state. A synoptic wind change in the mid to late afternoon turned winds from the northwest to the southwest and consequently changed the direction of fire spread and extended the length of the head fire. The wind change triggered development of a pyrocb, the lightning strikes from which ignited new fires downwind.

Due to advances in Numerical Weather Prediction (NWP) modelling over the past decades, accurate weather information is now produced at high spatial and vertical resolution. Consequently, the dangerous fire weather conditions were anticipated several days ahead, and communicated to fire agencies with a high level of confidence. However, the quantity of energy released by a fire the size and scale of the Sir Ivan fire will create a response in the surrounding atmosphere and capturing these processes is fundamental to understanding the complex environment.

During the Sir Ivan fire an extensive set of observations were taken, including detailed fire progression maps. These will be compared against our simulations to assess the skill of ACCESS-Fire simulations and explore how well the coupled fire-atmosphere model captures the influence of the fire's energy release in high terrain. A key question to examine is whether the coupling processes have a quantifiable influence on fire behaviour at particular stages of fire progression and whether features in the model results reconcile with the available observations.

Simulation results

We have performed simulations of both the Waroona and Sir Ivan fires, which from initial assessments have produced a very reasonable match against the reconstructed fire spreads. Simulations to date have used the CSIRO forest fuel (Vesta) fire spread model, and constant fuel loads, which is appropriate for the Waroona fire, but will be adjusted to variable fuels for Sir Ivan. Fire fields have been output at time steps of one minute, animations of which will be shown at the conference. Atmospheric data is output at longer intervals and more detailed analysis of the atmospheric fields will be explored once the fire simulations are optimal. Future analysis will include examining detail of processes such as the pyro-convection, ember storm dynamics and synoptic wind change.

Next phase

Comparison of our simulated fire perimeters has been subjective and, although our initial assessment is that the output is agreeably well matched with the observed perimeters, more formal verification is required and will be conducted during subsequent work. The verification will match fire output to the available time steps of the reconstructions prepared by DPAWs and RFS. The verification may prompt subsequent runs that attempt to capture fuel discontinuities, mitigation efforts or natural fire breaks. However, it is not the intent of our current work to produce a 'perfect' reconstruction but to explore the dynamical processes surrounding the extreme fire behaviour.

There are limitless options and questions to pursue with the analysis of the two fires and testing the capabilities of the modelling framework, however we intend to focus on the following questions:

Waroona

Figure 1 shows initial simulations of the Waroona fire. Our subsequent simulations will be increments initialised from known perimeters. The initial simulations have implemented a single fire ignition, which then ran for ~2 days to capture the periods of extreme fire behaviour. However, this is not a sound approach to modelling fire spread as it produces day-by-day compounding errors in the fire perimeter and is an unrealistic and impractical modelling approach. A more sensible approach is to re-initialise the fire perimeter from a known boundary at appropriate intervals, which would typically be at around 6-12 hours. Such an approach is consistent with regular re-starts, as performed in USA operations and in Australia using the Phoenix model.

We intend to initialise Waroona at three time points. The first will be the time of initial ignition (or fire identification), with the simulation continuing into the evening in order to capture the evening ember shower (12+ hours, similar to our current run). The second start will be the morning of 7 January, with the objective of providing an initial state to capture the extreme fire behaviour and unexpectedly fast rate of spread during the morning, which is hypothesised to be through entrainment of a meteorological low-level jet. The third restart will be late afternoon or early evening on 7 January, before the onset of the evening ember shower.

With this set of three simulations, we aim to examine the processes surrounding the two evening ember showers and the morning fire run on 7 January.

Sir Ivan

Our early runs (including Fig. 2) have used a constant fuel regime, which is a poor representation of the landscape the fire burned across. Detailed maps have been provided by RFS; these mosaic fuel maps will be implemented for the Sir Ivan fire. The planned analysis will compare the observations and model output, with a focus on comparison of the linescan images and simulated fire heatflux. We also intend to examine the plume depth and plume dynamics near the wind changes when the pyrocb occurred, and further explore a circulation that develops on the fire front post-wind change.

Acknowledgements

Thanks to the Bushfire and Natural Hazards Cooperative Research Centre and our end-users in fire and land management agencies for their continued support for the project. Thanks to our colleagues in the Bureau of Meteorology and the UK Met Office who have provided assistance with the ACCESS model. Thanks to our colleagues at Melbourne and Monash universities who shared the fire code.

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Peer-reviewed article

Improving flood forecasting skill using remotely sensed data

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ABSTRACT

This paper presents research undertaken to develop and implement a coupled hydrologic-hydraulic model which utilises remotely sensed data to improve flood forecasting skill in rural catchments subject to fluvial flooding. The discussion of literature reviews and subsequent knowledge gaps aids in the identification of key obstacles towards implementation. Collected data and modelling algorithms developed as part of the project are described before an overview of the progress towards implementation is given. To maximise the potential utilisation of this research end-users have been involved in providing data, setting up case studies, and defining research priorities and methods

Introduction

Similar to many countries worldwide, Australia has witnessed the destruction caused by fluvial flooding. Sadly, there is no indication that floods will become less frequent or severe as our climate changes (Goodess 2013). Flood warning systems mitigate detrimental impacts and increase community resilience. Flood warning systems are comprised of in-situ and remotely sensed (RS) observation networks, weather and flood forecasting models, flood warning dissemination systems, and emergency response procedures (Sene 2008). Spatially distributed RS data offers additional ways to constrain and update the hydrologic and hydraulic models used for flood forecasting. Practical benefits of using RS data when generating flood warnings include longer lead times, a greater understanding of the uncertainty in streamflow forecasts, the monitoring of floodplain surface water and an improved modelling of floodplain inundation dynamics.

This project focuses on the improvement of flood forecasting skill by developing methods to optimally merge RS data and hydrological and hydraulic models. Throughout this paper skill is defined to represent the ability with which the model is able to replicate observed data. The hydrological models simulate critical rainfall-runoff processes which describe the loss of water to evapotranspiration, the subsequent partitioning of incident areal rainfall into overland and subsurface flows, catchment storage, and ultimately the discharge hydrograph. Research tasks aimed to improve the hydrological forecast skill are targeted at the optimal assimilation of RS soil moisture (SM) data into the hydrological model. The hydraulic model takes discharge hydrographs as input to simulate the flood wave routing and predict the inundation depth and velocity at each point on the floodplain. Research tasks aimed to improve the hydraulic modelling skill include constraining hydraulic models with RS water extent data and obtaining flood extent from observed Synthetic Aperture Radar (SAR) data. Unfortunately, the accuracy, precision and timeliness of forecasts are limited by the model capability given observations and computational requirements. To maximise skill improvements made possible by RS observations, potential errors and biases must be adequately accounted for.

Traditional hydrologic rainfall-runoff models are forced, calibrated to, and updated with in-situ measurements such as precipitation and streamflow. In conjunction with increased computational capabilities, significant increases in the temporal and spatial availability of RS precipitation and SM have spurred a new generation of flood forecasting, which involves rainfall runoff models that demonstrate skill improvement from being forced, calibrated to or updated with RS observations (Li et al. 2016). Benefits obtained from RS data include an increased understanding of model dynamics, representation of internal processes, ability to estimate model parameters, understanding of uncertainty, and the ability to deliver forecasts with greater lead times. These advances will provide critical improvements to flood warnings issued to emergency management services.

Inundation monitoring and hydraulic modelling capabilities have increasingly benefitted from recent technological improvements, new satellites and constellations of satellites.

Due to their synoptic view of the flooded area, RS observations can effectively support emergency services. Moreover, RS techniques provide spatially distributed information on inundation dynamics, which can solve the well-known issue of data scarcity for the constraint of floodplain inundation models (Bates et al. 1997; Horritt 2000; Bates 2004; and Werner et al. 2005).

As opposed to point-scale gauged data, two-dimensional information of flood extent and level has the potential to provide more comprehensive and effective ways to constrain the hydraulic model, thus leading to more accurate predictions of floodplain inundation dynamics.

The synoptic view provided by remote sensing data offers novel opportunities for model calibration, validation, and real time constraint; however, a number of practical hurdles have yet to be overcome to enable their routine use in an operational framework. First, remote sensing is a relatively recent technology; availability of historical observations is limited and hindcast analysis of extreme events is not always possible. Second, despite the fact that the number of satellites and the acquisition frequency is deemed to increase in the future, remote sensing observations are generally discrete in time. Moreover, acquisition is generally still opportunistic. Third, quantities used for model constraint (e.g. soil moisture, water depth) are derived from remote sensing observations, as opposed to direct measurements by gauge stations. This feature, combined with relatively low spatial resolution, sensor and catchment-related features lead to remote sensing data uncertainty. Hence, remote sensing data are affected by larger uncertainties than gauged data (at the point) and improved methodologies for uncertainty assessment are still required. Finally, the need to rely on different providers (due to the short time span of the satellite missions or their low acquisition frequency) requires a methodology for the appropriate merging of datasets. Consequently, further research and experience are strictly required to fully disclose the potential of two-dimensional remote sensing observations.

The final outcome of this project will be a coupled hydrologic-hydraulic model which improves flood forecasting skill in rural catchments subject to fluvial flooding through the use of RS data. Flash flooding as a result of severe rainfall is not able to be addressed by this research. This manuscript provides an overview of research conducted to date on the path to meeting this outcome.

The project is funded by the Bushfire and Natural Hazards Cooperative Research Centre (CRC) and it aims to investigate the optimal use of remote sensing observations for the provision of more accurate and timely flood forecasts though coupled hydrologic-hydraulic models. The project started on May 1st 2014 and it will end on June 30th 2020. Intermediate and final deliverables have been discussed with the Australian Bureau of Meteorology (BoM) and Geoscience Australia (GA). The Commonwealth Scientific and Industrial Research Organisation (CSIRO) has constantly provided active feedback on the research developed by this project.

The continuous hydrologic modelling approach constrained with soil moisture both integrates and complements the current event-based and gauged-based predictive protocols of the BoM. The hydraulic model enables better understanding of floodplain inundation dynamics and the prediction of water depth and velocity in each point of the floodplain. Albeit, implementation of the coupled hydraulic model for any catchment in Australia is not feasible within the project timeframe, the methodologies developed within this project have the potential to enable floodplain inundation modelling in any Australian catchment. Specifically, this project will provide a roadmap for data collection, hydrologic data assimilation, model implementation, calibration, and constraint. Moreover, the results for the test sites can enable a better understanding of floodplain inundation dynamics in Australian catchments. Finally, this project is developing an algorithm for the detection and monitoring of floods using SAR data in vegetated areas. This capability will complement the existing GA protocols based on optical data.

Literature review

Application of RS data to improve hydrologic modelling skill

Precipitation and SM are the key hydrologic components that benefit from an increased availability of high-quality RS data. RS of precipitation can be used to force hydrological models when traditional in-situ measurements are not available or are inadequate. The blending of RS precipitation from ground and satellite-based radar is used to add value to precipitation estimates. Precipitation nowcasts and forecasts benefit from the assimilation of blended precipitation estimates. The potential for current uncertainties to propagate through models limit the usage of RS precipitation estimates to force current flood forecasts.

The RS of SM can aid flood forecasts by providing additional data for the constraint of hydrologic model parameters and model structural errors, as well as being used in data assimilation schemes to update flood forecasts as new observations become available. A review of the literature (Li et al. 2016) identified the following needs in the applications RS SN to flood forecasts:

- Ability of the modelled soil layer to represent the observed soil layer;
- Bias between the modelled and observed soil layer;
- Correct specification of the observed and modelled soil moisture errors; and
- Strategies to use multiple observations and products.

Further, it is noted that improvements in the ability to estimate the upper soil moisture layer will not necessarily lead to improvements in streamflow forecasts. This can occur as a result of a model's inability to concurrently simulate upper layer soil moisture and streamflow which are consistent with observations. The hydrologic modelling focus of this project was to use a model which aims to represent dominant hydrologic processes in the soil layer. Biases between modelled and observed soil layers were addressed through a joint SM and streamflow calibration scheme. The correct specification of observed and modelled soil layer errors in conjunction with strategies to use multiple observations is being dealt with through the implementation of a dual Ensemble Kalman Smoother (EnKS) which adapts to modelled and observed error structures.

Application of RS data to improve hydraulic modelling skill

The increasing availability of spatially distributed RS observations of flood extent and water level offers the opportunity for a comprehensive analysis of the predictive capabilities of two-dimensional hydraulic models. Nevertheless, such data availability requires a better understanding on how to effectively exploit the large amount of information offered by RS observations. An analysis of the state-of-the-art use of RS-derived observations of flood extent and water level to improve the accuracy of flood forecasting hydraulic models was presented in Grimaldi et al. (2016). The published literature have demonstrated that RS-derived observations of flood extent and water levels have the potential to improve floodplain inundation forecast accuracy.

Specifically, RS-derived observations can be used to constrain the parameters of the hydraulic model.

The low acquisition frequency and high uncertainty of RS observations are currently the main practical hurdles. Moreover, methodologies and protocols for the optimal comparison between RS-observations and model results are still under investigation. Consequently, RS-derived observations have so far been considered as a complement, not an alternative to field data for hydraulic model calibration/validation and real-time constraint.

Further research in the following areas is required to make full use of the new RS data sets:

- RS image processing algorithms;
- Optimal use of RS-derived information for the implementation of hydraulic models for flood forecasting;
- Definition of the most appropriate RS-derived observation (e.g. inundation extent and/or level) for the effective evaluation of the accuracy of modelled floodplain inundation dynamics; and
- Definition of RS-based protocols for the assessment of the parameter space of the hydraulic model to enable more accurate floodplain inundation predictions.

Methodology

To aid in defining a project scope that maximises the potential for utilisation, the end users at the Bureau of Meteorology (BoM) Geoscience Australia (GA) and New South Wales State Emergency Service (NSW SES) have been engaged since the inception of the project. These end users continue to provide valuable input which helps shape the clearest path towards implementation of state-of-the-art fluvial flood forecasting processes driven by hydrologic and hydraulic models.

The state of the art in operational hydrologic and hydraulic flood forecasting that takes advantage of RS data was identified in the two aforementioned literature reviews (Grimaldi et al. 2016; Li et al. 2016). Knowledge gaps and opportunities for development were identified therein. Data pertinent to the respective tasks were collected from responsible agencies. Two field campaigns were completed to measure river bathymetry at selected locations along the river systems. More specifically, the SonTek M9 HydroSurveyor Acoustic Doppler Profiler was used to obtain high resolution bathymetric data for approximately 20km and 16km in the Clarence River and Condamine-Balonne River, respectively.

The time and monetary expensive collection of bathymetric field data allowed the development of a high-resolution benchmarking dataset for the development of a low cost, data parsimonious methodology for the assessment of river bathymetry in data scarce catchments.

The next phase in the project involved undertaking various modelling tasks which addressed the identified knowledge gaps. As each modelling task reaches completion they are progressively rolled out for implementation.

Data

The Condamine-Balonne and Clarence catchments were selected as case studies for this project. Both catchments have been subject to major floods during the study period beginning 2008 and ending 2014. Furthermore, good quality RS observations are available for both catchments.

Specifically, the area of the Condamine-Balonne catchment downstream of Chinchilla was selected as an example of a slow-moving meandering river system in which floods gradually rise over several days. In contrast, the Clarence River catchment shown in Figure 1 is an example of a fast-moving river system. Both catchments are susceptible to flash flooding from heavy rainfall.

The data collected for the catchments include hourly precipitation and streamflow observations (Bureau of Meteorology, 2019), monthly PET from AWAP (Raupach et al. 2012), SMOS RS SM, SRTM-derived DEM-H (Gallant et al. 2011), the Dynamic Land Cover of Australia (Lymburner et al. 2011), SAR images from different data providers (Cosmo SkyMed, ALOS-PALSAR, Radarsat2); optical images from satellite (LANDSAT5 and LANDSAT7, SPOT5 and SPOT6, ASTER) and airborne acquisitions. Further, the algorithms and tools developed within this project allow a certain flexibility for different data sources.

Research components

The modelling tasks in this project cover three distinct, yet consequential topics, hydrologic modelling, interpretation of RS images, and hydraulic modelling.

Hydrologic modelling

The hydrologic modelling research tasks were designed to address the identified knowledge gaps. For a flood forecasting model to benefit from RS SM observations it is imperative that the model soil layers adequately represent observed soil layers. Owing to data restrictions and computational capabilities, operational flood forecasting models are commonly conceptual in nature.

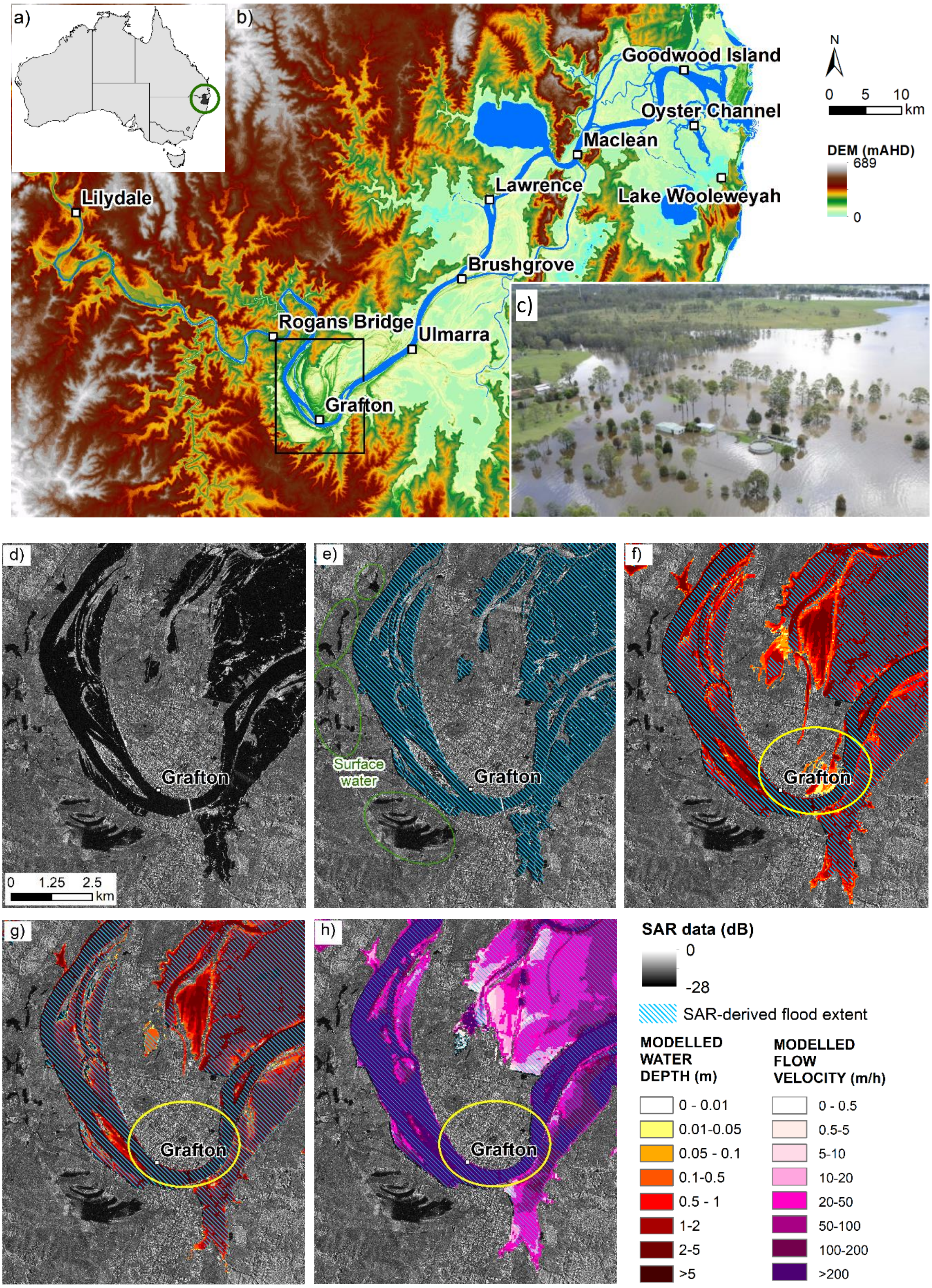

Figure 1: Panel a and b show the location of the Clarence catchment, and the Clarence catchment with the major towns, respectively; the black rectangle in panel b show the footprint of panels d, e, f, g, h. Panel c shows an aerial photography demonstrating the impact of flooding in the Clarence River (Photo supplied by NSW SES - Clarence Nambucca Region). Panel d shows the SAR data acquired during the 2011 flood (Cosmo SkyMed satellite); panel e shows the SAR-derived flood extent layer (green circles highlight surface water bodies not connected to the flooded area). Panel f shows the flood extent and depth values predicted by a preliminary model realization; the comparison with SAR-derived flood extent highlights false alarms in the townships of Grafton. Panel g and h show the improvement in modelled inundation extent and velocity obtained by using RS data for model evaluation.

Conceptual models represent salient rainfall-runoff dynamics and often represent complex rainfall-runoff dynamics with simplified assumptions that represent bulk catchment wide dynamics. Furthermore, it is common for conceptual models to yield similar skill in forecasting scenarios to more cumbersome physical models.

As RS SM becomes more accurate and readily available, it is often asked "how do we best include RS SM into our operational models"? One such answer involves the adaptation of a conceptual model such as GR4H (Perrin et al., 2003) to include a more physical representation of the soil layer. The hydrologic model GRKAL (Francois et al. 2003) does exactly this and is well suited to address the operational needs of a rainfall-runoff model that has the capability to benefit from RS SM observations.

Methods to deal with biases between modelled and observed SM are highly debated within the hydrologic community. If not treated appropriately biases between modelled and observed SM can lead to over or under-correction of states in data assimilation applications. The commonly used approach of cumulative distribution function (CDF) matching inappropriately assigns all of the bias to the observations and consequently results in a loss of information (Li et al. 2016). An alternative and less common approach of using SM observations in calibration has the advantage of retaining information (Li et al. 2016). This approach has been met with skepticism as it may degrade the ability of the model to simulate streamflow in the calibration, validation, and forecast periods. Research within this project has explored the impact of a joint calibration scheme that calibrates the GRKAL rainfall runoff model to both streamflow and SM. Results demonstrate that calibrating to SM and streamflow have a near-negligible influence on streamflow predictions and that internal ungauged gauged catchments observe improved streamflow predictions (Li et al. 2018). The influence of calibrating to SM and streamflow observations on data assimilation applications remains to be tested.

Assimilating streamflow into rainfall-runoff models for flood forecasting is the most widely adopted data assimilation approach to improve streamflow forecasts. The direct relationship between the streamflow observation and streamflow prediction ensures that assimilation of streamflow typically results in an improvement of the streamflow forecast. The updating of state variables such as SM with RS observations to improve flood forecasts has shown promising but mixed results (Li et al. 2016). Through the use of a conceptual model with a physically based soil layer and joint calibration scheme this project has begun to deal with some of the obstacles faced by improving flood forecasting skill in rainfall runoff models with RS SM observations. Strategies to correctly specify errors in observed and modelled soil layers for the dual assimilation of streamflow and RS SM are the focus of current research efforts. In the future, the outputs from the rainfall runoff models can be provided directly to emergency services or used as input to a hydraulic model to predict inundation depth and velocity at each point in the catchment.

RS image interpretation

Observations of floodplain inundation provide pivotal information for emergency management and can enable improved flood modelling capabilities. While sunlight and a clear sky are required for RS optical acquisitions, the 24-hour all-weather capability of SAR technology makes it a perfect choice for flood monitoring. A SAR is an active instrument that emits microwave pulses towards a target and measure the amount of microwave energy returned by backscattering off an object. Radar backscatter is mainly a function of surface roughness and the different response of smooth water surfaces and rough dry areas generally allows for flood mapping. However, the interpretation of the backscatter from flooded areas with emerging vegetation has been identified as one of the biggest challenges in SAR image analysis (Shen et al. 2019).

This project is developing an algorithm to automatically detect flooded vegetation using one single SAR acquisition and commonly available ancillary data (i.e. land cover, land use, and digital elevation models). The algorithm has been tested on three fine resolution images (one ALOS-PALSAR and two COSMO SkyMed) acquired during the January 2011 flood in the Condamine-Balonne catchment in Queensland, Australia. The results were validated using flood extent layers derived from high resolution optical images. In these case studies, state-of-the-art operational interpretation algorithms focusing solely on open water areas led to large omission errors with Overall Accuracy (OA) of 77 per cent, 65 per cent, and 75 per cent, respectively. Notwithstanding the difficulty to fully discriminate between dry vegetation backscatter heterogeneity and backscatter variation due to flooding using a single SAR image, the implementation of the proposed algorithm allowed the omission errors to be reduced thus achieving a final OA of 83.7 per cent, 81.5 per cent, and 85.7 per cent, respectively (Grimaldi et al. 2019). These results showed an overall accuracy larger than 80 per cent for all the test cases and hence encouraged the application of the proposed algorithm to other test cases and its extension to incorporate reference images and multi-polarised data in order to fully exploit the opportunities disclosed by recent satellite missions such as Sentinel-1 and NovaSAR.

Hydraulic modelling

The 2-dimensional, raster based hydraulic model used in this project is based on LISFLOOD-FP (Bates et al. 2010) which solves the inertial formulation of the shallow water equations to simulate inundation depth and velocity in each point of the catchment. This project is investigating optimal ways to use RS data to support the implementation and the evaluation of flood forecasting hydraulic models. First, since systematic errors cannot be removed through calibration and data assimilation, the use of RS data for model set-up can be of paramount importance for accurate floodplain inundation modelling. Second, RS-derived information can be used to evaluate the predictive performances of the hydraulic model. Third, RS-based parameter assessment protocols can be designed for the delivery of more accurate floodplain inundation predictions. These three tasks are being investigated using the hydraulic model as a stand-alone component of the flood forecasting chain. In other words, gauged discharge and water level data have been used as input data to the hydraulic model in this phase of the project. This choice had the purpose to use an accurate input dataset. In a following phase of the project, coupling strategies between the hydrologic and the hydraulic model will be investigated. Each model implementation is affected by a number of uncertainties and the cascading of these uncertainties has to be carefully evaluated. A preliminary analysis of the cascading of errors when coupling hydrologic and hydraulic models at the large scale was completed in Grimaldi et al. (2019). In this phase of the project, the hydraulic model was forced using measurements allowing investigation of the use of RS data in a simplified, controlled scenario.

The hydraulic model predicts the flood wave routing in the river system and, when the river capacity is exceeded, in the floodplain. Hence, accurate modelling of river flow dynamics is essential to simulate floodplain inundation. Bathymetric data are thus critical to the application of hydraulic models (Hilton et al. 2019; Wang et al. 2018). However, it is impossible to measure river bathymetry along the total river length, especially in large basins. Where the channel geometry is unknown, channel shape, depth, and roughness can be estimated through calibration, but different parameter sets can often map model predictions to the observed data generating an equifinality problem. Moreover, without the structural correction provided by an adequate geometrical representation, the sets of parameter values identified by calibration can lead to spurious nonphysical effects. Conversely, an approximated knowledge of river bathymetry can provide a more robust model setup (Neal et al. 2015). This project investigated the level of geometrical complexity required for the representation of river bathymetry in hydraulic flood forecasting models. More specifically, a numerical experiment was designed using the Clarence catchment as a case study to investigate an effective yet parsimonious representation of channel geometry that can be used for operational flood forecasting (Grimaldi et al. 2018). The analysis of a number of synthetic scenarios identified a rectangular, width-varying shape as the most effective simplified geometrical model. Width values can be derived from RS data while depth values can be assessed using a combination of global database and limited field data. Where river width data are not available, an exponential shape is recommended as the most viable solution. The proposed methodology for the preliminary assessment of river geometry has the purpose to support model implementation in data scarce catchments. Further, it has the potential to reduce the uncertainty of an ill-posed problem for RS-based model evaluation and constraint.

The use of RS-derived information for the evaluation of the accuracy of flood forecasting hydraulic models was then investigated using both the above described synthetic scenarios and real flood events as case studies. First, the numerical experiment based on the synthetic scenarios showed that distributed water levels derived from a synthetic RS observation, acquired as early as 24 hours before the flood peak at the input point of a short river reach, can enable the diagnosis of errors in the model implementation: flow propagation in low to increasing discharge conditions within the river strongly affects floodplain inundation dynamics with large discharge values (Grimaldi et al. 2018). Second, the modelling of the 2011 and 2013 flood events in the Clarence catchment showed that the combined use of RS-derived flood extent and RS-derived wet/dry boundary points enable an accurate evaluation of the predictive skill of the hydraulic model. Based on this analysis, a rapid methodology for the assessment of event-specific effective values of river roughness to enable more accurate representation of the flood event was formulated. More specifically, the comparison between modelled and observed wet/dry boundary points can guide the constraint of river roughness values within the footprint of the RS acquisition. The comparison between modelled and RS-derived inundation extent can then be used to assess the roughness value outside of the footprint of the RS observation. Such a rapid RS-based methodology to constrain the distribution of effective river roughness values has the potential to lead to improved floodplain inundation predictions in both gauged and ungauged catchments while limiting the computational time.

Further testing is required to extrapolate the findings of these analyses to other catchments. Furthermore, in a real case scenario, the impact of uncertainties in RS-derived observations on the use of this data for the diagnosis of errors in model implementation has to be carefully evaluated. Nevertheless, this project shows (i) the importance of structural correction provided by an adequate representation of channel geometry, (ii) the use of RS data for model implementation, and (iii) the potential benefit RS-derived observations of flood extent and wet/dry boundary points to improve inundation modelling skill.

Finally, RS-aided improved predictions of the input discharge hydrographs developed within this project (hydrologic model) are expected to significantly enhance the accuracy of predicted floodplain inundation dynamics. To validate this statement, the final phase of this project will explore optimal ways to couple hydrological and hydraulic models (Grimaldi et al. 2019).

Implementation

To facilitate the implementation of this research, the project team, the end-users and the CRC identified a number of key research outcomes that have strong ties to the end user objectives.

Implementation of hydrologic modelling algorithms

This project is developing algorithms to effectively assimilate RS SM along with streamflow into hydrologic models for flood forecasting purposes. There is the potential for forecasts enhanced by assimilation of RS data to be delivered to emergency services or used as input to a hydraulic model for the prediction of inundation depth and velocity at each point of the river system and of the floodplain.

The dual observation calibration routine, rainfall gauge optimization routine, and single and dual observation EnKS routines are expected to be able to be applied to a broad variety of conceptual hydrologic models. Whilst the primary purpose is for flood forecasting it is expected that these routines can add value to 3-7 day streamflow forecasts. These 3-7 day forecasts are typically used to regulate environmental flows, dam releases, water allocations and reservoir storage levels.

Currently, the assimilation of RS SM improves forecast skill for catchments with larger times of concentration. As the acquisition of RS SM data becomes more frequent the ability for RS SM to improve flood forecasting skill in flashier catchments. The recent inclusion of GRKAL and future inclusions of dual observation calibration and assimilation routines along with a rainfall gauge optimization routine in SWIFT2 will improve the BoM capability to forecast floods. A robust dual EnKS assimilation routine which includes calibration to RS SM and streamflow, optimization of rainfall gauge weighting, and allowance to update model and error structures will add value to flood forecasts by improving forecast skill and confidence. Greater confidence and forecast skill, leads to emergency services having more time to react to flood warnings.

Implementation of a novel RS image interpretation scheme

This project is developing an algorithm for the retrieval of inundation extents from SAR images. The Water Observations from Space web-service developed and maintained by GA (https://www.ga.gov.au/scientific-topics/earth-obs/case-studies/water-observations-from-space; Mueller et al. 2016) makes use of optical sensors to provide information of historical surface water observations to allow better understanding of surface water availability and dynamics. The algorithm for the analysis of SAR data aims to complement the current capabilities for water monitoring from space by enabling the incorporation of information at night-time and in clouded conditions.

Roadmap for the implementation of the hydraulic model

A comprehensive experience on the optimal use of RS observations to improve the implementation, evaluation, and calibration of hydraulic models for flood forecasts is being developed. While this project is focused on two specific case studies; the methodologies developed have made use of datasets available at the continental scale and thus have the potential to be used in a large number of Australian catchments. A roadmap for the optimal use of RS observations for the implementation and constraint of flood forecasting hydraulic models is being developed with the overarching aim to lead to the development of improved floodplain inundation prediction tools in many Australian catchments.

Conclusion

This manuscript outlines the project life to date beginning with the early conceptual stages. The pathway to a coupled hydrological-hydraulic model which utilizes RS data is demonstrated via the discussion of literature reviews and identification of knowledge gaps which form key obstacles towards implementation. Collected data and developed modelling algorithms are described before presenting an overview on the implementation of research to date. To provide robust results the project continues to research the impact of joint calibration and estimation of catchment rainfall on hydrologic data assimilation. Further, an algorithm for the inversion of SAR data into flood extent maps is being developed. Moreover, novel methodologies for the optimal use of RS-derived flood extent and level to constrain the hydraulic model are being tested. Lastly the coupling of the hydrologic model and hydraulic model has yet to be completed. The continual involvement of research end-users has been an integral component of implementing research to date.

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Peer-reviewed article

Flood vulnerability functions: detailed vs generalised approach

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ABSTRACT

Flood vulnerability functions for buildings (often called stage-damage functions) relate flood damage to the depth of inundation in the building. These functions are generally used in assessing flood risk and in evaluating cost-effective mitigation strategies for flood risk management. Flood vulnerability models are usually developed for a certain location by following empirical, analytical or heuristic procedures. They can be developed for a representative building type (detailed approach) or representing a mix of building types (generalised approach).

Geoscience Australia (GA) has developed a suite of flood vulnerability functions for a range of building types (detailed approach) that covers residential, commercial, industrial and community building land use types. These functions are best used in detailed micro level studies and are applicable to the highest resolution of building exposure information with flood vulnerability directly attributed to individual buildings.

This paper describes research with the National Flood Risk Advisory Group (NFRAG), the Australian Institute for Disaster Resilience (AIDR), state and local governments and industry to translate detailed vulnerability information into practical guidance for flood risk managers undertaking studies under the floodplain-specific management process as outlined in the AIDR Handbook, *Managing the Floodplain: A Guide to Best Practice in Flood Risk Management*.

This research derives generalised vulnerability functions for a mix of building and land use types. The generalised curves can be utilised at meso or macro level study and are intended to be applied at a resolution of built environment information readily available to floodplain managers.

Introduction

Globally floods have impacted many communities in the past, which, in extreme cases, have resulted in vast devastation and widespread disruption to the communities. In Australia, floods cause more damage on an average annual cost basis than any other natural hazard. Figure 1 shows the Average Annual Losses (AAL) by disaster type in Australia from 2007 to 2016 (DAE 2017).

The fundamental causes of this level of damage and the key factor contributing to flood risk, in general, is the presence of vulnerable buildings constructed within floodplains due to ineffective land use planning. The Bushfire and Natural Hazards Collaborative Research Centre project entitled 'Cost-effective mitigation strategy development for flood prone buildings' (BNHCRC 2019) examines the opportunities for reducing the vulnerability of Australian residential buildings to flood.

Aims and objectives

Within this BNHCRC project, a utilisation sub-project is initiated to develop vulnerability functions which are compatible with the level of detail of exposure information generally available to floodplain managers. This research focuses on assessing the flood vulnerability, as a crucial input to a flood risk assessment. This utilisation project aims to provide advice on assessing flood impact and risk to floodplain managers, insurance industry and other who may not have access to detailed building exposure information. It involves developing and testing a number of resolution options (from asset specific vulnerability assessments to a more generalised method) in a case study. This paper presents the outcomes of the utilisation project to develop generalised vulnerability functions which could represent typical Australian building stock at meso and macro level.

Approaches to develop vulnerability functions

Flood vulnerability functions (often termed as stage-damage functions) for key types of buildings provide information about building susceptibility to damage and associated repair costs due to an event. Vulnerability functions are critical input in flood risk analysis and therefore a fundamental requirement to use these functions is to represent the building stock within the study area appropriately.

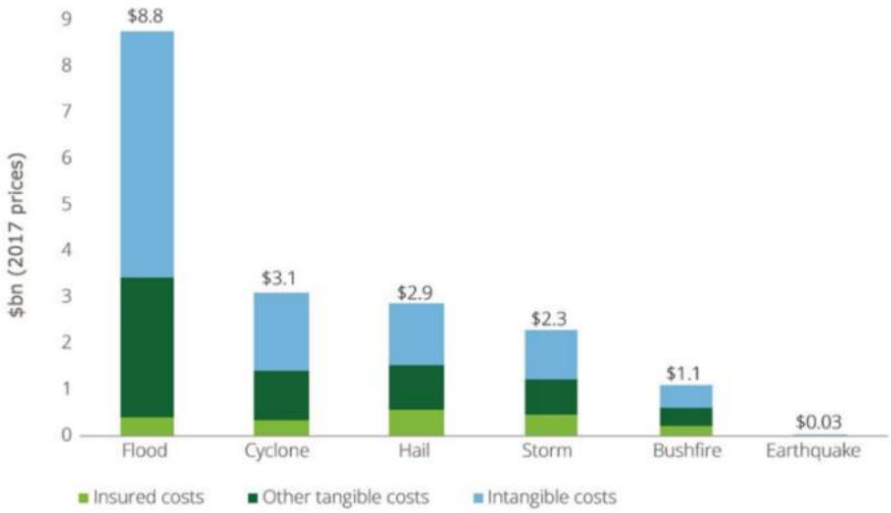


Figure 1: Average Annual Losses by Disaster Type in Australia from 2007 to 2016 (DAE 2017).

Detailed vulnerability functions

For this research study detailed vulnerability functions are sourced from Geoscience Australia (GA) which included flood vulnerability functions for residential, commercial, industrial and community building types (29 functions in total). These functions have been developed by using analytical approach. The main development steps included:

- Development of building categorisation schema to classify building stock into a limited number of typical building types,
- For each building type a representative floor and architectural plan is selected,
- For each building type the building fabric is divided into several components,
- For each component of each typical building type, the repair work to reinstate the building is identified at ten inundation depths,
- Each item of repair method is quantified and costed,
- For each inundation depth a Damage Index (a ratio of repair cost to replacement Cost) is calculated, and
- Finally, a vulnerability function is developed by plotting Damage Index on Y-axis and Inundation on X-axis.

Generalised vulnerability functions

For this research study six generalised vulnerability functions are developed at Statistical Areas Level 1 (SA1) level by aggregating selected GA's detailed vulnerability functions. This aggregation of GA's detailed vulnerability functions is based on exposure properties of representative SA1 areas for a mix of residential, commercial, industrial and community building types. The basic steps involved in the developing the generalised vulnerability functions are:

- Developing and comparing exposure data at different scales (SA1 and Mesh Block levels),
- Identifying appropriate level of assessment (in this study SA1 level is selected),
- Selecting six representative SA1 areas with predominant residential, commercial, industrial typologies and a mix of these,
- Development of aggregated Damage Index (weighted) at ten inundation depths, and
- Developing six generalised vulnerability functions for these selected SA1 areas.

Case study: Launceston

Launceston is floodprone and located within the Tamar River floodplain at the confluence of the Tamar, North Esk and South Esk Rivers in Tasmania. The suburb of Invermay in Launceston is the case study area for this research. Figure 2 shows the location map to show the study area in Tasmania. The exposure database is compiled for all buildings in the study area (1,276 in total) within the mapped PMF extent by sourcing building attributes from GA's National Exposure Information System - NEXIS (GA 2017).

This database is supplemented by a desktop study utilising Google street view imagery to record additional building attributes. Floor height information is provided by the Launceston City Council for all buildings within the 500 ARI extent map (LCC 2016).

Spatial scale of study

As mentioned in the previous section that spatial scale of study is an important factor while conducting flood risk assessment. For this comparative study two spatial scales have been explored for selection i.e. Mesh Blocks level and Statistical Area 1 (SA1) level as defined by ABS (2019). Mesh Blocks are the smallest geographical area and broadly identify land use such as residential, commercial, primary production and parks, etc. SA1 are the geographical areas built from whole Mesh Blocks and have generally been designed as the smallest unit for the release of census data. SA1s have a population of between 200 and 800 people with an average population size of approximately 400 people (ABS 2019).

Figure 3 and Figure 4 show the spatial boundaries within the study area at mesh block level and SA1 level, respectively. There are 91 mesh blocks and 20 SA1 areas in the study region. A mesh block level study requires data at a more refined level (quite close to micro level study) which many a times is not available to floodplain managers. Therefore, SA1 level is selected for developing generalised vulnerability functions.

Figure 2: Location map of study area, Launceston (Tasmania).

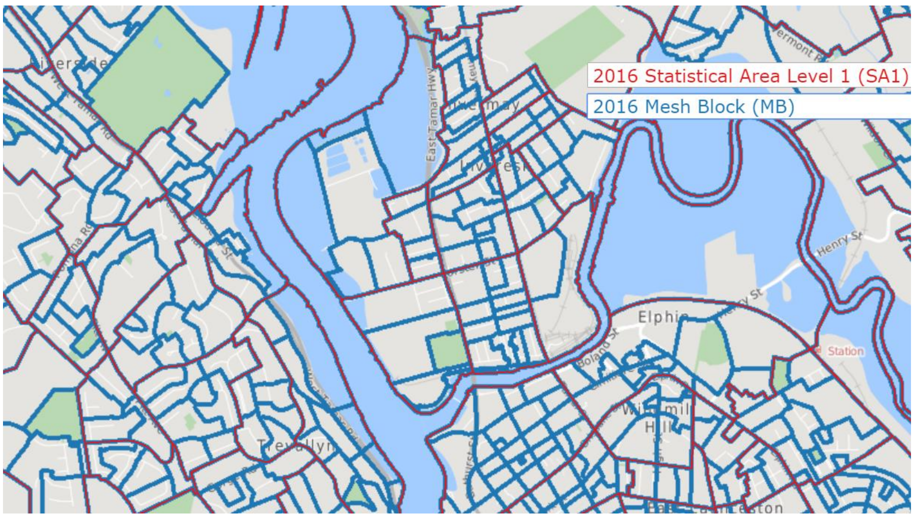


Figure 3: Spatial scale of Mesh Block areas (blue boundaries) in the study area (ABS 2019)

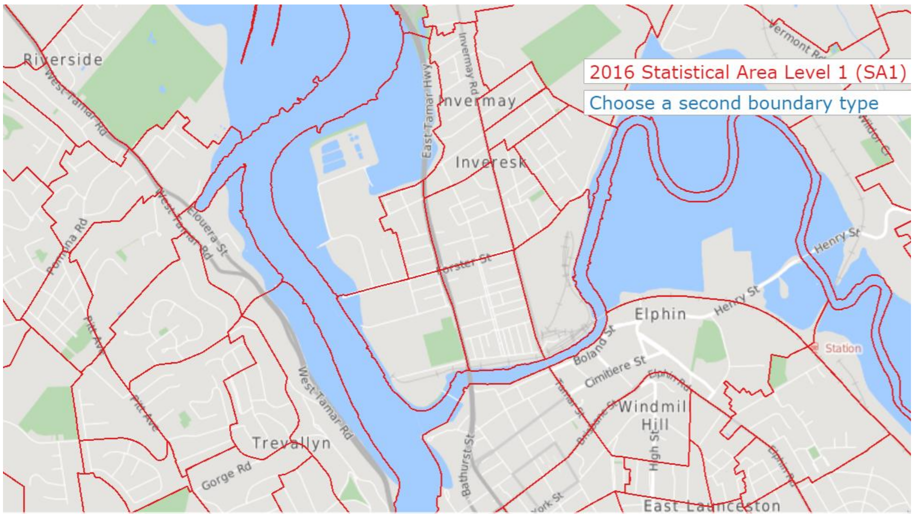


Figure 4: Spatial scale of SA1 areas (red boundaries) in the study area (ABS 2019).

Development of generalised vulnerability functions

After analysing the SA1 level exposure data, six typical SA1 areas are selected to represent the building stock in the study region. The selection of six SA1 areas is based on the exposure characteristics of each SA1 area which includes building usage (residential, commercial and industrial), wall material (weatherboard, veneer masonry, cavity masonry, concrete and metal), number of stories (single or double) and building age (pre-1960s and post-1960s). Table 1 presents the generalised function name and description of the representative SA1 areas.

Suitable functions from GA's suite of detailed functions are then chosen to generate generalised functions by weighted aggregation. Figure 5 shows the resultant generalised vulnerability functions (thick black curves) along with a comparison of detailed vulnerability functions chosen to be aggregated.

The derived generalised vulnerability functions are based on the weightage of the sourced detailed functions which strongly depend on the land use types, number of stories, building materials and age. The generalised functions for residential SA1s are found to be the most vulnerable followed by functions for commercial and industrial SA1 areas.

Table 1: Typical characteristics of generalised vulnerability functions

Sr Nr	Generalised vulnerability function name	Description (typical characteristics)
1	GRESN1	Usage: Residential Wall material: Weatherboard Storeys: Single storey Age: Pre-1960s
2	GRESN2	Usage: Residential Wall material: Brick veneer Storeys: Single storey Age: Post-1960s
3	GRCN1	Usage: Mostly residential but with commercial and industrial mix Wall material: Mix of weatherboard and veneer construction Storeys: Single storey Age: Post-1960s
4	GRCN2	Usage: Mix of residential, commercial and industrial Wall material: Mix of weatherboard and masonry construction Storeys: Single and double storey mix Age: Pre and post-1960s mix
5	GCOMN2	Usage: Commercial Wall material: Masonry construction Storeys: Single and double storey mix Age: Pre and post-1960s mix
6	GINDN1	Usage: Mostly industrial but with slight commercial and residential mix Wall material: Mostly metal construction Storeys: Single storey Age: Pre and post-1960s mix

(A) GRESN1

(B) GRESN2

(C) GRCN1

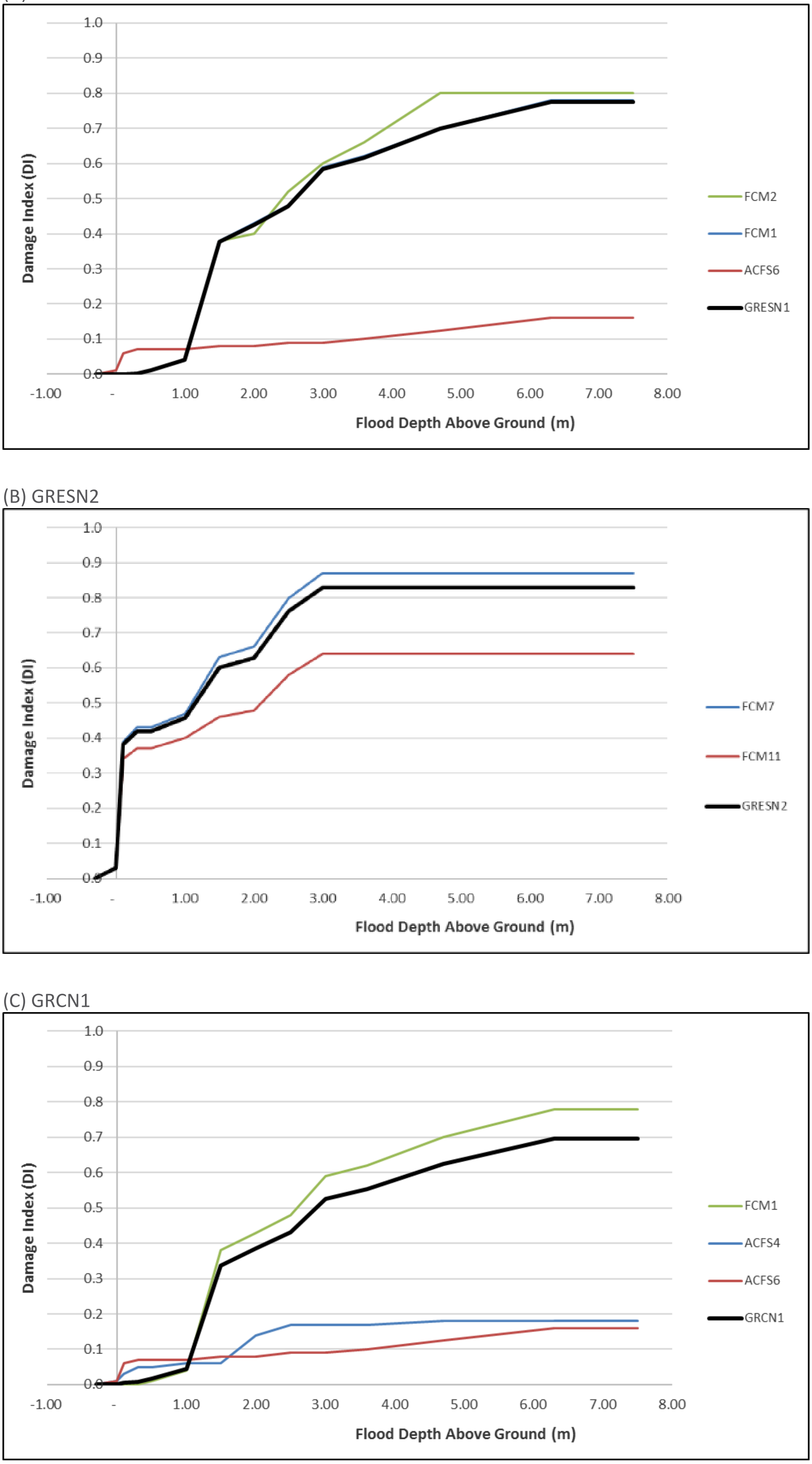
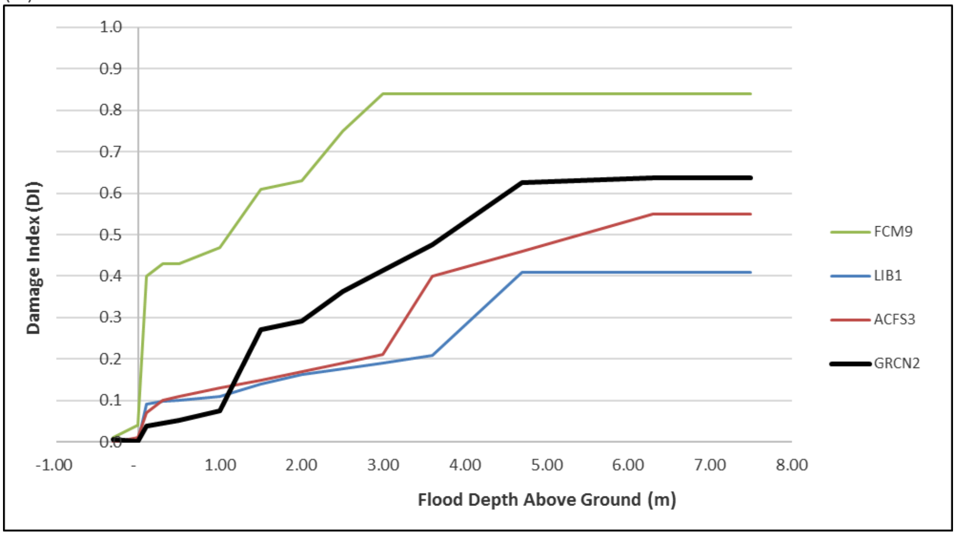
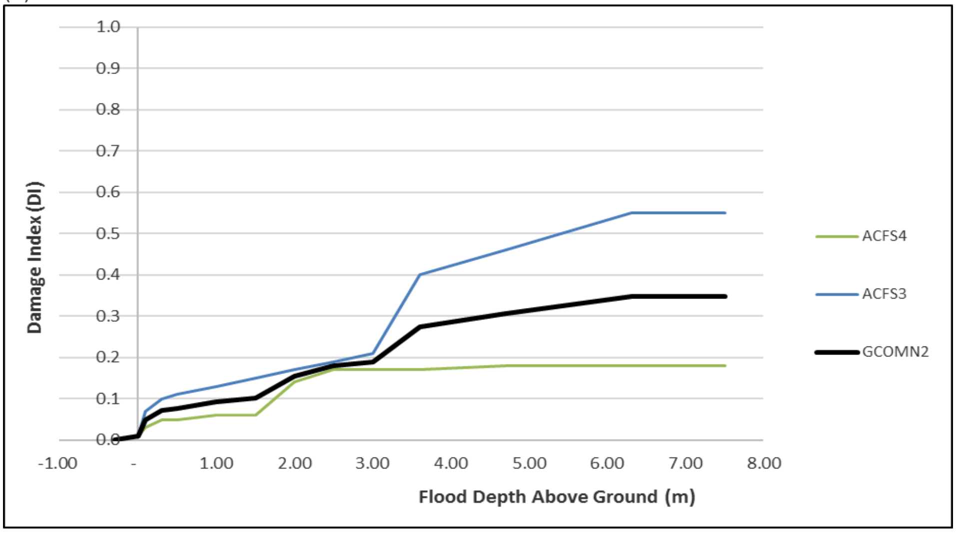


Figure 5: Flood Vulnerability functions: detailed and generalised.

(D) GRCN2



(E) GCOMN2



(F) GIND1

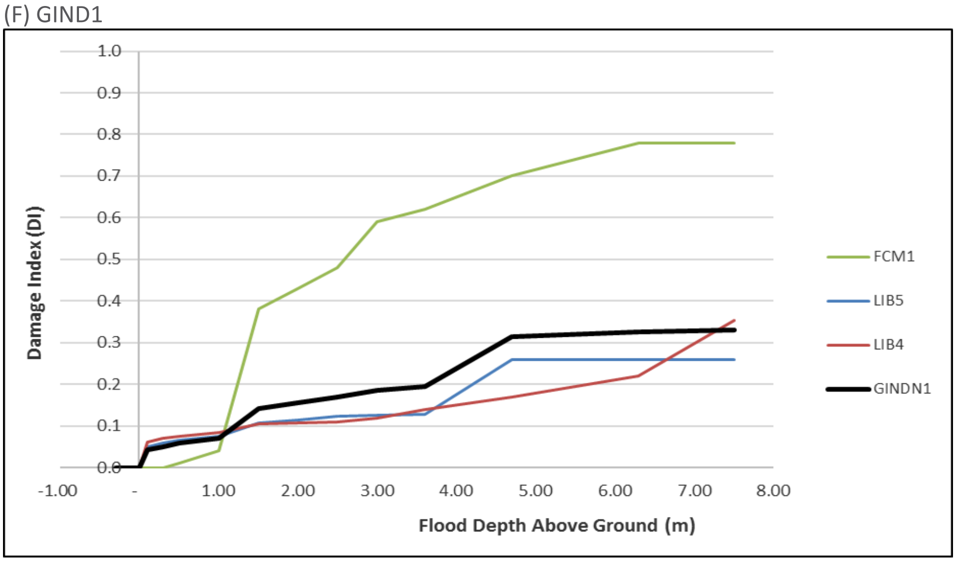


Figure 5: Flood Vulnerability functions: detailed and generalised (cont.).

Summary

Flooding is a major hazard in Australia, accounting for the largest economic losses of any single hazard (DAE 2017). Flood vulnerability functions should ideally be developed for typical building types of each study area which can represent the local building stock accurately (Te Linde et al., 2011). However, since developing these detailed functions is time consuming and expensive, the generalised functions, presented in Figure 5 and described in Table 1, are the alternatives available for meso to macro level studies.

This study has focused on developing generalised vulnerability functions at meso-scale which require less detailed exposure information. Within the utilisation project a more detailed study will be conducted to assess the application of the generalised vulnerability functions. Furthermore, the usefulness of generalised approach in assessing flood risk will be investigated along with analysis of the increased uncertainty associated with the simpler but more practical approach.

Research utilisation

The potential utilisation of this research could include:

- There is broad potential for the use of generalised functions by those who do not have access to detailed building exposure information. Users could include floodplain managers, insurance companies, flood consultants, state emergency services and impact modellers.
- The curves would allow consistent comparisons to be made across jurisdictions where exposure information may otherwise be inconsistent, benefitting decision makers in comparing flood impact and risk.
- The publication of the finalised generalised functions and use instructions through Australian Institute for Disaster Resilience (AIDR) will allow for widespread dissemination and access.

Acknowledgements

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Peer-reviewed article

Modelling the vulnerability of a high-set house roof structure to windstorms using VAWS

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ABSTRACT

Modelling the vulnerability of houses in windstorms is important for insurance pricing, policy-making, and emergency management. Vulnerability models for Australian house types have been developed since the 1970s and have ranged from empirical models to more advanced reliability based structural engineering models, which provide estimates of damage for a range of wind speeds of interest. This paper describes recent developments in the engineering based vulnerability modelling software: 'Vulnerability and Adaption to Wind Simulation' (VAWS), which uses probability based reliability analysis and structural engineering for the loading and response coupled with an extensive test database and field damage assessments to calculate the damage experienced by selected Australian house types. A case study is presented to demonstrate the program's ability to model progressive failures, internal pressurization and debris impact.

Vulnerability and Adaptation to Wind Simulation (VAWS) is a software package that can be used to model the vulnerability of small buildings such as domestic houses and light industrial sheds to wind (Geoscience Australia, 2019, Wehner et al., 2010a). The primary aim of VAWS is the estimation of the change in vulnerability afforded by mitigation measures to improve a building's resilience to wind storms.

VAWS consists of probabilistic modules for the 1. Wind hazard – external and internal pressures generated by the atmospheric wind and 2. Structural response – related to the structural system and capacities of the components and connections and load effects. The program is able to accommodate a range of house types for which the structural system, connections and the external pressure distribution for wind exposure from directions around the compass is applied as input data.

The critical structural components are probabilistically assigned their strengths and the wind loads are applied for winds approaching from a selected direction. Failure is initiated when the load exceeds the capacity of a critical component or connection as the wind loads are increased with increasing discrete wind speed increments. When components fail, loads are redistributed through the structural system. The cost of repair is calculated for the given level of damage and the damage index is calculated at each wind speed increment.

This paper describes the logic of VAWS including the main modules: the house type and structural system, external and internal pressure distribution, structural response, initiation and progression of damage, windborne debris impact, water ingress and cost of repair. A case study is presented to show the preliminary outputs of VAWS for a high-set Northern Australian house type.

Overall logic

The program is built around the high level sequence flow chart shown in Figure 1. The VAWS program takes a component-based approach to modelling building vulnerability. It is based on the premise that overall building damage is strongly related to the failure of key structural connections. The program generates a building model by selecting parameter values from predetermined probability distributions using a Monte Carlo process. Values include component and connection strengths, external pressure coefficients, shielding coefficients, wind speed profile with height, building orientation, debris damage parameters, and component masses. Then, for increasing gust wind speed increments, it calculates the forces in all critical connections using influence coefficients, assesses which connections have failed and translates these into a damage scenario and costs the repair. Using the repair cost and the full replacement cost, it calculates a damage index at each wind speed.

Key Parameters and Variability

The Monte Carlo process captures a range of variability in both wind loading and component parameters. The parameter values are sampled for each realisation of the modelled house and kept the same as the wind speed is incremented up to a set maximum.

- Wind direction: For each house, its orientation with respect to the approach wind is chosen from the eight cardinal directions either randomly, or set constant by the user.
- Gust wind profile: Variation in the profile of wind speed with height is captured by the random sampling of a profile from a suite of user-provided profiles related to the approach terrain.
- External pressure coefficients for zones and coverages: External pressure coefficients for different zones of the house surfaces envelope are randomly chosen from a Type III (Weibull) extreme value distribution based on wind tunnel data, with specified means and coefficients of variation for different zones of the house envelope.
- Strength and dead load: Connection strengths and dead loads for each realization are sampled from lognormal probability distributions specified by the user.

Water ingress: is estimated in order to account for the large costs associated with water damage to internal linings. Predefined relationships for water damage as a function of wind speed are selected based on the extent of damage to the house envelope.

Structural Response and Load Redistribution

The VAWS program accounts for load redistribution and progressive failures of the roof structure without the use of computationally intensive non-linear structural analysis by incorporating several simplifying assumptions. Connections considered in the analysis include: cladding fasteners, batten to rafter connections and rafter to top plate connections.

The program relates pressures applied to envelope zones to the cladding connection loads and the supporting structure using linear elastic influence coefficients. Once connections have failed, the effects of redistribution are preserved for

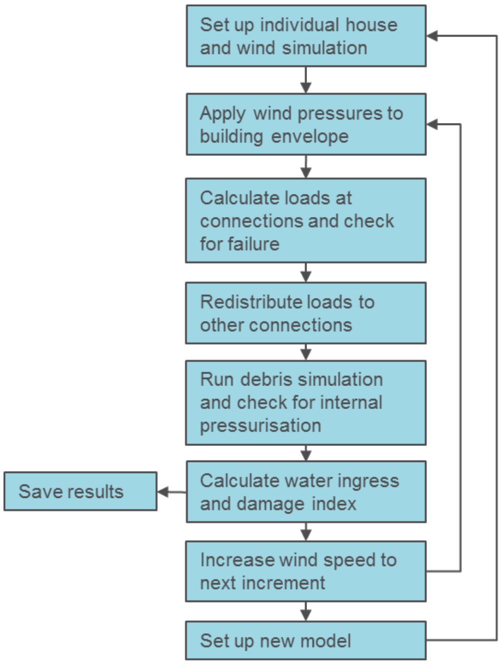

Figure 1: Vulnerability and Adaption to Wind Simulation (VAWS) program logic.

successive wind speed increments, thus ensuring that increasing wind loads act on the damaged structure rather than beginning anew with an intact structure. Following connection failures, redistribution of loads is modelled by changing the values of influence coefficients depending on the position of the failed connection in the load path.

Damage Costing

The program determines a repair cost for a damaged house by modelling the damage state(s) which a house is in at each wind speed and then costing the required repair work. The modelled house may have experienced one or more damage states (for example, loss of roof sheeting and debris damage to walls). The repair cost for any particular damage state is made up of two components: repair to damage to the external envelope and repair of consequential damage to the interior with repair of interior damage caused by water ingress calculated separately. Thus, the total repair cost for a house type at a wind speed is expressed as:

$$\begin{aligned}&\text{Total repair cost}\\&= \left(\sum_{\text{All damage states i}} \text{External envelope repair cost}_\text{i}\right.\\&\left.+ \text{Consequential internal repair cost}_\text{i}\right)\\&+ \text{Water ingress repair cost}\end{aligned}$$

The two components of the repair cost for each damage state i are calculated as below. The calculation allows for each damage state to only affect part of the total susceptible area (for example, only a corner of the roof may have lost its roof sheeting).

$$\begin{aligned}&\text{External envelope repair cost}_\text{i}\\&\qquad= \text{Total quantity}_\text{i} \times \text{Percent damage}_\text{i}\\&\qquad\times \text{Repair rate}_\text{i} \times \text{f}_\text{i}(\text{Percent damage})\end{aligned}$$

$$\begin{aligned}&\text{Consequential internal repair cost}_\text{i}\\&\qquad= \text{Internal repair cost}_\text{i} \times \text{Percent damage}_\text{i}\\&\qquad\times \text{f}_\text{i}(\text{Percent damage})\end{aligned}$$

Where fi(Percent damage) are functions adjusting the repair rate to allow for higher repair rates for extents of repair less than full repair. It is in the form of a quadratic equation $(a_1x^2 + a_2x + a_3)$ where x is the percent damage in a particular damage state and a_1 to a_3 are supplied coefficients.

The repair cost due to water ingress is calculated from the modelled degree of water ingress, the dominant damage state and repair costs supplied in the costing data as follows.

$$\begin{aligned}&\text{Water ingress repair cost}_\text{i}\\&\qquad= \text{Water ingress repair cost}_{\text{i},\%}\\&\qquad\times \text{f}_\text{i}(\text{Percent damage})\end{aligned}$$

Where $\text{Water ingress repair cost}_{\text{i},\%}$ is repair cost data supplied as part of the costing module for repair of damage caused by water ingress for a house. The costing algorithm contains logic to prevent double counting of repair to building components where component repair is nominated in multiple damage states.

The project expresses repair costs as a damage index calculated as:

$$\text{Damage Index} = \frac{\text{Total building repair cost}}{\text{Building replacement cost}}$$

This permits the results to be applied to other houses of similar generic type but different floor areas. The repair cost is then calculated by multiplying the damage index by the floor area and the replacement rate for the generic house type.

Case study: vulnerability of a high-set northern Australian house

The Group 4 house

The VAWS software was used to model the vulnerability of the roof of a high-set Northern Australian house. The model details and an interpretation of the results are presented in the following sections. The house is a high-set timber framed structure with metal roof cladding and fiber cement wall cladding, an example shown in Figure 2. The dimensions and structural system were determined from survey data and the resulting representative house was originally described in Henderson and Harper (2003) as the Group 4 House. Further study on the vulnerability of this house types was performed by Henderson and Ginger (2007).

The house is 12.6 m long, 7.3 m wide and 4.4 m tall including 2.0 m stumps. The roof structure consists of rafters at 10**°** pitch spaced at nominally 900 mm centers supporting battens also at 900 mm centers, which support corrugated metal cladding. The overall dimensions and locations of windows and doors are shown in
Figure **3**. A schematic of the roof structure and a framing plan showing the locations of battens and rafters is shown in Figure **4**.

Assumptions

This case study focuses on the modelling of structural damage to the roof of a population of Group 4 Houses. In order for the damage index to represent the cost of repair of structural damage, certain settings are implemented to ensure the extent of damage is calculated based on structural damage alone:

- Damage induced by water ingress is ignored.
- Debris damage is not costed so that the damage index excludes the cost of repair of wall cladding but allows for the effects of internal pressures.

Figure 2: Example of a Group 4 House type Henderson and Ginger (2007).

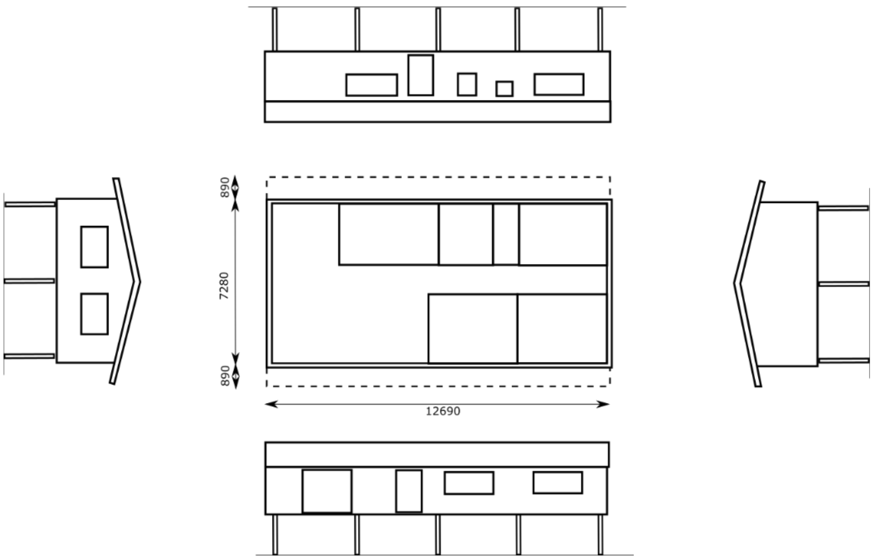

Figure 3: Overall dimensions of the Group 4 House, dimensions in mm.

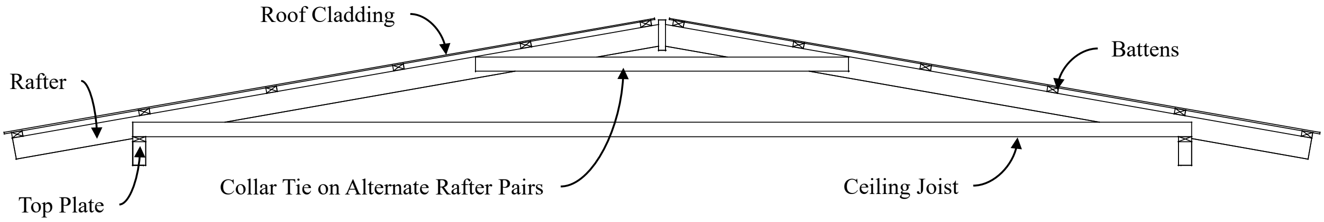

Figure 4: Roof structure of the Group 4 House.

Inputs

Wind pressures

Wind loads on the Group 4 House were determined by carrying out a wind tunnel model study. The model used was originally tested by Holmes and Best (1978) and has similar dimensions to the Group 4 House. The model was modified to reduce the size of the eaves to be more representative of the Group 4 House.

The tests were carried out in the 2.0 m high × 2.5 m wide × 22 m long boundary layer wind tunnel at the Cyclone Testing Station, James Cook University. The approach atmospheric boundary layer profile (suburban terrain, category 2.5 as per AS/NZS 1170.2) was simulated at a length scale of 1/50 using a 250 mm high trip board at the upstream end followed by an array of blocks on the tunnel floor.

Pressure taps were installed on the roof, wall and the floor of the model to measure the external pressures. Each pressure tap was connected to transducers located below the wind tunnel floor/turntable via a length of tuned PVC tubing. External pressures on the roof, walls and floor were obtained for approach wind directions (θ) of 0° to 360° in steps of 10°. The fluctuating pressures were low-pass filtered at 500 Hz, sampled at 1000 Hz for 30 s (corresponding to ~ 10 min in full-scale) and recorded as p(t) and statistically analyzed to give mean, maximum and minimum pressure coefficients referenced to the mean dynamic pressure at roof height:

$$C_{\overline{p}} = \frac{\overline{p}}{\frac{1}{2}\rho \overline{U}_h{}^2}, \qquad C_{\widehat{p}} = \frac{\widehat{p}}{\frac{1}{2}\rho \overline{U}_h{}^2},$$

$$C_{\breve{p}} = \frac{\breve{p}}{\frac{1}{2}\rho \overline{U}_h{}^2}$$

Where, ρ is the density of air and $\overline{U}_h$ is the mean velocity at roof height. The mean and peak pressure distributions were used to identify regions experiencing large wind loads, and for comparisons with data given in AS/NZ 1170.2. This AS/NZS 1170.2 equivalent quasi-steady aerodynamic shape factor $C_{fig} = C_{peak}/G_u^2$, where $G_U = (\hat{U}_h / \overline{U}_h)$ is the velocity gust factor. Here $\hat{U}_h$ and $\overline{U}_h$ are the 0.2 s gust wind speed and mean wind speed respectively at roof height.

Pressure distributions

The average of the minimum pressure coefficients obtained for approach winds within a 45° sector was used to derive the pressure distributions used for eight cardinal directions. The wind pressure distributions for a cornering wind sector 225 ±20° is shown in
Figure **5**. These wind tunnel derived pressures account for local pressure effects in flow separation regions and are used for the application of load to cladding and immediate supporting members such as batten to rafter connections. The pressures are factored by 0.5 for load application to major structural elements to account for area averaging effects of pressure fluctuations on the tributary area of the element.

Analysis of pressure coefficients with wind direction θ, show that the windward edge of the roof experiences the largest (mean and peak) suction pressures and the (windward) wall is subjected to positive pressures. These pressures are generally close to values given in AS/NZS1170.2. The underside of the eaves are subjected to pressures similar to that on the adjacent wall surface. Roof cladding, battens and rafters near the windward gable-end experience the largest wind pressures.

Internal pressure coefficients are calculated following the logic contained in the wind loading standard AS/NZS 1170.2 depending on the distribution and sizes of openings in the walls. The presence of openings is determined by modelling debris impact during a storm and pressure-induced failures of windows and doors.

The internal pressure in the nominally sealed house with the envelope intact is small, i.e. the internal pressure coefficient $C_{pi} = 0$. However, the failure of a door or window on the windward wall from wind pressure or debris impact with increasing wind speed can result in the internal pressure reaching the values of the external wall pressure at the dominant opening $C_{pi} = 0.6$ or more.

Connection strengths

Connection strengths are derived from engineering judgement and testing conducted at the Cyclone Testing Station. Some strengths are modified to account for load sharing effects. Strengths are assigned to connections in the VAWS model using log-normal probability distribution functions, with the mean strengths and coefficients of variation shown in Table 1.

Damage costing data

Cost of damage is calculated based on the number of failed connections, with each connection type corresponding to a tributary area in m^2 that would be affected during a failure, as shown in Table 2. Cost of damage in dollars is then calculated based on the envelope repair rate shown in Table 2. A damage index is calculated based on the ratio of the repair cost to the cost for full replacement of the house. In this case study, the replacement cost is set to the replacement cost for the roof and associated linings and finishes such as ceilings, eave linings, cornices and painting. This ensures that damage indices will reach 1.0 for complete failure. Costs associated with wall debris damage, loss of wall cladding, wall collapse and racking are not modelled in this case study.

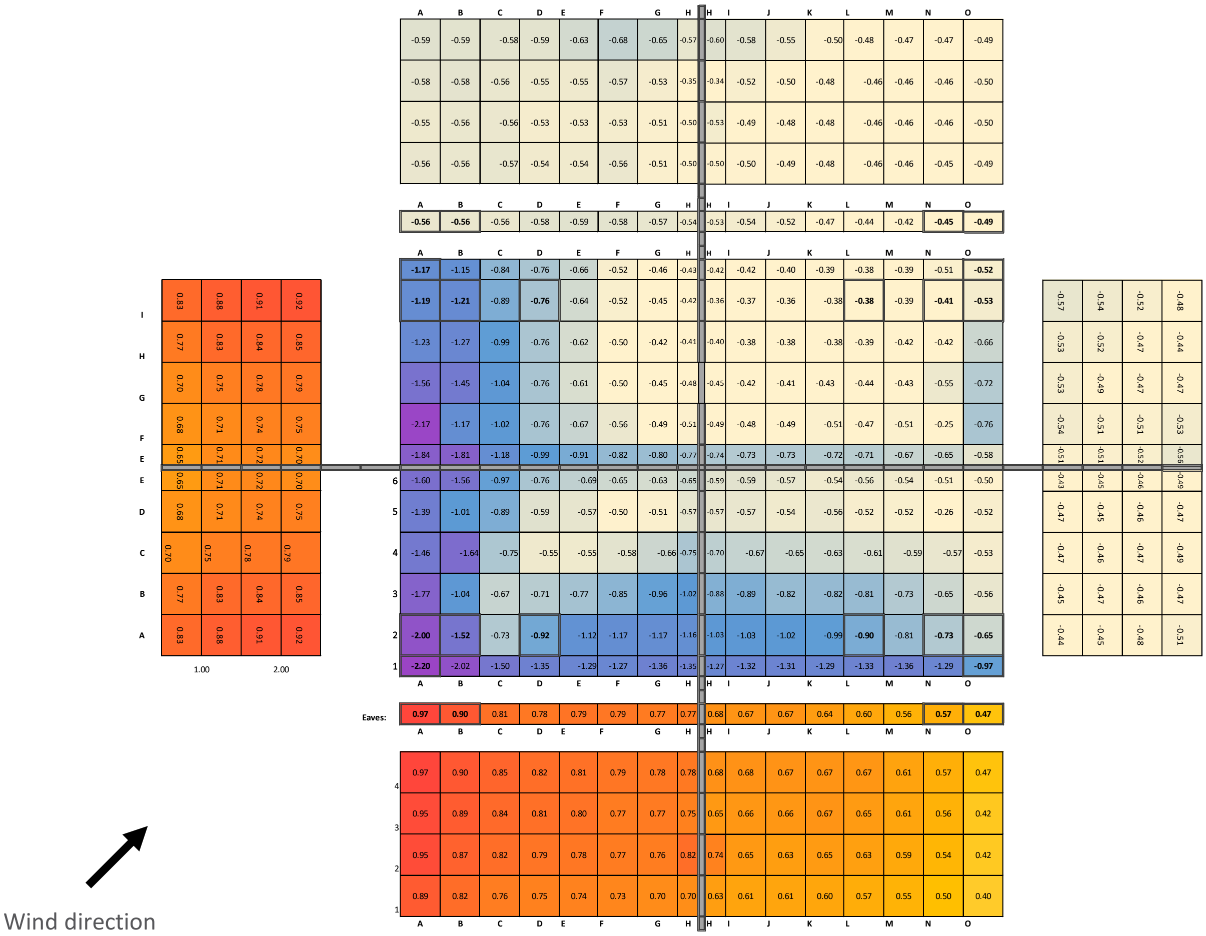

Figure 5: C_{fig} pressure distribution for the sector 225 ±20° on the roof, walls and the underside of the eaves of the wind tunnel model.

Table 1: Connection strengths.

Connection Type	Strength mean (kN)	CoV
Sheeting **(for approx. 4 fasteners)**	2.7	0.1
Batten to Rafter Connection	1.5	0.3
Rafter to Top Plate Connection	5	0.3

Table 2: Damage costing coverages and unit costs.

Failure Mode	Total Surface area $[m^2]$	Envelope repair rate $[\$/m^2]$
Loss of roof sheeting	113.4	72.40
Loss of roof sheeting & battens	113.4	184.2
Loss of roof structure	113.4	317.0

Results

Results for a single realisation

As described in previous sections, the VAWS software simulates the failure of connections and redistribution of loads to neighbouring connections in detail. Although several simplifying assumptions are involved, the vulnerability curves determined are based on structural failure behaviour that would occur during a wind storm.

Results for a single realisation of the wind and structure simulation for a south west wind direction are presented in this section. The external pressure distribution on the roof of the house is shown previously in
Figure **5**. The connection strengths within the house for this realisation that were sampled from the log-normal probability distributions shown in Table 1 are shown in Figure 6.

The VAWS program does not run a time history of wind pressures but increases the wind speed in increments to represent the increase in wind speed through a wind storm. Based on the repair cost and cost for full replacement, a damage index is calculated for each wind speed increment. As damage increases with increasing wind speed, the data points of damage index trace a vulnerability function for that house realisation, shown in

Figure 7 . The onset of damage occurs at approximately 37 m/s with complete damage to the roof structure for this realisation (damage index =1) occurring at approximately 45 m/s, due the failure of rafter to top plate connections with increased loads due to internal pressurisation from debris impact.

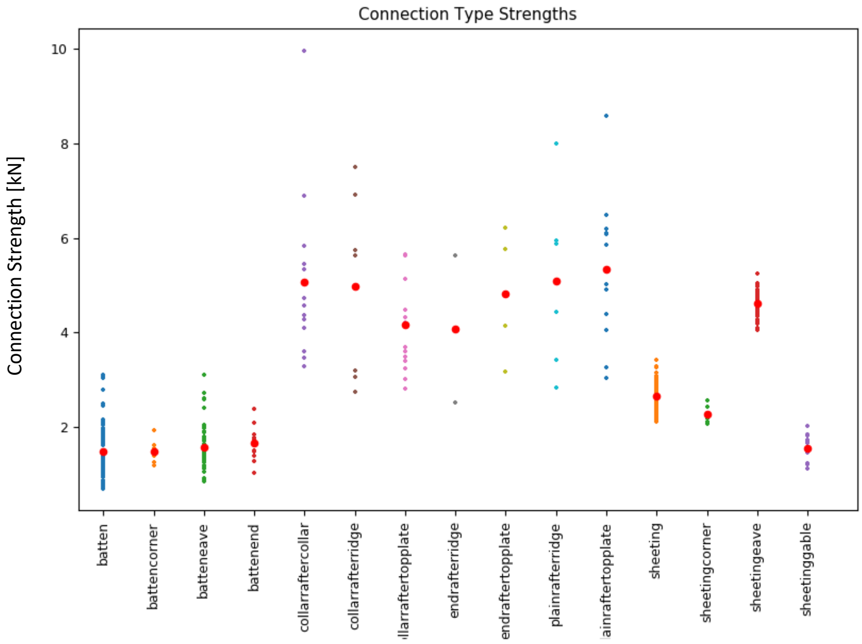

Figure 6: Sampled connection strengths for a single realisation of the Group 4 House, red dots indicate the mean.

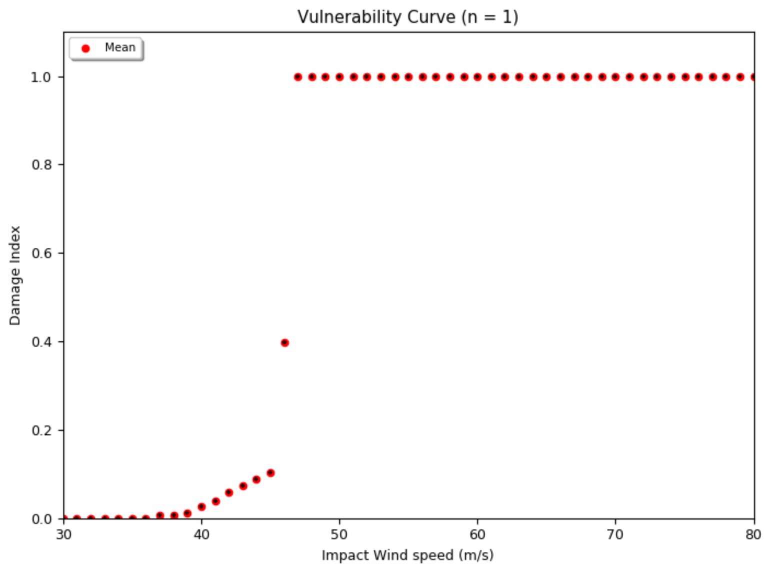

Figure 7: Vulnerability curve for a single realisation of the Group 4 House.

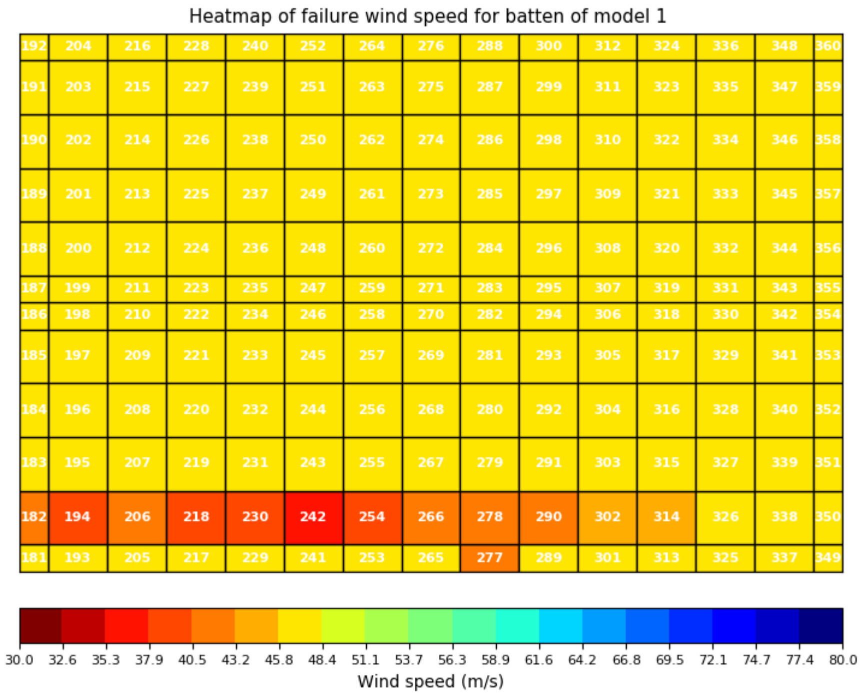

Figure 8: Plan view of house roof showing failure wind speeds for batten to rafter connections for a single model run at wind direction 225 ±20°. Note that large swathe of yellow indicating failure of all remaining connections at about 45 m/s caused by internal pressurisation.

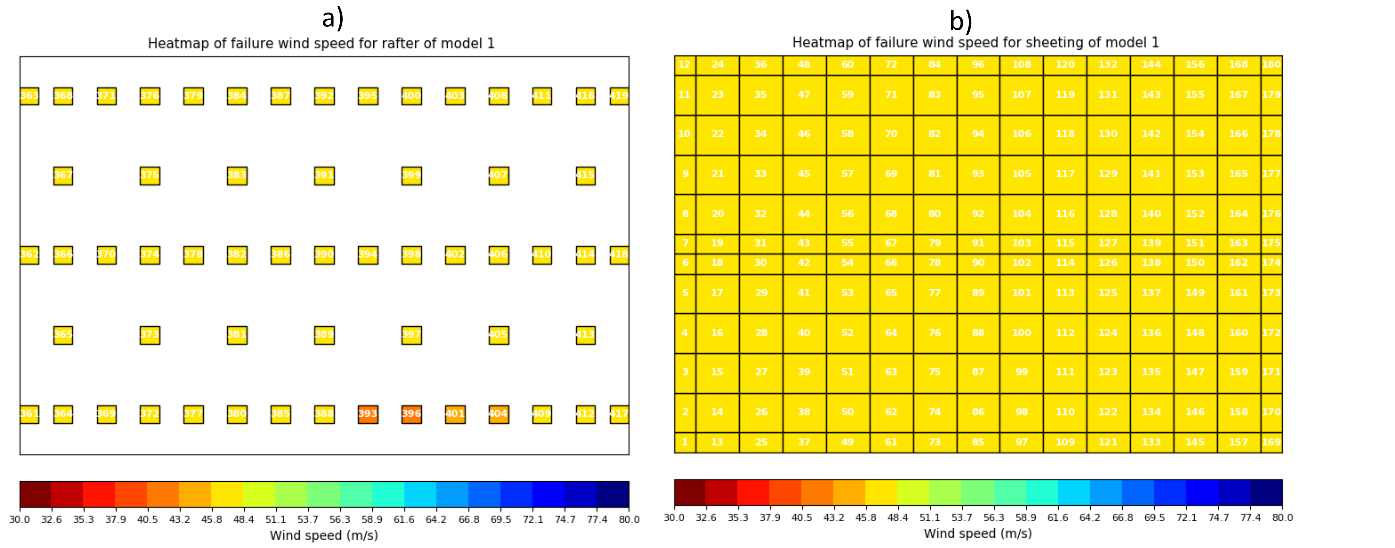

Figure 9: Plan view of house roof showing failure wind speeds for roof to wall connections and collar ties (a) and roof cladding (b) for a single model run at wind direction 225 ±20°. Note the numerous connections coloured yellow denoting failure at about 45 m/s caused by internal pressurisation.

Damage to the structure is presented in a series of 'heat maps' that show the gust wind speeds at failure of three different types of connections. These diagrams indicate how loads are redistributed and how damage spreads through the structure. Locations of initiation and spread of failure through the structure is indicated by bands or sections of roof zones that fail at a range of increasing wind speeds.

For this realisation, the batten to rafter connections are the first to fail at a wind speed of approximately 37 m/s, as shown in

Figure **8**. This is expected for this house type, where batten to rafter connections are generally the weakest link in the tie down chain. Batten to rafter failures cause loads to be redistributed to neighbouring intact batten to rafter connections along the same batten to the left and right. For a SW wind direction, failure initiates at the second batten in from the windward roof edge (connection no. 242). Failure then propagates along the batten towards the left and right with increasing wind speed increments.

Load redistribution due to roof to wall connection failures is determined by varying influence coefficients for vertical reaction forces of failed connections and adjacent connections. For this realisation, roof to wall connection failure initiates near the middle of the roof (Figure 9a) and is due to high loads being transferred here due to the failure of batten to rafter connections (Figure 8) initiated to the left of this location.

For this realisation, internal pressurisation occurs due to debris impact on a door or window at about 45 m/s, as shown in

Figure **10**. The sudden increase in loads immediately causes the failure of remaining roof to wall connections. Roof cladding failure causes loads to be redistributed to other cladding fasteners on neighbouring battens i.e. loads are redistributed along the direction parallel to the roof corrugations. However, in this realisation the cladding fasteners sustain no damage, but all fasteners are costed as failures when the entire roof structure is removed due to internal pressurisation as shown in Figure 9 b).

Results for multiple realizations

The main purpose of VAWS is to determine vulnerability functions for a population of similar types of houses. Using a desktop computer, the VAWS program can run hundreds of realizations of a house type within minutes to determine vulnerability functions for a population of houses. The results of 100 realizations of the Group 4 House type are presented in this section. Each realization is assigned a wind direction, gust wind speed profile, external pressure coefficients and connection properties. Load redistribution and connection failures are calculated for each realization as described in the previous section and internal pressurization is determined based on the debris impact module.

The damage index based on cost of repair for each realization is calculated at increasing wind speed increments and the results for each realization (black dots) together with mean damage index (red dots) are shown in **Figure 11**. The wind speeds causing the onset of damage for most of the houses ranges from 35 to 45 m/s and complete damage occurs from 45 to 55 m/s. Such onset and complete damage thresholds are similar to observations from post windstorm damage investigations conducted by the Cyclone Testing Station (Boughton et al., 2017).

In this case study, two realizations do not experience complete structural damage even at very high wind speeds (80 m/s). These particular realizations are those where the failure of a leeward window has caused a negative pressure within the building, thus reducing uplift loads on the roof structure. Such reductions in pressure are possible in reality, however, wall racking failures that are not modelled in this case study would most likely occur at such high wind speeds. As such, the non-failure behavior of the two realizations is largely artificial.

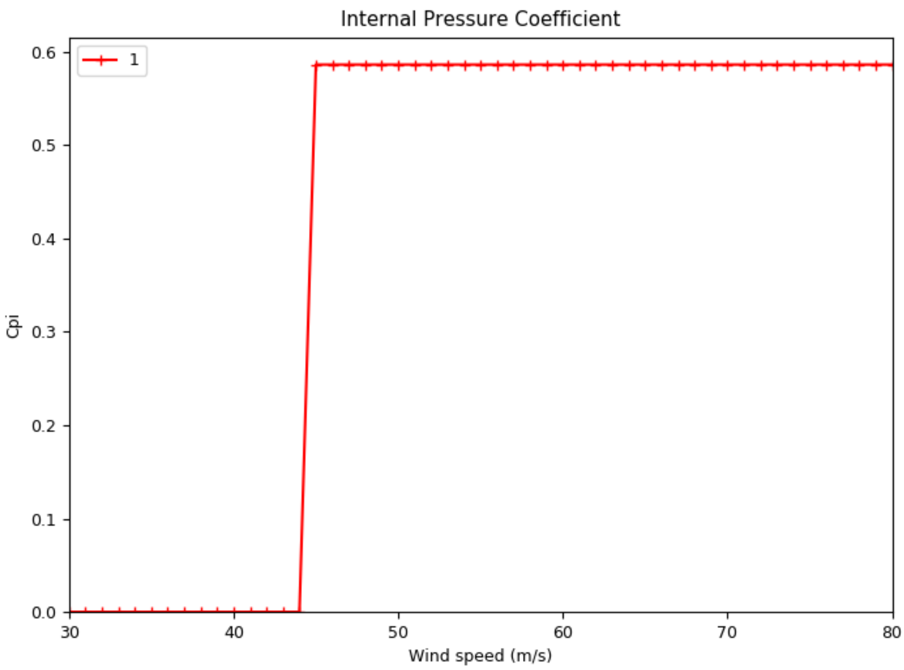

Figure 10: Internal pressure coefficients for a single realisation (red line) as a function of wind speed, indicating internal pressurisation occurring at approx. 45m/s due to debris impact.

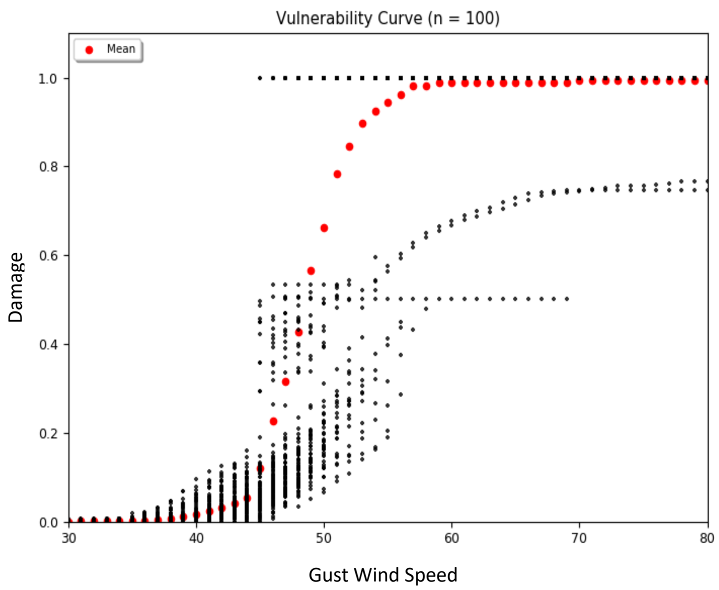

Figure 11: Vulnerability results for 100 realisations of the Group 4 House. The horizontal axis is the 0.2 s gust wind speed at 10m at the house of interest.

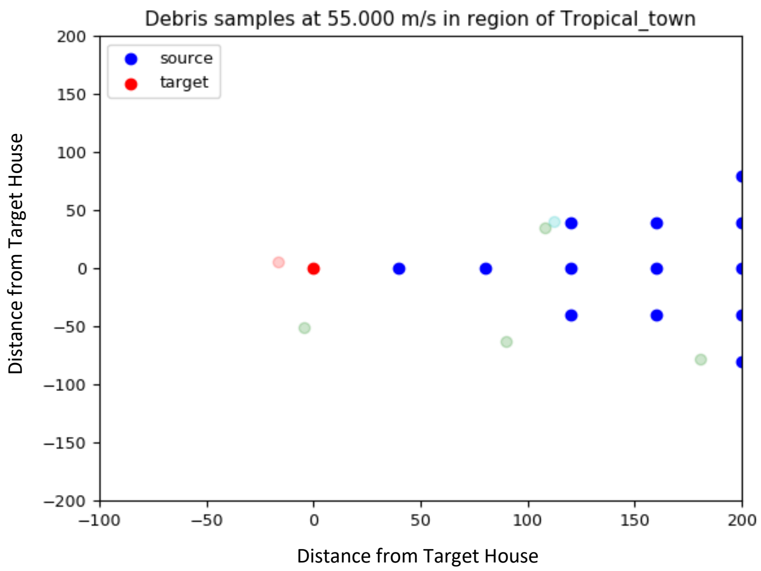

Figure 12: Debris sources and the target house. Faint cyan, green and red dots represent the landing sites of compact, sheet and rod shaped debris items respectively.

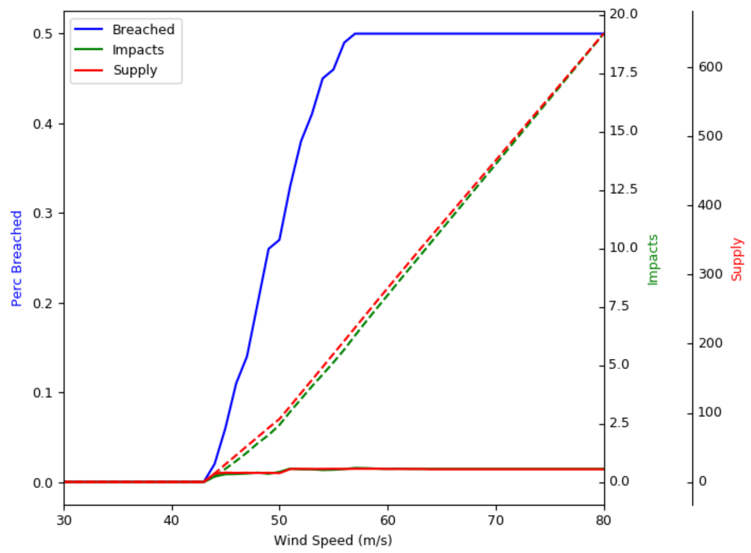

Figure 13: Debris generation, impacts and percentage of envelop breaches as a function of wind speed. Debris item supply and impacts are shown as red and green lines respectively. The plots of debris item supply and impacts are provided for individual wind speeds (solid lines) and also as a cumulative plot (dashed lines).

Windborne Debris and Internal Pressures:

The trajectories, generation and exhaustion of windborne debris is modelled in detail through a process described in Wehner et al. (2010b). An example of debris landing locations, sources and the target house, for a single realization at a single wind speed are shown in Figure 12.

The modelling of debris allows for cost of damaged wall cladding to be determined, more importantly breaches of the building envelope through broken windows trigger the internal pressurization of the house. The overall percentage of breached houses in the population increases from zero to approximately 50% as wind speeds increase from 40 to 55 m/s, shown in Figure **13**.

Calibration

The VAWS software output is checked based on engineering judgement and observations from past damage surveys. Additionally, the heuristic vulnerability curves (Timber Ed, 2006) provide a starting point for validating the output of VAWS. Furthermore, structural behavior is assessed using individual runs with a single wind direction and studying only one connection failure mode at a time. Results are compared with more detailed studies by Parackal (2018).

Conclusions

This paper outlined the overall logic of the VAWS software package and presented a case study of high-set Northern Australian house type. The VAWS program quantifies the vulnerability of a population of house types in Australia accounting for the variability in wind speed, external and internal pressures, debris impacts and connection strengths. Significant advances in modelling compared to previous empirical vulnerability models lie in the simulation of debris impacts and in the load redistribution and progressive failures of connections in the structure. The software allows the reduction in vulnerability afforded by retrofit to be easily modelled by re-running a simulation with the connection strength parameters adjusted to suit the strengthening work.

The case study presented demonstrated load redistribution and spread of failure in the Group 4 House for increasing wind speeds. Although several simplifying assumptions are used to model failure efficiently, the modelled behavior estimates a similar extents of failure that would occur in a windstorm.

The simulation of 100 realizations of the Group 4 House allowed the fitting of vulnerability curves to the calculated damage index at each wind speed increment. Wind speeds of onset and complete failure of houses compare satisfactorily with observations from damage investigations. Next steps in the development of VAWS include the modelling and calibration of wall racking failures, water ingress costs and assessing the vulnerability of several other Australian house types.

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Peer-reviewed article

The physical impact of strong winds and heavy rain on residential housing: a pilot study

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ABSTRACT

Research in the social science area have pointed out that "traditional" hazard-based forecasts and warnings may not be well understood so that mitigating actions for the protection of life and property are not taken (Demuth et al. 2012). The extension of a hazard forecast towards the description of impacts on the forecast recipient might effect a more suitable mitigating response and has led to an emerging and growing desire among National Hydrological and Meteorological Services for impact-based forecasts and warnings (Harrowsmith 2015; World Meteorological Organization 2015).

A number of major weather services (e.g. UK Met Office, Bureau of Meteorology) have therefore introduced impact-based services in recognition of the above findings. Since 2011 the UK Met Office has issued impact-based warnings where the warning level is derived from a risk matrix in a partly subjective procedure (Met Office 2018). In a related manner, the Extreme Weather Desk at the Australian Bureau of Meteorology has recently developed the Community Hazard Risk Outlook. Forecasters subjectively rate the expected impact level of a model-predicted hazard on a range of assets from which an aggregated impact level is calculated. Combined with a subjective likelihood assessment the UK Met Office risk matrix concept is again utilised to derive an overall hazard risk.

In addition to subjective or partly subjective impact specifications, the factors influential in the final likelihood, location or magnitude of an impact can be delivered as layers, which leaves their integration to the user. An example of such a system is the Global Hazard Map, also produced by the UK Met Office (Robbins and Titley 2018).

Introduction

There are comparatively few attempts to quantitatively and objectively integrate the various hazard, exposure and vulnerability components to calculate a final impact output. One such hazard impact model is the Vehicle Overturning Model which combines probabilistic hazard information with exposure and vulnerability data to produce a forecast of vehicle overturning risk (Hemingway and Gunawan, 2018; Hemingway and Robbins, 2019). A second example is the Surface Water Flooding hazard impact model (Aldridge et al. 2016).

In this paper we outline early steps towards a potential future Australian wind and rain hazard impact model through a combined effort of Geoscience Australia's capability for impact simulation, and the Bureau of Meteorology's provision of detailed spatial hazard grids.

The impact forecasting workflow

In the project, we use a paradigm of Hazard – Exposure – Vulnerability – Impact ("HEVI") for evaluating the physical impact of an extreme weather event. This paradigm reflects the integrated nature of impacts, and the dependence of the final outcome on the interaction of the three components (Figure 1). If any of the three components is reduced, then the overall impact is reduced. For this project, we formulated a specific definition of each of the components (reference?). Due to the cross-cutting themes involved in impact modelling, it is important that all stakeholders understand the terms used in communicating "impact"provides the definitions of the terms used for the project. While these definitions for hazard and exposure can cover a wide range of phenomena and assets, we restrict ourselves to wind speed and rainfall for the hazard, and to residential houses for exposure. More details on each of these components are provided in the hazards, exposure and vulnerability sections below.

Table 1: Definitions of the core terms used in impact forecasting.

Hazard	Exposure	Vulnerability	Impact
A severe weather event that has the potential to cause impacts to people, buildings, infrastructure, agriculture, environmental assets and communities. For this project, we are exploring the wind and rainfall elements of east coast lows.	The elements that may (or may not) be impacted by a hazard event. Elements at risk includes dwellings or households, buildings and structures, public facilities and infrastructure assets.	The degree to which a building, structure, or other exposure element, is damaged by a given intensity of hazard.	The consequences of a hazard event on an asset - the physical damage to an exposure element due to a hazard event. Commonly uses qualitative descriptions such as "slight", "moderate", "major" or "complete"

The interaction of the three components can be non-linear. For example, the vulnerability, examined in the section on vulnerability below, is often a non-linear function of the hazard magnitude, with a twofold increase in the hazard commonly leading to much more than a twofold increase in impact. An example is the pressure force exerted by the wind - a doubling of the wind speed leads to a four-fold increase in the wind pressure. Further, the calculation of impact, discussed in the impact section below, is performed on the building scale but must be aggregated to larger geographic areas in order to reduce the influence of uncertainties. Despite this, the uncertainty in each of the workflow components combines to result in substantial levels of uncertainty in the impact, making verification challenging. There are additional challenges to verification, which will be explored in the verification section.

Each of the impact components vary in space, with the hazard also varying in time as the weather forecast evolves. Thus, the impact forecast can be expected to vary spatially and temporally. The challenge for a forecaster or emergency manager is to combine the individual components in a meaningful way, with sufficient time to guide decision making within the context of their operations for communicating threats to the public – in the form of suitably worded and targeted warnings – or making preparations to reduce or respond to the impacts of an impending extreme weather event.

There are challenges in bringing together the components of hazard, exposure and vulnerability for a nationally consistent view of the potential impacts of extreme weather. In the hazard space, the choice of weather forecast variables can greatly influence the predicted impact. In utilising numerical weather prediction model data (or, equivalently, reanalysis data), model grid spacing, choice of model physics parameterisations and available diagnostic variables can influence the resulting impact products.

Knowledge of the exposed assets, in a consistent manner across the country, means there are challenges in defining key attributes where available data may be limited or only available as aggregate statistics. Similarly, it is not feasible to understand the vulnerability of individual buildings across the country, so the assets need to be categorised on the basis of a small number of attributes such as building age or roof type, so we can assign the most appropriate vulnerability model (from a limited number of such models) to each asset.

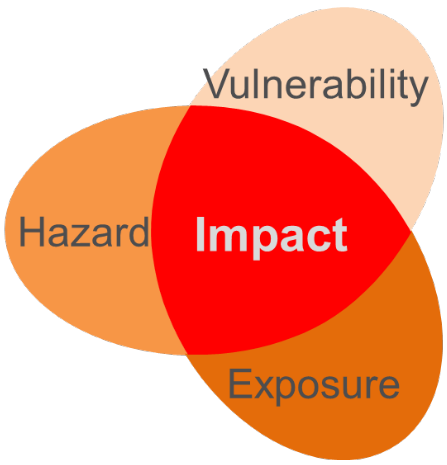


Figure 1: Integration of the three components – hazard, exposure and vulnerability – to arrive at an estimate of impact (after Zscheischler et al. 2018).

The resulting impact information is intended to assist forecasters and emergency managers in formulating warnings or preparing for an event. Two key questions that need to be addressed is what type of impact information is of use to these end users, and what decisions are being made? Is the indicative damage state of residential buildings suitable to guide decisions, or are other metrics of more value? These questions should be addressed in developing a future plan for utilising impact-based forecast products, but are not explored in detail here.

Hazards: how do we represent severe weather?

In choosing forecast weather elements as hazard representation, it is important to understand how these elements are observed, forecast and affect impact. The language we use to describe weather typically deconstructs the atmosphere into discrete components. However, atmospheric variables are complex and vary continuously in space and time. An example of this is in the description of wind which can fluctuate rapidly between extremes. Standard conventions describe this distribution as some mean component and a fluctuating "gust" which characterises the extreme values. But the duration over which this mean value and gust are calculated must be specified. The World Meteorological Organization (WMO) recommends a definition based on a running 3-second mean wind, with the 10-minute mean and 3-second maximum within a 10-minute interval the mean and gust for that interval (World Meteorological Organization 2008). Correspondingly, efforts have been made within model development to mirror these observations as output diagnostics (Sheridan 2018).

Within the Unified Model, which underpins the suite of numerical weather prediction models at the Bureau of Meteorology, a parameterisation of the surface gust, based on the work of Beljaars (1987), the 3-second definition above is used. This is readily converted to a 0.2-second duration gust which is commonly used as the hazard measure for wind vulnerability relations (Harper et al. 2010).

There are similar issues with the description and measurement of rainfall. While the total amount of rain will clearly modulate the effects of flooding and impact soil moisture (which has implications for tree fall and landslides), intense rainfall over short durations can lead to flash flooding and, when combined with strong winds, rain ingress (Blocken and Carmeliet, 2004). As with wind, structures and assets respond differently: a particular drainage system may cope well with a large amount of steady, accumulated rainfall spread over 24 hours, but may struggle to dissipate high intensity rainfall over a period of 15 minutes.

The key question then, is how to broadly characterise the hazards in order to capture the spread of impact over these varying scales. In this regard, the project is somewhat limited by the output of the chosen numerical weather model, BARRA: the Bureau of Meteorology Atmospheric high-resolution Regional Reanalysis for Australia (Su et. al. 2019). There are two key drivers behind the choice of this model. Firstly, atmospheric reanalyses such as BARRA provide a model estimate of the atmosphere constrained by observations to form a spatially continuous record over long periods. Reanalysis output can therefore be used to estimate a suite of weather variables at a particular time and location, not necessarily near an observation station. This is advantageous when considering historical severe weather events as the reanalysis output is generally more accurate than forecasts produced by operational models and provides a good estimate of hazardous weather during the period of interest. Secondly, the BARRA dataset comprises a 12 km horizontal grid spacing suite over the Australian region (BARRA-R) and a number of nested, 1.5 km horizontal grid spacing suites over some of the major Australian cities (BARRA-XX). These suites are akin to the operational ACCESS-R and ACCESS-C forecast models (Bureau of Meteorology 2010; Bureau of Meteorology 2013; Puri et al. 2013), respectively, used by Bureau of Meteorology forecasters and on which future impact forecasting will be based. For the chosen case study in this paper, the 20-22 April 2015 Dungog East Coast Low (ECL; Pepler and Coutts-Smith 2013; Speer et al. 2009), the spatial extent of damage lies within the domain of the BARRA-SY reanalysis dataset incorporating the region around Sydney. Model output referenced henceforth is extracted from this dataset.

In order to represent the hazards that most closely produce the observed impact on residential housing through our workflow, we consider a range of wind and rain metrics which best characterise the inherent variation to each model output weather element of interest. For wind, these are the event maximum surface (10-m) mean windspeed (designated PSMW), 10-m wind gust (PSWG) and a "neighbourhood" wind gust (NSWG) calculated as the maximum within 40 km of a point over the course of the event. Event maxima are calculated from 10-minute reanalysis fields during the 72-hour period from 03 UTC 19 April 2015 to 03 UTC 22 April 2015. The neighbourhood wind gust provides some allowance for model placement errors in the spatial location of strong winds. In addition to these three surface fields, the event maximum "gradient-level" windspeed at 900 hPa (roughly 900 m AMSL) is calculated at each point in order to provide a supplementary characterisation of the wind energy in the lower atmosphere (PGWS). Combined, these four metrics (Figure 2), provide a reasonable characterisation of the maximum near-surface wind strength variability over the course of the event.

Likewise, the rain hazard is represented at a point by the event maximum rainfall accumulated over periods of 10 minutes (PIRR), 1 hour (P1RR) and 6 hours (P6RR), calculated from model data output at rolling 10-minute intervals. The total event rainfall accumulation at a point (PTEA) is also considered. These intervals are chosen in order to represent rain impact from the closest reanalysis field to the instantaneous scale (10 minutes), through medium-duration rain events (1 and 6 hours) up to the full event rainfall. As with wind, a neighbourhood metric is calculated for the event maximum 1-hour rainfall (N1RR). A matrix showing all wind and rain metrics calculated is shown in Table 2.

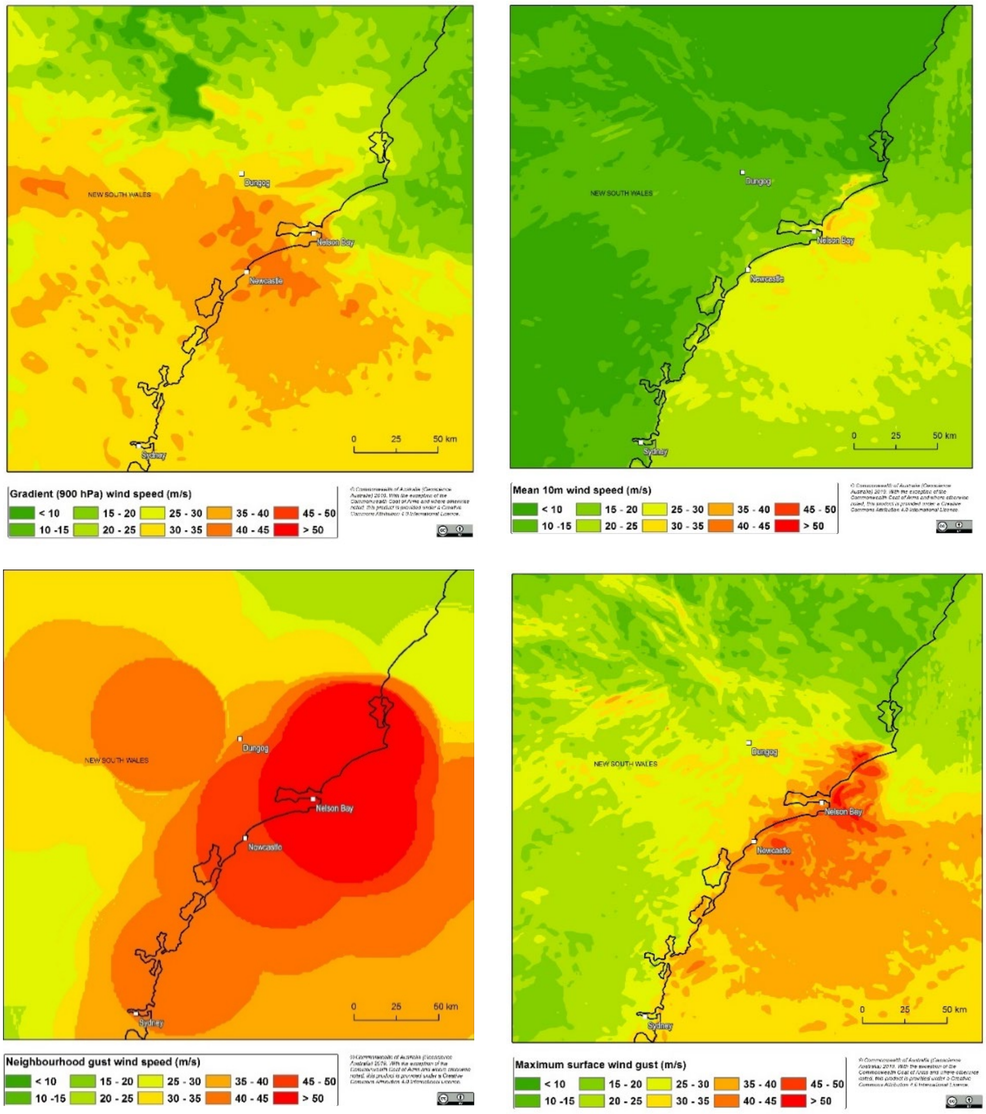


Figure 2: Four characterisations of wind hazard for the 2015 East Coast Low event, as simulated in the BARRA-SY reanalysis (clockwise from top left): point gradient wind speed, point mean wind speed, point gust wind speed and neighbourhood gust wind speed. All values are in units of metres per second.

Table 2: Nine hazard types (5 for rainfall impact, 4 for wind impact) are extracted from the high-resolution reanalysis dataset BARRA-SY. A Quadratic Discriminant Analysis (QDA) will utilise each of the wind and rain fields below to determine which combination of wind and rain hazard proxies possesses the optimum predictive capability for residential housing damage for the 2015 East Coast Low event.

Metric	Description	Use
PSWG	Event maximum point surface wind gust (estimated 3-second duration)	Impact forecast, QDA
PSMW	Event maximum point surface mean wind (estimated 10-minute mean)	Impact forecast, QDA
NSWG	Event maximum neighbourhood surface wind gust	Impact forecast, QDA
PGWS	Event maximum point gradient-level (900 hPa) wind speed	Impact forecast, QDA
PIRR	Event maximum point 10-minute accumulated rainfall	QDA
P1RR	Event maximum point 1-hour accumulated rainfall	QDA
P6RR	Event maximum point 6-hour accumulated rainfall	QDA
N1RR	Event maximum neighbourhood 1-hour accumulated rainfall	QDA
PTEA	Point total event accumulated rainfall	QDA

Exposure: what will be impacted?

The list of elements exposed to an extreme weather event can be extensive, with different stakeholders having different assets of interest. For example, State Emergency Services may prioritise the impacts to buildings, while electricity transmission line operators would prioritise impacts on their transmission lines and substation assets. Businesses and lifeline utilities, including energy, water, communication, and transport will also be impacted. Although they play a significant role and are of interest to emergency services and the owners and operators of those assets, due to the interdependencies and complexity of these networks they are not addressed in this project.

To constrain the scope of this pilot study, residential buildings, comprising semi-detached and separate houses, are initially selected as the asset class for the demonstration of the project workflow. Geoscience Australia's National Exposure Information System (NEXIS; Power et al. 2017) contains nationally-consistent construction type information for these house types.

NEXIS contains publicly available exposure information. Where building-specific information is not publicly available, NEXIS derives attribute information based on transparent statistical methods and rules. There are challenges arising from the available source information used to define the various methods, and the derived NEXIS attributes may not reflect the actual constructional information at a local scale (individual buildings). Statistically derived building attributes are one of the many sources of uncertainty in the quantitative calculation of physical impacts on residential buildings.

Vulnerability: how much damage will be caused?

The last step in the workflow to forecast impact is to estimate how much damage is caused by the forecast hazard to the inventory of exposed assets. To make this estimate, relationships between some measure of damage and hazard magnitude are used. Such relationships can be either vulnerability functions or fragility functions.

Vulnerability functions relate average damage suffered by a population of similar assets to hazard magnitude. Fragility functions relate proportions of a population of similar assets in different damage states to hazard magnitude. Often, both types of functions are presented as S-shaped curves although there is no requirement to do so. This is particularly the case for flood hazard where the required repair increases in a series of steps as water depth increases.

Vulnerability and fragility functions can be developed by three methods: heuristic estimation, analytical computation and, finally, empirical data. In terms of measuring damage, or the vertical axis of a vulnerability

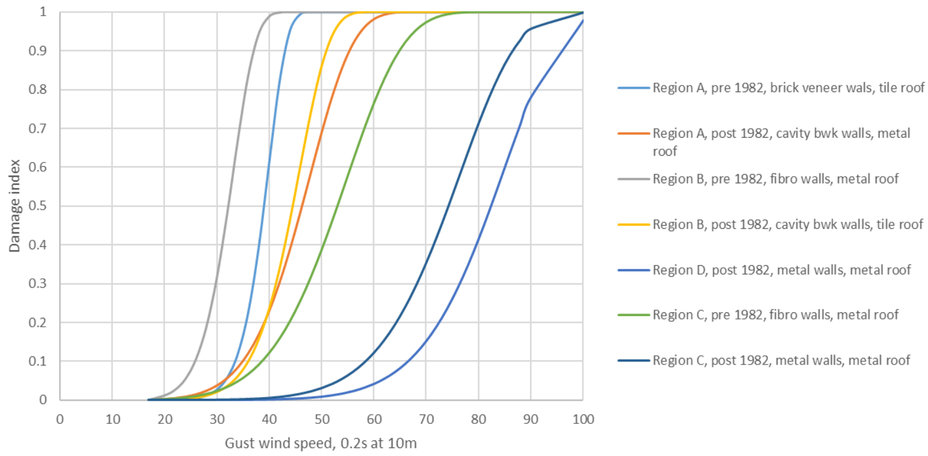


Figure 3: Heuristic vulnerability functions for a range of WA house types exposed to severe wind hazard (Boughton, 2018).

curve, damage index is often used as this is a non-dimensional measure of damage which is defined as repair cost divided by replacement cost. Since it is non-dimensional it can be applied to any building of the relevant type irrespective of building size.

Heuristic vulnerability and fragility functions are developed by people experienced in observing or estimating loss from natural hazard qualitatively estimating a vulnerability function informed by their experience and any available empirical data. Figure 3 shows an example set of heuristic vulnerability curves for a selection of Western Australian house types exposed to severe wind hazard (Boughton 2018).

Analytical vulnerability and fragility functions are developed using an engineering model to estimate damage caused by a hazard of a certain magnitude and then costing the repair of the modelled damage. Figure 4 shows an example of an analytical vulnerability function for a modern house type exposed to riverine (low velocity) inundation. In this instance, the repair work at a range of inundations depths (hazard magnitudes) was documented and the repair work costed. The repair work at each depth was divided by the house's replacement cost to produce a damage index and the points plotted.

Empirical vulnerability and fragility curves are produced by fitting functions to scatters of points of damage against hazard magnitude. The empirical data can be sourced from a variety of sources such as:

- Postal surveys,
- Insurance loss data,
- Post-disaster surveys,
- Rapid damage assessments, or
- Emergency service call-out records.

Figure 5 shows example empirical damage data for a single storey brick-veneer slab-on-grade house exposed to riverine flooding.

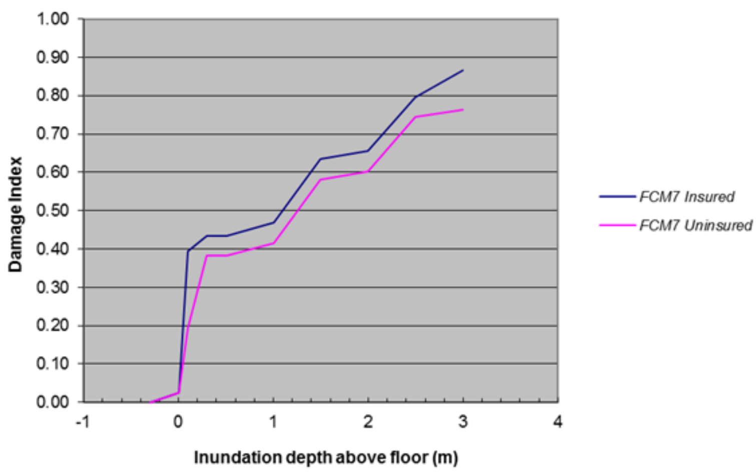
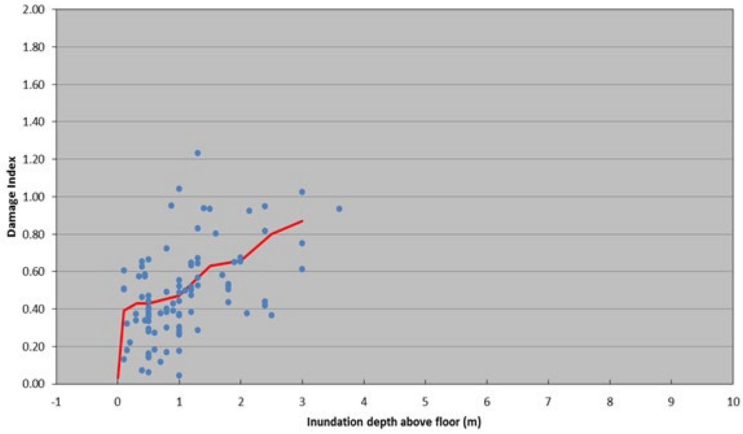
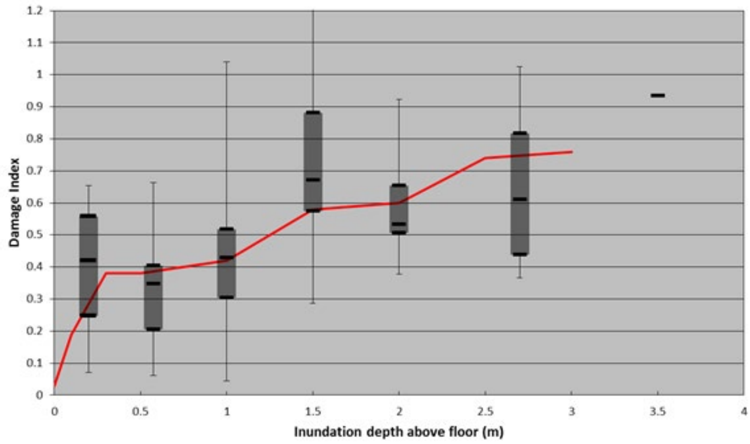


Figure 4: Analytical vulnerability function for a single storey brick veneer, slab-on-grade house exposed to riverine flood hazard (Wehner et al. 2017).



(a)



(b)

Figure 5: Empirical data sourced from a postal survey of damage incurred due to flooding to the same house type as Figure 4. Figure (a) shows the scatter of data and Figure (b) shows a box plot for the same data. In each figure the red line is the analytical vulnerability curve shown in Figure 4 (Wehner *et al.*, 2017).

The choice of using either vulnerability functions or fragility functions to estimate damage depends on the required output from the impact forecasting. For example, impact expressed as estimated numbers of houses in different states may be of more use to an emergency manager than an estimate of the aggregate repair bill across an event footprint, whereas the insurance industry would be more interested in the latter.

The above examples of vulnerability and fragility functions relate damage to a single hazard: wind or flood. The BNHCRC Impact Forecasting project is examining a workflow to forecast impacts to residential houses from storms. Storms (such as ECLs) can cause damage via several mechanisms:

- Direct structural damage caused by wind loads exceeding the strength of building components,
- Wind-borne debris,
- Tree-fall caused by wind actions on trees close to buildings,
- Water ingress resulting from rainfall (wind-driven or not).

Whilst some heuristic vulnerability curves for houses exposed to wind exist, these could be improved using empirical data for calibration. No existing vulnerability or fragility functions use rainfall amount or rainfall rate as a hazard measure. Furthermore, the hazard measure used for the wind vulnerability curves is often the 0.2s gust wind speed at 10m at the building of interest. This is a quantity that is not presently forecast by the numerical weather prediction models used by weather services around the world.

The project attempted to generate project-specific fragility functions for residential houses exposed to storm hazard from empirical data sourced from the NSW Emergency Information Coordination Unit (EICU). Figure 6 shows a plot of damage state plotted against model forecast surface gust wind speed. Each black dot represents a data point. There is no relationship of increasing numbers of houses in higher damage states with increasing hazard magnitude. Figure 7 shows damage state plotted against forecast maximum 6-hour rainfall rate. Again, there is no relationship of increasing numbers of houses in higher damage states with increasing hazard magnitude.

The figures illustrate that there is a complex relationship between multiple perils and resulting damage.
To explore the potential use of a combined damage predictor (wind and rainfall measures) the project investigated combinations of four different measures of wind hazard and five different measures of rainfall hazard.

Figure 8 shows the results of the investigation. The combination of hazard measures that yielded the best results (highest probabilities) is the point 10-minute accumulated rainfall (PIRR) and the point maximum gradient wind speed (PGWS) shown in the top right-hand panel of Figure 8.

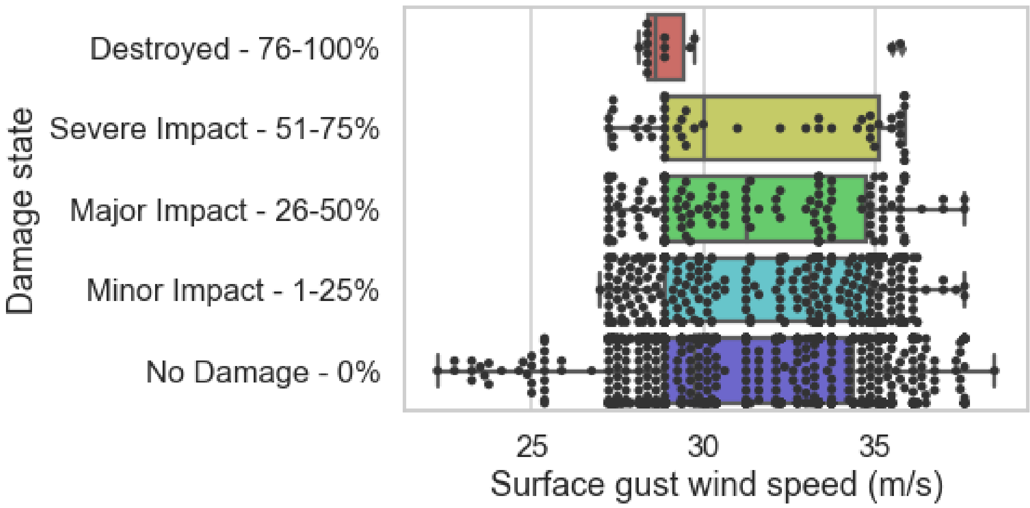


Figure 6: Fragility data from 2072 EICU damage assessments for the 20-22 April 2015 ECL storm plotted against the event maximum surface gust wind speed (PSWG) simulated by the BARRA-SY Reanalysis.

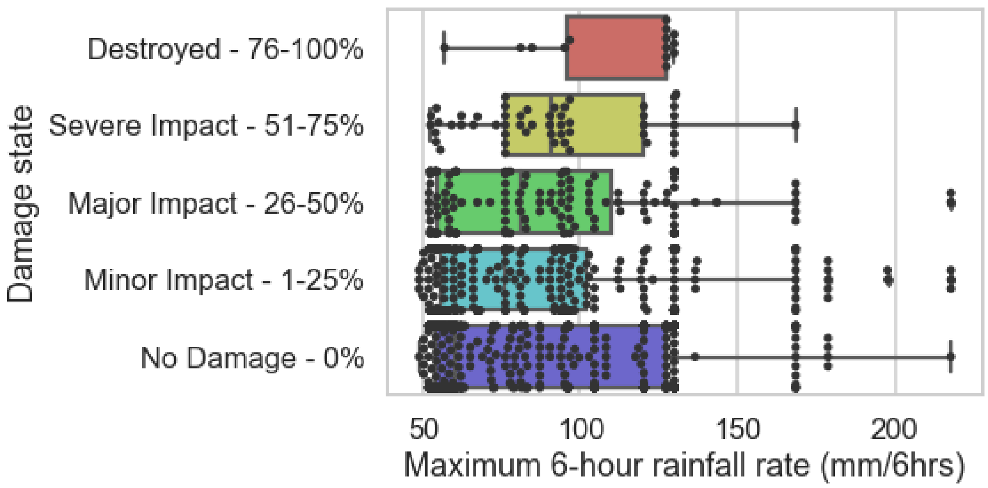


Figure 7: Fragility data from 2072 EICU damage assessments for the 20-22 April 2015 ECL storm plotted against maximum 6-hour rainfall rate (P6RR) modelled by the BARRA-SY Reanalysis.

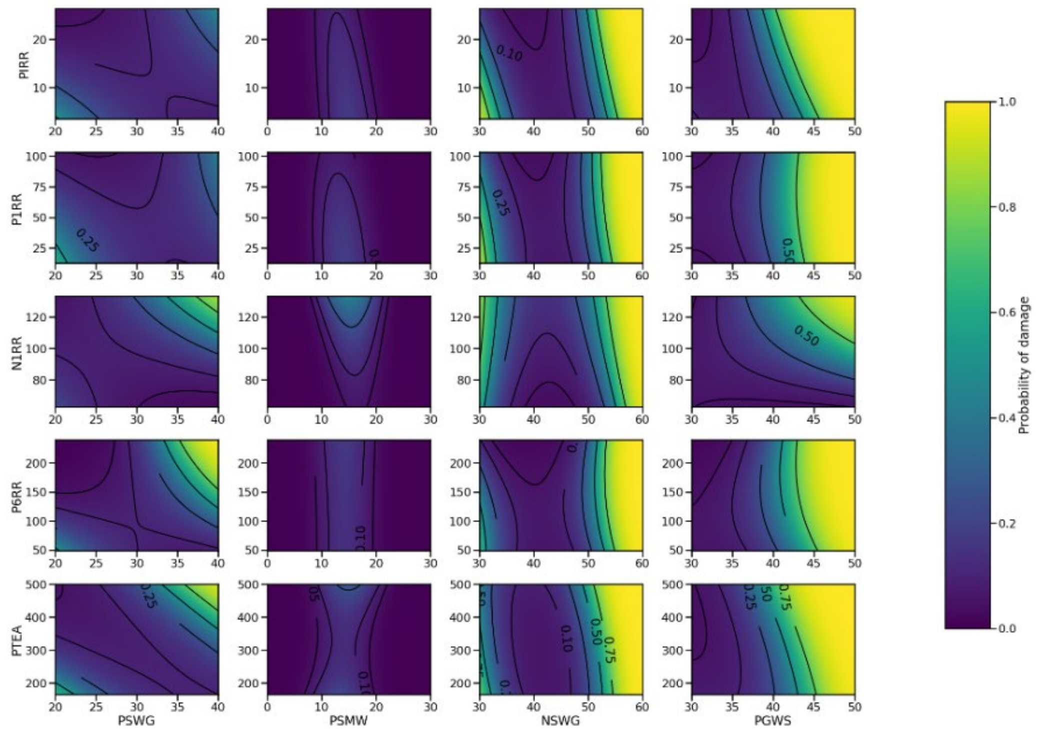


Figure 8: Quadratic discriminant analysis (QDA) of damage arising due to combination of rainfall and wind hazards. The colours represent the probability of a building being damaged in an event with the prescribed wind and rainfall hazard levels. See Table 2 for definitions of hazard parameters. "Damaged" is defined as EICU damage ratings in the categories moderate, extensive or complete. Contour intervals are 0.25.

The project's work has highlighted the benefit that empirical damage data gathered during rapid damage surveys and emergency services call-outs can bring to improving the understanding of the relationship between damage and causative hazards. However, to be of use for quantitative impact prediction some basic attributes have to be collected:

- Location of the observation,
- The nature of the building where the observation is made,
- The causative hazard or hazards, e.g. direct wind damage, water ingress, tree fall, etc., and
- The severity or degree of damage.

The above data needs to be collected in a consistent manner across events and jurisdictions.

Impacts: what does the forecast look like?

Impacts are calculated at individual building level, so that each asset is assigned a specific hazard magnitude and resulting damage index. To reduce the influence of uncertainties, largely associated with the definition of exposure, the results of the impact calculations are aggregated to larger geographical areas by attributing the mean damage index to this area, in line with the statistical definition of exposure attributes (see SA1 area definition below). The mean damage index is then expressed in terms of five damage state categories, as mapped out in Table 3. The aggregation from the individual building scale to the areal scale reduces the likelihood of users attributing a high level of spatial precision to the results (akin to our earlier discussion on the "neighbourhood" hazard definition).

Figure 9 shows the mean damage state for SA1 geographical areas (Australian Bureau of Statistics, 2019), derived using the point maximum surface wind gust (PSWG) hazard variable. The values are determined as a damage ratio for each building point in the region, then averaged across the geographical area. The values are then mapped to indicative damage states (Table 3) for dissemination. In general, the areas of highest damage are close to the coast, where gust wind speeds are highest

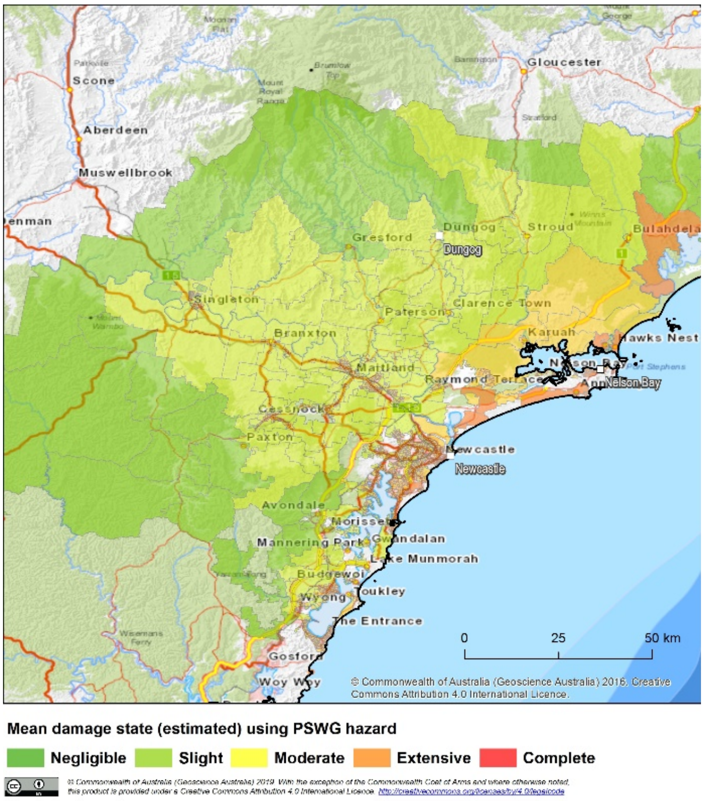


Figure 9: Forecast mean damage state due to point maximum surface wind gust (PSWG) on residential buildings, aggregated to SA1 geographical regions for the 20-22 April 2015 Dungog ECL.

Accuracy: how do we verify this?

It is important to verify forecasts to measure their accuracy and facilitate continual model improvement. Impact forecast verification requires observed impact data, ideally in the same format as the forecast. For example, a temperature forecast for a particular time can be compared with the observed thermometer reading in an unambiguous way. Verifying an impact forecast, however, is complicated as the observations are not routinely conducted and there is no standardised format. For the Dungog ECL, impact observations are available from two sources. Rapid damage assessment (RDA) data compiled by Fire and Rescue NSW for the Emergency Information Coordination Unit (EICU), or by analysing State Emergency Service (SES) callout data. EICU data (**Error! Reference source not found.**) provide a measure of the level of damage inflicted upon a structure within five qualitative categories: Negligible, Slight, Moderate, Extensive, Complete. Unfortunately, this data has limited spatial coverage, and is typically concentrated around urban centres. Conversely, SES callout data provides better spatial coverage, but records emergency response due to a range of issues (tree fall, power lines down etc.) and there is no clear way to disaggregate the damage reports by hazard within the dataset. The callout data also doesn't capture any detail of the damage level. Instead, a "service demand" parameter can be calculated to determine the comparative impact across SA1 areas (for a definition, see Australian Bureau of Statistics, 2019) where relatively high service demand is assumed to correspond to relatively higher impact:

$$Service\ demand = \frac{number\ of\ callouts\ per\ SA1}{number\ of\ houses\ per\ SA1}$$

Because the service demand is spatially complete and applies to SA1 areas, this measure is more readily compared with the output of an impact forecast than the EICU data which are collected in limited areas only. An example is shown for wind gust impact on residential buildings (Figure 11). While not strictly like-for-like, comparison of the spatial impact forecast with the relative service demand can be used to answer a number of questions regarding the skill and utility of the wind impact forecast. For example:

- How well does the prediction discriminate between different observed outcomes?
- Does the forecast rank SA1 area impact in the same order as the service demand is observed?
- Does the location of maximum forecast impact match the location of highest service demand?
- Is the area of total damage well predicted?

The relative importance of these questions is determined by the end-user of the forecast. For example, the ability to predict where the maximum impact will occur can help target the warning message and assist in planning where to deploy responders. Having confidence in the total damage area would help agencies to plan for a response of an appropriate size.

Table 3: Definition of damage states for residential separate houses.

Damage state	Damage index range	Description for residential houses
Negligible	0.0 – 0.02	Little or no visible damage from the outside. No broken windows, or failed roof deck. Minimal loss of roof cover, with no or very limited water penetration.
Slight	0.02 – 0.1	Moderate roof damage that can be covered to prevent additional water ingress. One window, door or garage door broken.
Moderate	0.1 – 0.2	Major roof damage, moderate window breakage. Minor roof sheathing failure. Some water damage to interior.
Extensive	0.2 – 0.5	Major window damage or roof sheathing loss. Major roof cover loss. Extensive damage to interior from water.
Complete	> 0.5	Complete roof failure and/or failure of wall frame. Loss of more than 50% of roof sheathing.

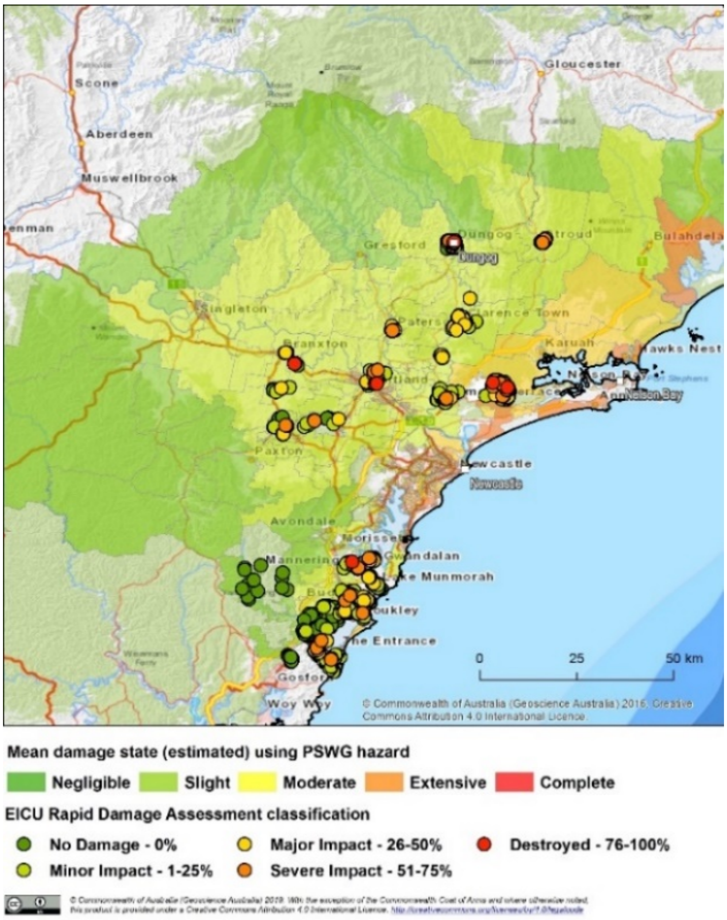


Figure 10: Rapid Damage Assessment (RDA) data from the Emergency Information Coordination Unit (EICU) overlaid on the predicted mean damage state based on BARRA-SY using the point maximum surface wind gust (PSWG) as the wind hazard for the 20-22 April 2015 Dungog ECL.

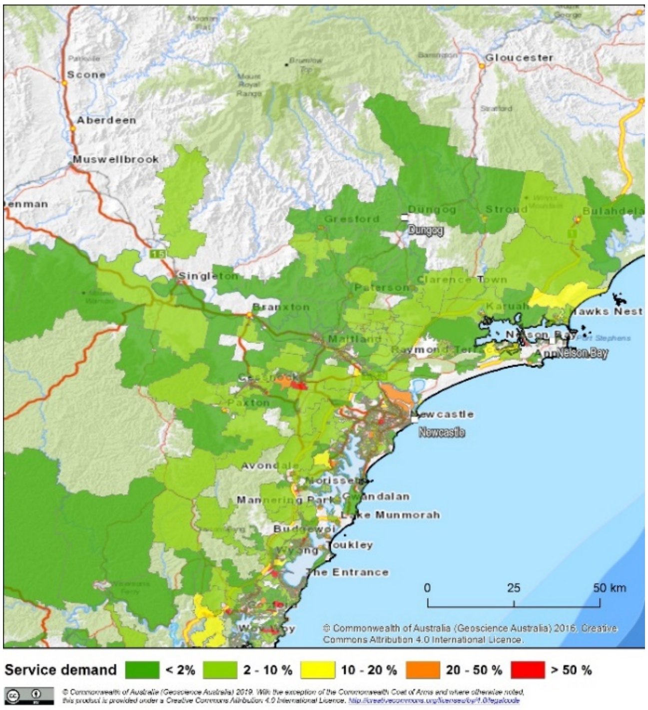


Figure 11: SES service demand averaged across SA1 areas, for the 20-22 April 2015 Dungog ECL.

The damage assessments by the EICU (**Error! Reference source not found.**) and the SES (Figure 11) show damage information that implicitly aggregates over all hazards and intermediary impacts including water ingress, flooding and tree fall. This mismatch between modelled and reported impacts is one of the primary drivers complicating the comparison of the impact modelling results with the ground truth damage data. In **Error! Reference source not found.**, the spatially selective damage survey approach inherent in the EICU data does not allow for a proper evaluation of predicted impacts in areas where no EICU reports are present. The predicted impact highlights an area north of Newcastle as a more severely affected region due to wind damage, and many of the EICU "destroyed" ratings can be found in broadly the same area. The spatial extent of the predicted impact area of negligible or more severe damage broadly captures the area in which the EICU carried out damage assessments, indicating that the model-predicted impact area is reasonably placed. In Figure 11, the predicted impact area highlights the coastal zone as the primary damage area, but the correspondence to the detailed service demand areas is rudimentary.

While the above approach is reasonable given the limitations of the observed data, improvements to the survey process are necessary to provide quantitative guidance on the accuracy of a spatial impact forecast. An ideal dataset combines the spatial coverage of the SES callout data with the damage state description of the EICU survey. Additionally, a report containing linkages between damage and the associated hazards could, for example, help to distinguish between wind and flood damage as well remove incidents related to tree fall and other events not considered within the workflow. In reality, impact is often a complex result of multiple hazards. Improved data and survey procedures will aid forecast verification as well as drive an enhanced understanding of structural response and vulnerability to a range of hazards.

Summary and the way forward

To date we combined wind hazards from a 1.5 km numerical weather prediction model with exposure data from NEXIS and heuristic vulnerability functions to calculate, without human input, spatial physical impacts on residential housing in Australia. The workflow that produced the calculated wind impact was tested on the 20-22 April 2015 East Coast Low event that was associated with three fatalities near Dungog, New South Wales. An attempt to derive case-specific empirical vulnerability functions revealed that the residential building damage (impact) in the Dungog event is not well explained by either the wind or the rain hazard as sourced from the high resolution (BARRA-SY) reanalysis data. A specific combination of the wind and the rain fields, determined by a quadratic discriminant analysis applied to 20 wind and rain hazard predictor combinations, appears to have a stronger linkage to the observed impact, underscoring yet again that physical impacts tend to be multi-hazard in origin.

The focus now, naturally, turns towards the usefulness and quality of the impact outputs that we can produce. Early verification attempts revealed that the required matching of predicted impact data with compatible damage assessment data on the ground is currently not fully achievable. On the modelling side, there is a need to capture how multiple and potentially interacting hazards lead to an integrated impact. On the damage data collection side there is a need to standardise and categorise the degree of damage and to link it to the underlying hazard or hazards that caused the damage. Moreover, an uplift in the availability of exposure data is essential for the future improvement of quantitative spatial physical impact prediction as it removes the large uncertainties associated with the need to infer building attributes from the currently available datasets.

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Peer-reviewed article

Experiences with the global impacts of climate change

Rick McRae, ACT Emergency Services Agency.

ABSTRACT

Textbox Australia's emergency managers are in the grips of climate change. The climate is changing in Canberra, where I work. In turn that is affecting the spectrum of incidents that we as emergency managers are responding to. This involves the community through the risks to the community (that we seek to mitigate).

I seek to explore this through my direct experiences on the job: as an emergency manager, as a technical expert and as a research scientist. Our climate in Canberra has changed, and has changed dramatically, starting with the 1997 El Niño event when our climate started following what is termed the "Hockey Stick Curve" (Mann et al, 1999). A typical summer now involves: extreme heat, extreme atmospheric moisture, extreme storms and extreme raised dust. By using the hockey stick concept it is clear that this is not the "New Norm", rather that the situation may deteriorate quickly.

Looking more widely, across the nation, we have seen challenging wildfire outbreaks in Queensland, Tasmania (twice) and other areas. My work as a fire behaviour analyst (FBAN) makes it clear that our prior expectations are losing their validity. What do we replace them with? Looking globally, I have deployed to Canada as an FBAN and I am collaborating as part of a global atmospheric research project looking at the growing impact of fire thunderstorms (pyroCbs). This required monitoring of smoke impact on the Greenland Ice Cap, and its potential impacts. I was in the IMT for two of the world's most significant pyroCb events. We are seeing this new wildfire problem occur in new regions, starting with Australia in 2001, but now expanding rapidly every year.

Staggering changes, devastating impacts and massive challenges - are we adapting correctly? I offer some take-home messages to help, covering observing, sharing, preparing and adapting.

Discussion

I am an emergency manager and, among other things, my publication records suggests climate change scientist. I would like to review my direct experiences with global climate change and discuss how significant these are. I would like to use my personal experiences to highlight how we should not downplay where climate change is taking us in Australia.

To start with, I have seen a number of fires that have burnt through a peat, or organic, soil layer in highland swamps, down to the basement gravel. In the 1980s I was involved in geomorphology studies in the Blue Mountains of NSW (Holland, et al., 1992a & 1992b). We took peat samples and had them radiocarbon dated. East Australian peatlands started forming at the end of the last ice age (Hope, et al., 2017). Modern fires are burning peat soils that have lain in place for ten thousand, and perhaps up to fifteen thousand years. That is unsustainable.

Speaking of peat soils, I have been deployed as a Fire Behaviour Analyst to serious wildfires in northern Tasmania on two recent occasions. On both there were "unprecedented" fires burning in or near World Heritage listed areas, with remnants of the vegetation of the ancient Gondwana supercontinent. This vegetation is definitely not meant to carry hot wildfires.

We hear a lot about the world nearing a 1.5 degree warming threshold. Average temperature over the whole year over the whole globe may be doing this, but what is happening locally and seasonally – and driving emergency incidents - can be a very different picture. Many years back I worked out an expected, sinusoidal daily maximum temperature curve for Canberra Airport. I have software that looks at daily departures from this. It looks at running average departures over 30 and 90 day windows through the summer, spanning back eighty years. I was dismayed when it showed that over some recent years we had reached a 90 day average departure of over 4°C. If you look at summer days over the last 12 months the average departure reached 4.5°C - see Figure 1.

That suggests a serious problem for Canberra with heatwaves. In recent years the Bureau of Meteorology has used the Extreme Heat Factor, or EHF, to measure heatwave severity (Nairn & Fawcett, 2013). Typically in a Canberra summer there will be a few runs of up to a week where the EHF is positive. I talk with duty officers from ACT Ambulance Service and ACT Health about how close we are to the activation trigger for the Extreme Heat Sub-Plan of the ACT Emergency Plan (now reviewed in 2019). Usually we get close, but do not reach the trigger point. Community advisory messages may be issued by ACT Health.

In the 2018-2019 summer we exceeded the trigger for a four day period (Figure 2). This was the most extreme heatwave on record for Canberra (Bureau of Meteorology, 2019).

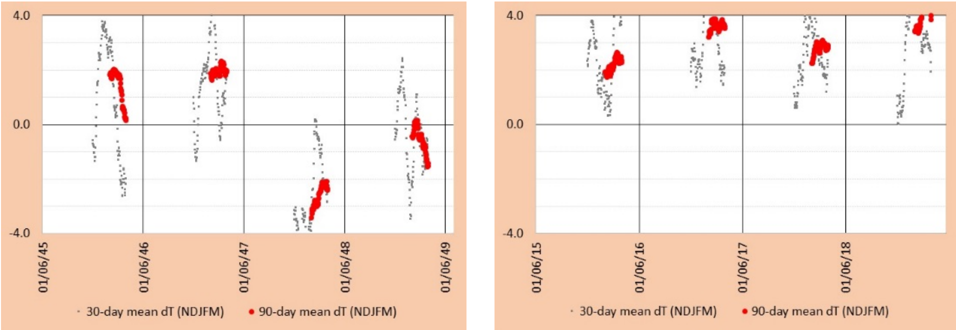

Figure 1: A comparison of summer temperature anomaly (dT) trends for Canberra Airport across two four year blocks. [Data: BoM, Plot: McRae]. (A) The past: temperature anomaly fluctuations vary around a mean of zero degrees, using data for July 1945 to June 1949 as a representative interval. (B) Modern reality: temperature anomaly fluctuations vary around a higher, and rising mean. (Maxima: 30d to 7.4°C, 90d to 4.5°C) Data for July 2015 to June 2019.

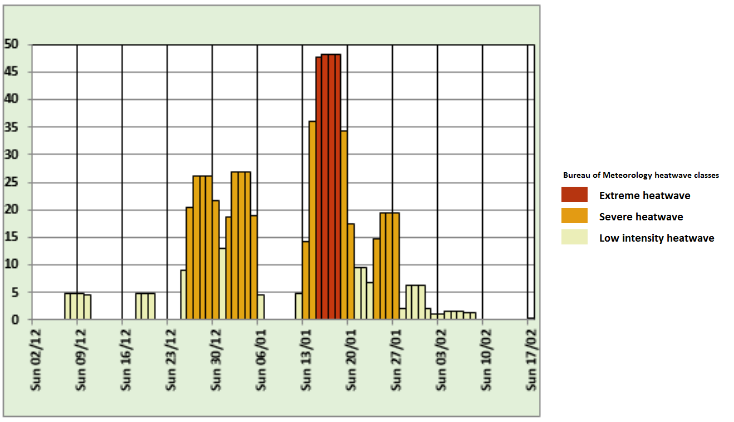

Figure 2: Canberra EHF plot fort summer 2018-2019, showing 54 days over 0 in 3.5 months. [Data: BoM, Plot: McRae]

Canberra's record temperature is 42.2°C, recorded on 1st February 1968. In eighty years of records we had logged fifteen 40°C days. In one month, January this year, we logged five more. The underlying frequency of 40°C days can be modelled mathematically, and this shows roughly a doubling every 9 years since 1997.

Climate scientists coined the term "hockey stick graph" for a depiction of the onset of new, hotter trend in the global climate. (See discussion on this at https://www.newscientist.com/article/dn11646-climate-myths-the-hockey-stick-graph-has-been-proven-wrong/) Data modelling from the US (berkeleyearth.org) shows that for many sites in south-eastern Australia climate data trends could be colloquially termed to be hockey stick curves, and that their inflection points occurred during major El Niño events, such as 1997. The 1997 inflection point in Figure 3 makes it look like a hockey stick graph. We can look at the impacts of the hockey stick on 40°C days by referring to the 1939 to 1997 frequency (Figure 3). The trends since 1997 are very significant (Figure 4).

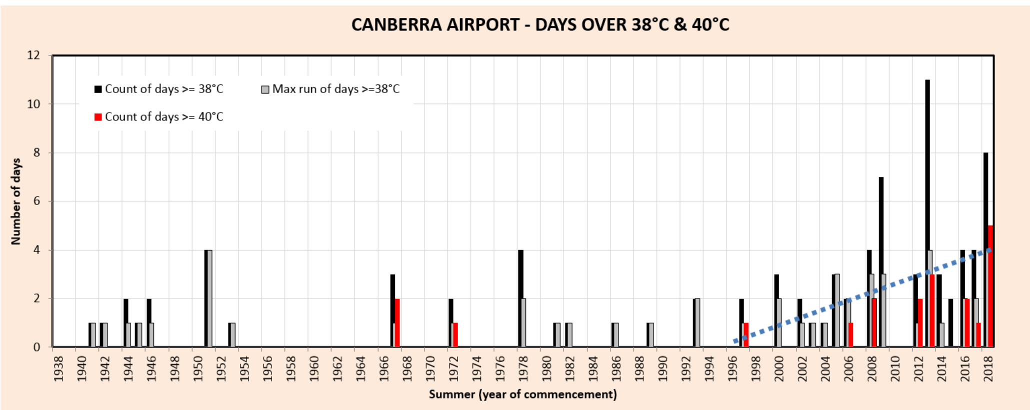

Figure 3: Annual counts of hot days for Canberra Airport [Data: BoM].

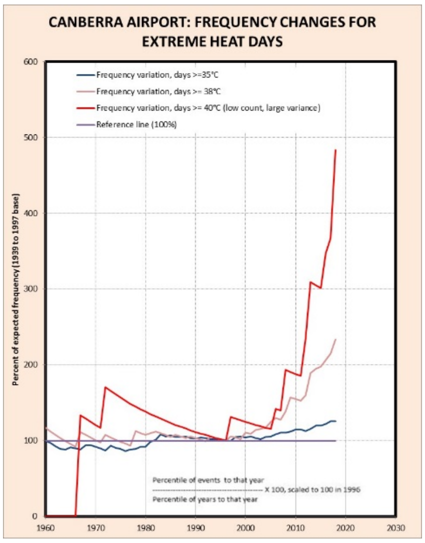

Figure 4: Canberra hot day relative frequencies, with 1997 values set at 100%. Compared to that baseline: 35°C days are now 30% more common, 38°C days are now 133% more common, and 40°C days are now 383% more common [Data: BoM, Analysis & plot: McRae].

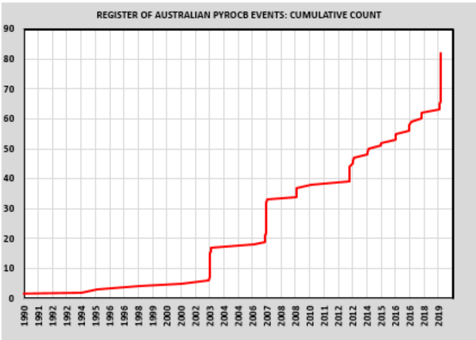

Figure 5: Australian pyroCb register [Di Virgilio, et al., 2019].

The frequencies hot days are rising so quickly that there is now room to fit a 45°C day. A key thing about hockey stick curves is that there is no new normal. Over the next 9 years there could be some major new records set for Canberra.

When people think heat in Australia, they naturally think bushfires. There is a clear and widespread expectation of major impacts on bushfire activity. Thinking in terms of a McArthur Meter (Luke & McArthur, 1978), hotter weather means rotating the dials clockwise, giving higher FDI values. Easy. Alas, there are some important reasons why it is not easy.

Globally there has been detailed scrutiny of wildfire blow-up events. These happen when fires couple with the atmosphere overhead (Sharples, et al., 2016). This involves processes not found on a McArthur Meter. Normally if you know the weather, the terrain and the fuel you can predict what the fire will be doing. This is called steady-state fire behaviour. In dynamic fire behaviour, interactions occur between the weather, the terrain and the fire. These can produce very different fire behaviour. In an unstable atmosphere, coupling between the fire and the atmosphere allows the plume to push to high levels and perhaps reach the Stratosphere (Fromm, et al., 2010). This most extreme form of wildfire behaviour is known as a fire thunderstorm, pyro-cumulonimbus or pyroCb.

In 1978, a global monitoring project commenced with the launch of the NIMBUS 7 weather satellite. Ever since, scientists have looked for injections of aerosol into the otherwise clean upper atmosphere (Fromm, et al., 2010). While looking for volcanic ash and the signs of nuclear tests, they also picked-up wildfire smoke in the Stratosphere. This is the tell-tale sign of a pyroCb.

From 1978 until 2001, Australia had experienced two confirmed pyroCbs and two other possible events (McRae, et al., 2015). Since 2001 another 78 events have been logged (Figure 5). That includes a 33% increase during 2019**.**

This staggering shift in frequency is a major challenge for Australia. In 2003 Australia's fire services knew very little about pyroCbs, or of the blow-up events that cause them. Then the 2003 ACT fires impacted on Canberra (Fromm, et al., 2006). I was the Planning Officer on the 18th of January, and it was clear in hindsight that we had no idea what was going on. The lack of knowledge about extreme fire behaviours and their complex interactions with the environment meant that inquiries set up to review the 2003 ACT fires were limited in their ability to explain how the fires behaved and why that behaviour was not predictable. It was only in later years that the science was done and formalised. The previously unknown fire behaviours identified in the 2003 ACT fires made those fires amongst the most scientifically important wildfires in Australia. That is a big claim but it is easily justified.

First documentation of the impacts of an Australian pyroCb on the atmosphere (Fromm, et al., 2006).

First ever confirmed pyro-tornadogensis event (McRae, et al., 2013).

The discovery of Vorticity-driven Lateral Spread, a main driver of blow-up fire events (Sharples, et al., 2012).

Validation of the Nuclear Winter Hypothesis (Fromm, et al., 2006).

The 2003 fires were closely scrutinised by the global science community. I co-authored a prominent science paper on them along with colleagues from Australia, the US, Canada and Israel (From, et al., 2006). They were among the most severe fire events ever logged, so Australia had gained international attention.

Six years later the Black Saturday fires in Victoria became the most intense fire event ever recorded (see for example Dowdy, et al., 2017), and then Australia became the source of a series of key case studies (such as Fromm, et al., 2012 and McRae, et al., 2015).

Canada, the US and north-eastern Asia (mainly Siberia and Mongolia) have long experienced pyroCbs during major fires in the boreal forests. In 2001 Australia joined them in routinely producing pyroCbs. In 2010 western Russia joined term, followed by Europe and South America in 2017. It is likely that southern Africa joined in 2018. This is a rapid expansion of a major problem (McRae, 2019).

To summarise the problem in Australia, the risks to the community from steady-state bushfires is, and has long been, well managed by fire services. So, in rough terms, 5% of the damage comes from these 95% of the fires. The other 5% of fires, driven by dynamic fire spread processes, cause 95% of the damage.

I deployed to British Columbia as an FBAN in 2017. They were having their worst ever fire season. On the 12th of August they experienced the most severe wildfires ever recorded, globally (Peterson, et al., 2018, Struzik, 2019). So for the second time in my career I was in the IMT for a globally significant wildfire.

In Quesnel we were sitting for day after day in heavy smoke. We could see parts of the fire ground from the air, but there were large tracts that were no-fly due to a lack of visibility. There were days when it was clear that the fires would be exhibiting extreme behaviour and that fire crew safety was a priority. I knew that satellites could see a lot more of a fire when a blow-up events occurs, and that there was potential for this happen. I alerted my global research collaborators and satellite images were given close scrutiny.

Since 1978 Stratospheric aerosol loads had been measured on the 0 to 15 scale for the Aerosol Index (AI). On the 12th of August AI got to 45. Systems had to be re-designed to handle it (Colin Seftor, pers. comm., 2017).

As the smoke load was cleared by a wind shift, the clear air had no convective cap, and free-convection occurred in eight separate plumes in the next few hours. This smoke was injected to high altitudes and moved north. Unfortunately just to the north, close to Great Slave Lake there was an east-west line of fire over 250km wide that was injecting massive smoke loads to lower levels. So north of GSL the air had elevated smoke concentrations across most of the troposphere (Figure 6).

What damage could this do? It crossed the North Pole and entered Russia. It crossed the Greenland Ice Cap. One of the reasons that the north polar ice cap is melting is discoloration of the ice. In briefings we discussed how pumping over it the largest smoke injection ever seen cannot be a good thing (Thomas, et al. 2017 & Hsu, et al., 1999), and how this may contribute to climate change. There were settlements in the Yukon and North West Territories where, for three days in a row, the skies were darkened and there was none of the expected cycling of temperature through the day. This same effect had been demonstrated from the 2003 Canberra fires (Mitchell, et al., 2006 & Fromm, et al., 2006).

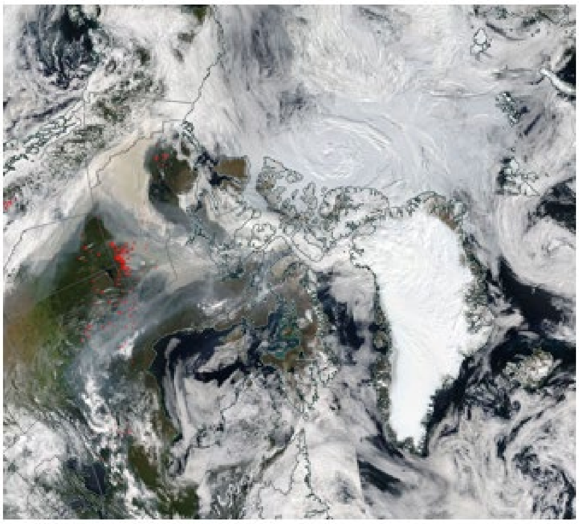

Figure 6: Fire hotspots (red dots) and smoke, northern Canada, 13th August 2017 [Image & Data: NASA WorldView].

Just before I travelled to Canada, there was on-line discussion of a wildfire burning in Greenland (see Earth Observatory website). No life or assets were under threat from this fire, but it was a clear sign that things were getting unusual. Recently, there were more wildfires there, near Sisimiut.

I wish that I would see no more clear signs of global climate change while I work. I suspect, however, that I will. The 2018-2019 fire season had a number of key aspects to it that supports this conclusion.

The fire outbreak in SE Queensland was unprecedented. While satellite imagery often hinted at coupled fire-atmosphere events (see links on http://www.highfirerisk.com.au/h8_videos.htm), these did not produce pyroCbs. The combination of drought and weather caused fire impacts in places and in vegetation types that are not meant to see wildfires. The burning of tropical rainforest is likely to cause long-term damage.

The Kimberley region saw some widespread fire activity (Figure 7). The whole region was constantly producing non-fire Cbs, but it also seems to have produced a tropical pyroCb with lightning. The key aspect of this is that, prior to this, there had never been a confirmed pyroCb in the tropics. Anywhere. In either hemisphere. Confirming tropical pyroCbs requires a high level of confidence, to allow them to be distinguished from Cbs. If tropical pyroCbs are now possible, then a lot more tropical vegetation is coming under threat.

Unfortunately, in July and August 2019 the international group confirmed four tropical pyroCbs in tropical savanna in Bolivia. Smoke from one of these passed over Canberra.

Tasmania, as I mentioned earlier, had serious wildfires in the 2018-2019 summer. A lot of effort was expended keeping fire out of pristine Gondwana-relict forests around the Walls of Jerusalem, and critical impacts were closely avoided.

The Victorian high country saw a tightly clustered group of pyroCbs. While this was not unprecedented, the repeated burning of these areas may have long-term ecological and hydrological impacts.

The ACT has seen major dust storms over the years. This year we saw a lot of them. This reflects the severity of the inland drought and the impacts on rangeland ecosystems. We gained skill in alerting our community to the potential for more dust events, and "Dust Event" went from a novelty to an entry on the standard hazard list, along with bushfires, floods, storms and so on.

The most interesting aspect of this summer that reflects climate change was the grass curing. The usual rule book was thrown out - for the first time since I started looking, three decades ago, the curing value basically flat-lined. It sat within 10% points of 70% for nine months, between July and March (Figure 8). Typically in Canberra curing is high at the end of winter, due to frost, then it plummets for the spring growing season, and rises steeply after the onset of summer heat. None of these happened.

This reflects the change in the balance between heat and moisture. The impacts of hot air on grasslands are fairly clear, but hot air has the capacity to carry more water and the potential to produce more thunderstorms. The convergence of inland and coastal air masses produced regular storms over the ACT. The grass was able to hang on “a bit green”, but never built-up high fuel loads. All the while grazing pressure was intense.

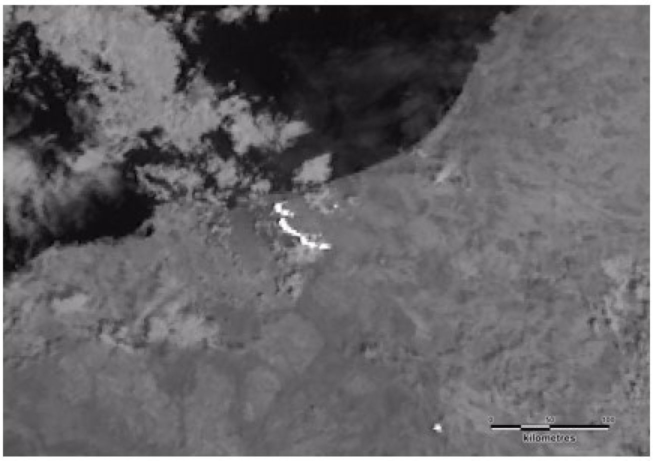

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Figure 7: Infrared view of flames 120 km east of Port Hedland, WA, and other fires on 15th November, 2018. Fire shows as white [Himawari-8 Imagery: SSEC].

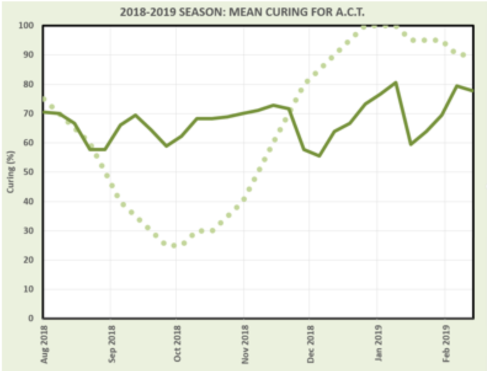

Figure 8: Canberra curing trend, 2018-2019 (solid line), compared to typical season pattern (dotted line) [Data: LandGate, WA, Plot: McRae].

In February 2018 we had a 100 year Average Return Interval flash flood event in North Canberra. This was a salient event, driven by the Dew Point Temperature exceeding 21°C (an extreme value for Canberra). This is still within inter-annual variability, but may become more likely in the future (AdaptNSW).

So, what are my "take home messages"?

Firstly, for me, as an active FBAN, climate change is no longer just the elephant in the room, it is the big angry grizzly bear threatening to tear our limbs off. Secondly, it has changed what fire services have done in Australia for the last 18 years, and we have barely acknowledged this. Thirdly, other allied services are increasingly having to deal with the impacts of climate change – for example town planning, health services, ambulance services – and we cannot tackle this in isolation. Fourthly, understanding the problem requires broad-scale collaboration. I am routinely liaising with researchers in numerous countries, and by working together a more comprehensive picture is developed. Fifthly, do as I have often done, and change your foundation concept set completely. We are all learning rapidly, and this will only accelerate. Finally, it is only by being prepared to observe what goes on around us that we will learn. Build observational capabilities that can be deployed at major incidents, and also develop the tools to create intelligence from the resulting data. Observe, share, prepare and adapt.

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ABSTRACT

A proposed integrative conceptual framework has been developed for the Australian context to promote understanding, uptake and action toward the Paris Agreement for Climate Change, the Sendai Framework for Disaster Risk Reduction (DRR) and the 2030 Agenda for Sustainable Development using the National Framework for Disaster Risk Reduction. It is hoped that through compatibility with the existing Australian Work Health and Safety culture, this integrative framework can help promote understanding, uptake and action. WHS 2.0: World Health and Safety is designed to 'bolt' disaster risk reduction values and actions onto existing Work Health and Safety values and infrastructure in ways that are straight forward to understand. Implementation of such a conceptual framework will have positive impacts across society in terms of improved social, cultural, environmental and financial resilience.

Peer-reviewed article

WHS 2.0 World Health and Safety: integrating disaster risk reduction and sustainable development into every workplace using the Sendai Framework, Paris Agreement and the Sustainable Development Goals

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Introduction - identifying a gap in understanding and implementation of existing frameworks

Lofty frameworks are not all easily translatable into people's Key Performance Indicators. One might readily ask what the Sendai Framework, Paris Agreement and the 2030 Sustainable Development Agenda have got to do with employment arrangements. A manager might also consider whether they could implement any of the frameworks and still afford to pay staff? The world is changing, and Paris, Sendai and the Sustainable Development Goals (SDGs) are designed to help society adapt. The kinds of changes they urge will certainly reduce harm in this new era of risk (United Nations Framework Convention on Climate Change (UNFCCC) 2015, United Nations International Strategy for Disaster Reduction (UNISDR) 2015, UN General Assembly 2015).

The National Framework for Disaster Risk Reduction has translated the Sendai Framework for Disaster Risk Reduction into a framework for action in the Australian context. While acknowledging that governments and large industry hold responsibility for substantial change, it directs all sectors to manage and reduce disaster risks that fall within their scope of responsibility, neither creating new risks nor exacerbating existing risks. It also outlines that investment in disaster risk reduction can have broad social and economic benefits across all sectors regardless of whether a hazardous event occurs (Department of Home Affairs 2018, p. 3-4, p.21). Disasters cost Australia $18 billion year (Deloitte Access Economics 2017).

By not only managing disasters, but also managing the risk of disasters the effect will be to:

- Reduce disaster induced harm
- Reduce disaster induced costs
- Increase quality of life and opportunities (Department of Home Affairs 2018)

The Risk Informed Development paper (Opitz-Stapleton et al. 2019) says that all new developments need to be risk informed which means that world is no longer accepting a 'blind-eye' approach to disaster risk in human decision-making frameworks. While this significant change is increasingly well understood, there is still a substantial gap in terms of implementing risk informed development and decision-making frameworks in Australian workplaces, including even Emergency Agencies whose primary role is involved with Disaster Risk Reduction, or in Environmental Agencies whose primary role is in environmental resilience.

What is required is prompt uptake of Disaster Risk Reduction and Sustainable Development, yet many people may be:

- Unaware of the concepts
- Unaware how to integrate them into operations
- Unaware how to pay for required changes.

While the Sendai Framework, SDGs, Paris Agreement and the National Framework for DRR are related, reference each other, and call on 'all of society' for implementation, it can still be confusing for any individual, organisation or government department to understand the relationships between them and how they can be implemented within current workplace operations. Furthermore, without integration into core values how can a company or society justify efforts towards the goals? As such the National Framework for Disaster Risk Reduction remains the terrain of high-level executives in large operations and is not yet achieving a groundswell cultural shift even though we are one-third through the 15-year commitment of Sendai, Paris and the SDGs. Implementation is voluntary, haphazard therefore comprehensive action is not observable.

Siloed frameworks under consideration for an integrative conceptual framework

There are several frameworks intended to reduce disaster risk and increase community, cultural and environmental resilience which this proposal hopes to interlink.

Work Health and Safety legislation and culture has improved safety and reduced workplace injuries in Australia since the 1970s with notable advances since legislative updates in 2002 and 2012. The underlying goal is to value human life over profits (Inspire Education 2013). The current strategy, Australian Work Health and Safety Strategy 2012-2022 (Safe Work Australia 2012) aims to further reduce workplace deaths by 20 per cent, as well as time-off claims and musculoskeletal injuries by 30 per cent. The Hierarchy of Hazard Controls is a commonly used system of understanding different types of hazard control. There are laws, strategies and international standards OHSAS ISO 18001 and AS/NZS 4801 designed for ensuring that organisations have Occupational Health and Safety and Occupational Health and Safety Management Systems.

Environmental Resilience has been developed through EMS – ISO 14000 series to promote effective environmental management systems in organisations through standardisation. The ISO 14000 series began in 1996 and was revised in 2004 and 2015 and relates to the ISO 50001 Energy Management System.

Business Continuity tools are broadly available through both government and ISO standards. Examples include Get Ready NSW, Australian Council of Social Services (ACOSS) Six Steps, Business.gov.au and the Emergency Management frameworks, ISO 22301 – Business Continuity, ISO 31000 – Risk Management and ISO 27001 - Information Security.

The Paris Agreement on Climate Change has been internationally ratified with the purpose of reducing the risks associated with climate change by keeping global warming well below two degrees above pre-industrial temperatures.

The Sendai Framework on Disaster Risk Reduction is the global blueprint to reduce disaster risk. It is a 15-year international framework that shifts focus from disaster management to cross-sectoral disaster risk management. It targets risk awareness, risk governance, risk management financing and actions to reduce risk and build better. The expected outcome across the next 15 years is to realise 'the substantial reduction of disaster risk and losses in lives, livelihoods and health and in the economic, physical, social, cultural and environmental assets of persons, businesses, communities and countries.'

The 2030 Agenda for Sustainable Development are a whole of society approach towards sustainable development. The SDGs establish that sustainable development and disaster risk reduction are interconnected, that without disaster risk reduction, gains in sustainable development, which have taken years to establish, can very quickly be reversed. Conversely risk-informed sustainable development strengthens the very drivers of resilience such as health and wellbeing, sustainable cities and life on land which enable people, environments and economies to respond and recover well when extreme events or disasters occur.

> *Risk-informed development allows for development to become a vehicle to reduce risk, avoid creating risks and build resilience. Only resilient development can become sustainable development; sustainable development initiatives will fail unless they are risk-informed. Risk, resilience and sustainability knowledge and actions need to go hand-in-hand.*
>
> Opitz-Stapleton et al. (2019, p. 10)

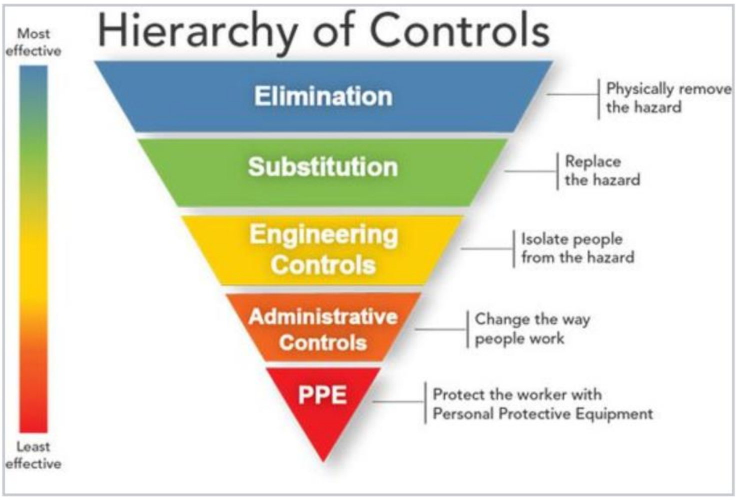

Figure 1: The Hierarchy of Controls, which is commonly known in Australian workplaces. Infographic by the US National Institute for Occupational Safety and Health (NIOSH 2015).

One key driver of resilience underlying the Sustainable Development Goals is trust between people, which is social capital, without which sustainable development could not be viable. Corporate social responsibility (CSR) is a voluntary model with which organisations are generating social capital. Potential coherence between corporate social responsibility, social capital and the Sustainable Development Goals could be investigated further.

The National Framework for Disaster Risk Reduction (Department of Home Affairs 2018) steps forward from the National Strategy for Disaster Resilience (Council of Australian Governments (COAG) 2011) and integrates the Sendai framework for Disaster Risk Reduction for the Australian context, including the Sustainable Development Goals and the Paris Agreement. It clearly articulates the drivers for change and outlines four key priorities for action; understanding disaster risk, accountable decisions, enhanced investment, and governance, ownership and responsibility. The Framework outlines that while Governments and large industry need to take coordinated action to reduce disaster risks, all sectors must cultivate a culture of disaster risk reduction awareness and action (Department of Home Affairs 2018).

The National Framework for Disaster Response complements the National Framework for Disaster Risk Reduction and the Sendai Framework. Rather than being a single document, it includes various disaster response arrangements such as the AIIMS (Australasian Interagency Incident Management System) and laws such as the State Emergency Service Act.

Problem identified – Poor implementation and enduring risk exposure

Climate change is increasing disaster risks while population growth and urbanisation is exposing more people to those risks. Since 2007, Australian disaster recovery has cost an average of $18 billion per year which is predicted to rise to $39 billion per year by 2050. This calculation does not include predicted effects of climate change, nor the intangible costs of disasters such as ongoing social and economic impacts which are estimated to be equal to or higher than the tangible costs (Deloitte Access Economics 2017, cited in Department of Home Affairs 2018, p. 6).

> *As disaster risk increases, the capacity of communities and systems to be resilient is diminished. This [National Framework for Disaster Risk Reduction] focuses on reducing disaster risk as one key component of enabling resilient communities and economies in Australia.*
>
> Department of Home Affairs (2018, p7)

Meanwhile Australian workplaces and economies grapple with and perhaps resist (Phelan, Henderson-Sellers & Taplin 2012) understanding the agreements, their relevance and applicability to each operation, even as 95% of companies in the Global Crisis Survey acknowledge that they are anticipating a crisis of some description (PricewaterhouseCoopers 2019). However, the agreements for disaster risk reduction cannot be effectively implemented if it is unclear how they relate to each workplace and work role.

Hypothesis – An integrative conceptual framework could improve outcomes

If the frameworks of disaster risk reduction - Sendai, Paris and the SDGs - can be understood in a way which is compatible with existing cultural infrastructure, it will result in improved implementation and consequent reduction of risk, harms and cost across the Australian economy.

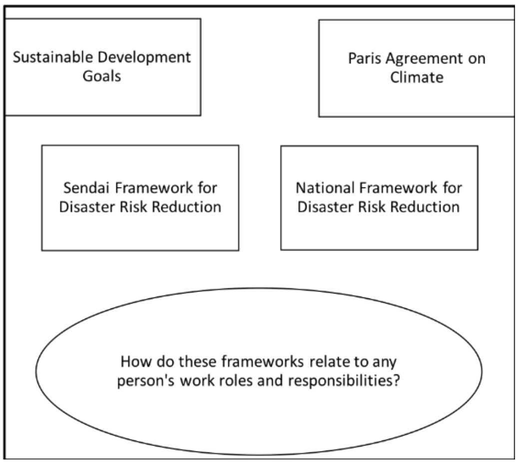

Figure 2: The links between these agreements and individual work responsibilities are not clear.

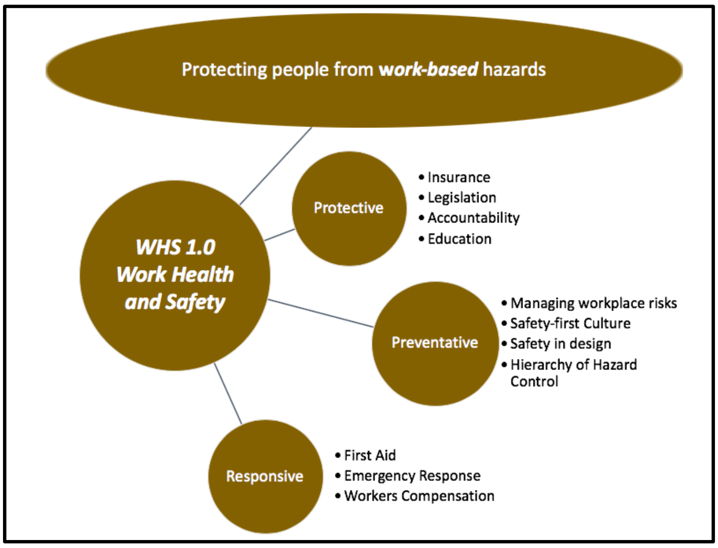

Figure 3: Work Health and Safety is a system that values people over profit. It protects people from work-based hazards through minimising the chances of people getting hurt while also ensuring that there are well understood systems to minimise harm when things do go wrong.

Proposal and discussion – An integrative conceptual framework: WHS 2.0

Broadly speaking WHS 1.0 Work Health and Safety is about reducing dangers in a workplace and knowing what to do when things do go wrong. It is a value of care for people in the context of everything that could go wrong in a workplace. Workplaces are complex interacting systems and as such, WHS legislation has ways of managing complex risks.

WHS 2.0: World Health and Safety is a proposed integrative framework which recognises that workplaces are part of the complex systems of the world. It acknowledges that exercising a community of care within the workplace is not complete without considering and managing risks for the hazards of the world. Every workplace in Australia has a fire evacuation plan but WHS 2.0 works towards ensuring every workplace also has relevant World-Health and Safety Emergency Procedures such as utility failure, flood and bushfire action plans. It asks for example how to communicate effectively with staff in the case of an event when telecommunications and/or transport systems may be disrupted. It asks how to exercise duty of care for staff and clients in such an event, and how to design resilient work systems that enable flexibility and problem solving for an emerging situation which does not fit a prescribed response plan.

Design for collaborative survival rather than competitive advantage is a priority. This is at the heart of the transformation of the business model. Conventional business resilience and contingency planning has focused on attaining a competitive advantage to leverage profit from being the last business standing in a crisis. However, this is counter to the Sustainable Development Goals which focus on 'leaving no-one behind'. Like WHS 1.0, WHS 2.0 contains a moral directive to value people over profit. Therefore, crisis response as well as business as usual should include values of sustainable development and corporate social responsibility. As WHS 1.0 has provided improved outcomes for the whole economy through its embedded value, so will WHS 2.0.

Figure 4: World Health and Safety is a proposed integrative framework. It is also a system that values people over profit. It protects people from world-based hazards through minimizing the chances of people being harmed while also ensuring that there are well understood systems in place to minimise harm when things do go wrong.

These values will underpin business models which profit through supporting the wellbeing of the whole, rather than models which profit through the suffering of others such as modalities of disaster capitalism. In this frame, crisis response is not only about maintaining business continuity to maintain market-share, but to follow duty of care for staff and clients. More broadly that an organisation could aim to maintain business continuity to provide services and/or staff for disaster prevention, response and recovery.

In New Zealand there has already been some progress toward integrating the Sendai Framework for DRR into the Health and Safety at Work Act for example through interfacing with the 2017 earthquake-prone building regime (Ministry of Business, Innovation and Employment (NZ) 2017). In a parallel integrative project, also in New Zealand, Phibbs et al. (2016) have synergised the Sendai Framework with Public Health concepts to facilitate better understanding of Sendai's holistic approach to risk reduction.

Relating the Hierarchy of Hazard Control from WHS 1.0 to WHS 2.0

The hierarchy of hazard control can be used to understand and manage risk throughout organisations from strategy level, to training, to everyday work practice. It could also be used to understand and integrate the big three frameworks for disaster risk reduction; Paris, Sendai and the SDGs. For example if there is a risk identified in a workplace, such as a dangerous bandsaw, the Hierarchy of Hazard Control can be used to manage this risk, and reduce potential harm. In identifying and managing world-based hazards the same Hierarchy could be applied.

Priority 1 Elimination poses the question of eliminating the risk. It asks whether the workplace can do without the dangerous bandsaw. In the case of WHS 2.0 World Health and Safety includes managing global hazards which result in increased risks for all, such as climate change. Agreements which relate to eliminating or mitigating these hazards include the Nuclear Non-proliferation Treaty, and the Paris Agreement on Climate. A WHS 2.0 policy would be consistent with and actively implement such agreements.

Priority 2 Substitution poses the question of safer options, for example renewable energy, which are consistent with mitigating climate risks and the Paris Agreement.

Priority 3 Engineering asks if it is possible to redesign or move people away from a hazard. In the case of the bandsaw, it would include design safety improvements such as a better guard and automatic power shutoffs. In the case of WHS 2.0, Engineering controls would include elements of Sendai Framework for Disaster Risk Reduction such as understanding disaster risk, managing disaster risk and reducing disaster risk through building better resilient infrastructure.

Priority 4 Administration seeks to manage risk through providing training and accountability. In the case of the bandsaw, a user would for example complete training and their fatigue levels might be monitored. In the case of WHS 2.0, disaster risk governance (UNISDR 2015) seeks to attribute disaster risk exchanges more explicitly through clear agreements.

Priority 5 Personal Protective Equipment or PPE offers a final layer of protection when all risks cannot be managed. Safety glasses and hearing protection offer immediate protection for the worker using the bandsaw. In the case of WHS 2.0, the quality of resilience is what is needed to be able to 'bounce back' when a risk cannot be completely controlled. In order to build resilience into society, the Sustainable Development Goals provide a broad-based ground-up framework for sustainable (risk informed) development which can improve quality of life in ways which give people and communities better capability to 'bounce back' from adverse circumstances that could not be prevented.

Considering that world-based hazards can be reduced, not eliminated, ground-up sustainable development which is compatible with both risk management and hazard elimination will produce resilience and wellbeing in people's daily lives, thereby reducing vulnerability, risks and hazards.

A Hierarchy of Hazard Controls prioritises top down change whereas it can be seen that Work Health and Safety also goes hand in hand with a bottom up safety-first culture where people look out for hazards and take care for each other's wellbeing. When top down and bottom up approaches are used, governance systems take responsibility yet also empower all staff to become equipped and act effectively.

Through risk mitigation, risk management and building resilience, organisations can establish a WHS 2.0 system which works to reduce disaster risk from the sky down (Paris Agreement reducing greenhouse gasses) and ground-up (SDG 15 - Life on Land), and broadly to provide enhanced social and environmental quality of life with immediacy.

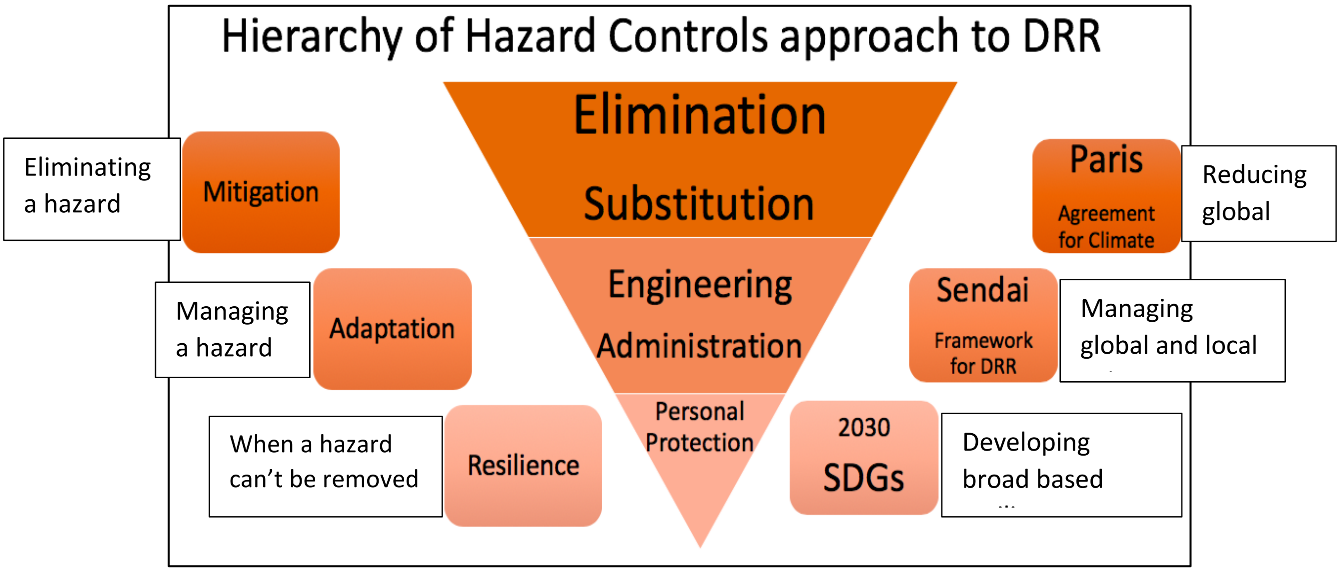

Figure 5: A hierarchy of hazard controls approach to disaster risk reduction (DRR) which visualises interconnections between mitigation, adaptation and resilience with Paris, Sendai and the SDGs.

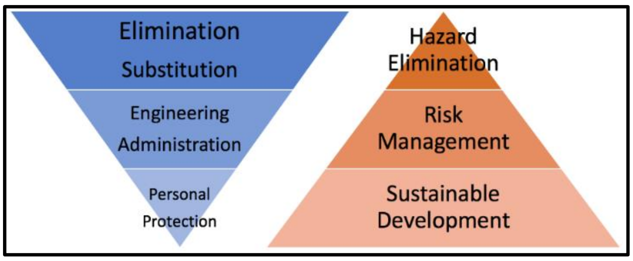

Figure 6: Top-down and bottom up hazard elimination and sustainable development.

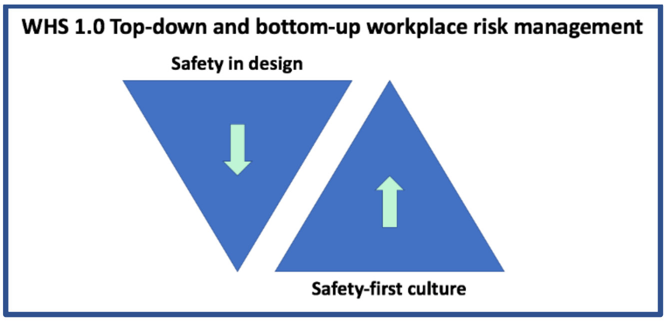

Figure 7: WHS 1.0 Top-down and bottom up workplace risk management.

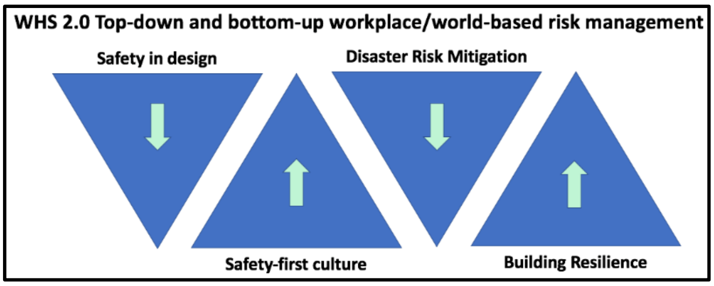

Figure 8: Working from the sky to the ground and ground-up gives both poetry and meaning to World Health and Safety which integrates Paris Agreement, Sendai Framework and the 2030 Agenda for Sustainable Development.

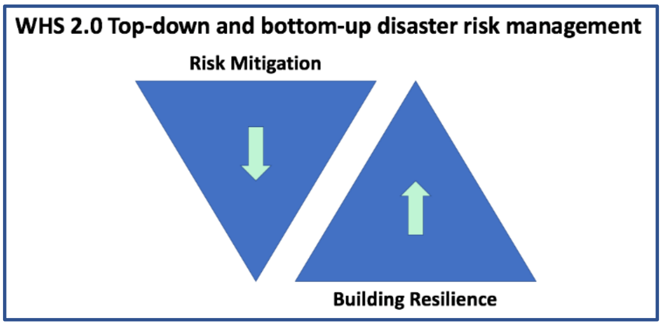

Figure 8: Combining top-down and bottom-up approaches is consistent across Work Health and Safety and World Health and Safety. This can be transposed into a logo concept for WHS 2.0 as illustrated.

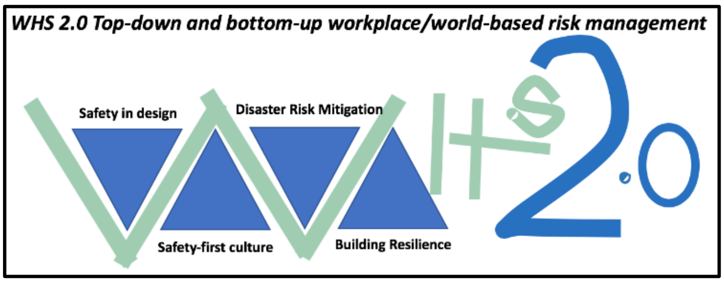

Figure 9: WHS 2.0 is a straight forward concept which demonstrates relevance between people's working lives and the International frameworks for disaster risk reduction.

Establishing baselines and monitoring success

Suggested first steps for any organisation could be to engage the existing WHS committee to evaluate baseline policies in terms of disaster preparedness such as communicating effectively with and maintaining duty of care of staff and clients during world-based crises such as utility failure or super-storm.

Another step would be to engage business continuity planning so that operations can be maintained throughout various foreseen and unforeseen crises.

The third stage would be to do a gap analysis, baseline evaluation of values, policy and practice to develop a strategy to minimise and monitor the disaster risk impacts of the organisation. The intent is to monitor that each operation is not exacerbating world-based disaster risks. This could be done through implementing:

- Paris Agreement reductions in greenhouse gas emissions
- Complying with the Sendai and National Frameworks for Disaster Risk Reduction
- Identifying how to support local and distant drivers of resilience by implementing the Sustainable Development Goals, environmental and cultural resilience policies

A model of business resilience which increases net disaster risks is now contra to national and international standards (Department of Home Affairs 2018). Through the proposed integrative framework of WHS 2.0 organisations, managers and staff could more readily understand and implement the international frameworks for reducing disaster risks. They can provide net benefit through delivering services and products that can also reduce vulnerability of staff, clients and environment. WHS 2.0 World Health and Safety enables organisations from all sectors to clearly see and apply next-level duty of care for people and environment which national and international governments have so clearly mandated and for which the economics are compelling (Deloitte Access Economics 2017; Department of Home Affairs 2018).

The questions as to investment capital for disaster risk reduction and emerging sustainable business models remain unexplored in this paper, however the costs of not adapting are clearly escalating. The Department of Home Affairs (2018) urge accountable decision making and enhanced investment for disaster risk reduction as priorities two and three of the Framework. The Framework includes empowering communities, individuals and small businesses to make informed and sustainable investments and urges all entities to consider potential avoided loss (tangible and intangible) and broader benefits in all relevant decisions (Department of Home Affairs 2018, p. 9).

While the question of paying for disaster risk reduction remains open, it is hoped that this proposed integrative conceptual framework, WHS 2.0 World Health and Safety, is of assistance to organisations and workers of all types in:

- Gaining awareness of the relevance of disaster risk reduction
- Developing ways to integrate disaster risk reduction into their daily and strategic operations through existing Work Health and Safety frameworks

Conclusion

There is an innate connection between the values of Work Health and Safety and the values of Disaster Risk Reduction. Using a Work Health and Safety lens to apply the values and goals of disaster risk reduction across every workplace can help to make DRR concepts accessible to people in all parts of society and stimulate urgent, complex-systems implementation in a way which truly increases resilience. Next steps for this research are to establish some case-study organisations to document the application, effectiveness and impact of WHS 2.0 policies and practice.

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Peer-reviewed article

Safety awareness of firefighters and their perception of fire risks in cladding fires

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ABSTRACT

Owing to the extensive use of polymers in building products, there is the urgent need to resolve the present fire risks of highly combustible cladding products. Apart from understanding the risks associated with cladding materials on buildings, it is also essential to evaluate the underlying risks of existing non-compliant materials on buildings for residents, owners, and the public, and for firefighters during the management of such fire events. In this article, a fire risk perception survey was constructed by a collaborative effort from Fire and Rescue New South Wales (FRNSW) and University of New South Wales. The survey can be subdivided into four major parts, i) demographics, ii) risk awareness and identification associated with cladding material, iii) the firefighter's own perceived risk associated with cladding fires and iv) risk mitigating behaviours. The majority of the questions are designed with five distinctive levels (i.e. ranging from rare to almost certain, or negligible to very high), and it will be distributed to firefighters from major states and rural fire agencies around Australia. The results will formulate a large and comprehensive database to increase our understanding of the firefighter's risk perception associated with combustible cladding materials.

Introduction

Existing cladding materials such as polyethylene (PE) sandwiched between steel panels, wood-plastic composites and high-performance concrete with polymeric blends have been identified as the root cause in a number of severe fire incidents. These incidents include the Dubai skyscraper fires in 2015 and 2016 (Bannister 2015), Lacrosse Tower fire in Melbourne 2016 and the London Grenfell Tower fire in 2017 (Pasha-Robinson 2018). Furthermore, toxic emission from the pyrolysis of polymers, especially asphyxiated gases such as CO and HCN are responsible for the majority of deaths and injuries in building fires (Morikawa et al. 1993). Recently reported building cladding fires in Australia as well as in other countries have certainly created a heightened awareness by the public and have propelled governmental authorities and commercial identities to act on the risks associated with the non-compliance of such structures that have erected in the building and construction landscape (Senate 2017, 'The Grenfell Tower Inquiry' 2018, Czoch and Shukla 2018). With the constant increase in population density and compactness of building occupants on both the work and residential environment in major cities in Australia (especially Sydney and Melbourne), it is paramount to resolve the present fire risks of highly combustible building products.

Composite sandwich panels (cladding) are commonly found as surface finishes in building façade systems or Exterior Insulation Finishing Systems (EIFS) and External Thermal Insulation Composite Systems (ETICS). A diagram of a typical exterior façade system is shown in Figure 1. These systems are designed to be cost-effective solutions for thermal insulation, weather resistance and aesthetic external wall finishes. Composite sandwich panel may be included in the initial building design or added at later stages as part of refurbishment or maintenance during the life of building property.

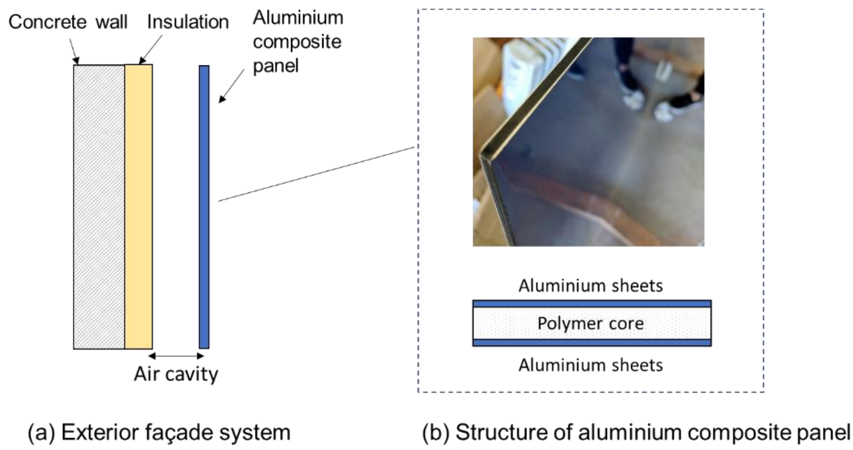


Figure 1: Diagram of (a) components of an exterior façade system and (b) the structure of the aluminium composite panel.

Aluminium composite cladding panels (ACP) consist of two thin metal sheets bonded to a central polymer insulating core. The polymer cores are often highly flammable materials such as polyethylene (PE), polyisocyanurate (PIR) or polyurethane (PUR). When ignited, the melting and dripping effect are often found to promote the fire spread vertically across the levels of the buildings, which significantly limits the amount of time for egress process, and difficulties for firefighters to access into the building to fight the fire internally or rescue trapped occupants. Based on evidence from past cladding fire incidents, the fire usually develops into an uncontrollable blaze within 10-15minutes. In addition to the flammability of cladding panels, many other factors influence the fire hazards of exterior façade systems (Bonner and Rein 2018). These include the width of the cavity between the insulation and the external panels, the types of insulation material, the installation of fire barriers in between levels, and the structural weaknesses of joints and connection between individual panels that deteriorate with high temperature (Chen et al. 2019). Fire spreading into the air cavities can cause the flame length to extend significantly to seek oxygen for combustion (Babrauskas 2018, Kim et al. 1974). There are three mechanisms which enhance the flammability in a cavity compared to a normal surface: i) increase radiative heat transfer because of the cavity, ii) increase upward flame spread from the chimney effect and iii) decrease in convective cooling from external air causing an extension of the flame height inside the cavity (Chen et al. 2019). This mechanism enables the fire to spread rapidly and hidden within the cladding system, which can be very dangerous for firefighters as hidden fires can lead to a buildup of asphyxiant gases within the panel and sudden flashovers. Furthermore, exterior façade fires also pose a significant threat of breaching compartmentation. This causes immense difficulty for firefighting operations because the most common fire strategy for high-rise buildings involves confining the fire to its floor of origin for an extended period after its initiation (Colwell and Martin 2013).

Apart from understanding the risks associated with non-compliant materials on buildings, it is also essential to evaluate the underlying risks of existing non-compliant materials on buildings for residents, owners, and the public, and for firefighters during the management of such fire events. Risk perception can be attributed to many factors including organisation factors (i.e. staffing levels; employer response of breaching the standard operating procedures) and individual factors (i.e. personalities, behavioural, attitudinal and situational biases). Risk tolerance or acceptable risks are often determined by the incident commander for emergency response personnel. The levels of risk tolerance could also be highly dependable on training, environment and education background of each firefighter. Since firefighters are generally more experienced in fire situations, they may not perceive risks the same way an ordinary person. More often, firefighters are at times oblivious to the potential fire hazards they may encounter. Therefore, it is important to construct an effective method to effectively determine the fire fighter’s confidence level in various fire situations and addressing the risks that they are experiencing. Despite these concerns, there are few studies on how firefighters process and manage risks associated with combustible cladding materials (Anderson et al. 2017). In this study, qualitative research was conducted to provide a deeper understanding of the attitudes, beliefs and perception of firefighters toward fire risks associated with combustible cladding materials. The data was collected by an online survey constructed and distributed by a collaborative effort from The University of New South Wales and Fire and Rescue New South Wales.

Methodology

An online survey was performed to investigate the fire risk perception of firefighters associated with combustible cladding material. The survey was conducted on March 20 - May 20, 2019. It was completed by a total of 439 participants consisting of firefighters from major states and rural fire agencies around Australia. This research was approved by the UNSW Human Research Ethics Advisory Panel (approval number HC180884).

Participants

The survey was completed by a total of 439 participants which includes 287 (66.90%) from Fire and Rescue New South Wales (FRNSW) and 78 (18.18%) from Queensland Fire and Emergency Services (QFES) and 64 (14.92%) from other Fire Services in Australia. A full distribution of all the participating fire agencies is shown in Figure 2.

In terms of experience, 331 participants (75.40%) had over 10 years of firefighting experience, 49 participants (11.16%) between 5 to 10 years and 45 participants (10.25%) with less than 5 years of experience. Additional demographic questions regarding the participant's rank and zone were given to FRNSW participants. There is a good distribution of different ranking officers and zone locations. For example, among the participants, there were different ranking officers from FRNSW ranging from Firefighters to Deputy Captains or above and from all the regions in NSW. The majority of the participants were from Inner Sydney (Metropolitan East) which accounted for approximately 35.18% of all responses from FRNSW. A summary of the demographics of all the survey participants is shown in Table 1 & 2.

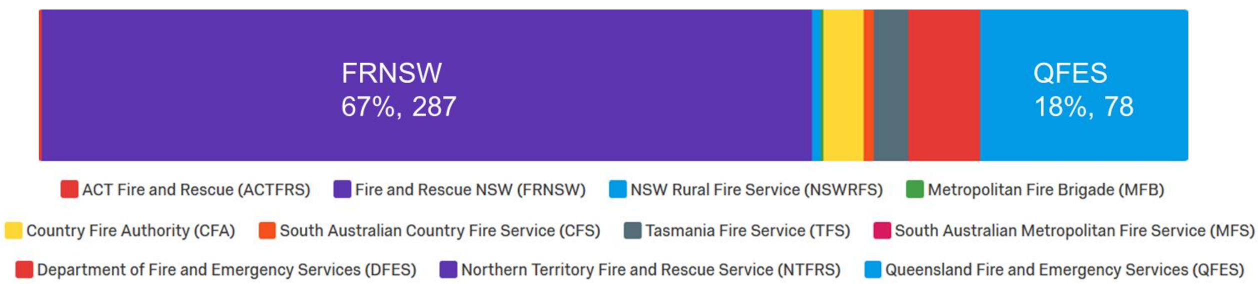


Figure 2: Distribution of the different fire service agencies in the survey participants.

Table 1: Summary of all the survey participants in terms of fire service agency and experience

Fire Services	%	Count	Experience	%	Count
Fire and Rescue NSW (FRNSW)	66.90%	287	Over 10 years	75.40%	331
Queensland Fire and Emergency Services (QFES)	18.18%	78	5 to 10 years	11.16%	49
Department of Fire and Emergency Services (DFES)	6.29%	27	Less than five years	10.25%	45
Country Fire Authority (CFA)	3.50%	15	Not a firefighter	3.19%	14
Tasmania Fire Service (TFS)	3.03%	13			
South Australian Country Fire Service (CFS)	0.93%	4			
NSW Rural Fire Service (NSWRFS)	0.70%	3			
Metropolitan Fire Brigade (MFB)	0.23%	1			
ACT Fire and Rescue (ACTFRS)	0.23%	1			

Table 2: Summary of the participants from Fire and Rescue New South Wales

Rank	%	Count	Zone / Response Area	%	Count
Recruit firefighter	0.35%	1	Metropolitan East	35.18%	95
Firefighter to Leading Firefighter	41.61%	119	Metropolitan South	11.11%	30
Station Officer or above	32.52%	93	Metropolitan North	12.96%	35
Retained firefighter	15.38%	44	Metropolitan West	18.52%	50
Deputy Captain or above	8.04%	23	Regional North	7.77%	21
Other - Please specify	2.10%	6	Regional West	5.55%	15
			Regional South	8.88%	24

Table 3: List for critical factors associated with combustible cladding fires.

Critical factors associated with combustible cladding fires
Rapid vertical and horizontal fire spread
Fire spread to surrounding structures due to falling molten/burning debris
Internal fire extension on multiple levels
Overrun sprinkler and hydrant systems
Multiple floor evacuations/rescue
Difficult evacuation of immobile occupants
Evacuation and warning system failure or unavailability
Obstructions causing difficult access for aerial appliances
Toxic smoke affecting occupants and/or bystanders
Structural collapse

Questionnaire Design

An 18-item questionnaire was constructed to investigate the risk perception associated with highly combustible cladding materials. The questionnaire was reviewed by FRNSW Fire Investigation and Research Unit (FIRU), as well as the UNSW ethical team. It was approved by the UNSW Human Research Ethics Advisory Panel (approval number HC180884). The questions can be subdivided into four major parts, i) demographic questions such as the participant's fire agency, experience and rank (Q1-3), ii) Risk awareness and identification associated with cladding material (Q4-Q9), iii) the firefighter's own perceived risk associated with cladding fires (Q10-Q14), and finally, iv) Risk mitigating behaviours (Q15-Q17).

Questions 4-9 were designed to explore risk awareness and identification of combustible cladding. The participants were asked to identify from the buildings at risks of combustible cladding from 12 images of building structures. Then they were asked to rate the likelihood of occurrence for a list of critical factors widely associated with combustible cladding (see Table 3) and the consequences of encountering these factors using the 5-point Likert scale.

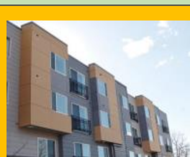
Questions 10-14 explore the firefighter's own perceived risks regarding cladding material and ask questions such as the likelihood of them facing cladding fires, the number of at-risk buildings in their zone and what are their most significant concerns and priorities when faced with such an incident. The last set of questions from Q15-Q17 deals with risk mitigation behaviours and the preparedness of the firefighter when attending fires involving cladding. The participants were asked if they have conducted any pre-incident planning (PIP) or Home Fire Safety Checklist (HFSC) for cladding buildings in their area, or any community engagement educational programs to the community. The questionnaire was first distributed in fire stations in the NSW state by FRNSW and was later extended to other fire agencies in Australia. The results will formulate a broad and comprehensive database to increase our understanding of the firefighter’s risk perception.

Results

Risk Awareness and Identification

The participants were asked to identify from the buildings at risks of combustible cladding from 12 images of building structures of which 6 have aluminium composite panel (ACP) installed. Table 4 shows a list of all the images and the number of times the images have been selected by the participants as having ACP. The results showed an almost equal distribution among all the images. In terms of correctly identifying buildings at risk of combustible cladding, 178 (53.78%) participants had the correct 6 images in their answers, which includes 92 (27.79%) responses that have selected all 12 images. Only 3 (0.09%) participants correctly identified all 6 images without any additional selection in their answer. The average accuracy rate (determined by dividing the number of correct images by the number of selected images) is approximately 0.5869 or 58.6% which is slightly higher than random guess (50%). Distribution of the accuracy rate for all the participants is shown in Figure 3. The results suggest that the majority of firefighters have difficulty correctly identifying combustible cladding. Based on the raw selection counts for each image, the participants are slightly more bias towards selecting images with reflective, smooth surface finish, a characteristic often associated with aluminium cladding. Nevertheless, cladding panels can also include powdered surface coatings or wood grain effects depending on architectural design. The results were also aligned with most of the question feedback from the participants which highlighted that any cladding materials in a façade fire are treated as highly flammable unless advised otherwise.

Table 4: List of building images with combustible cladding material. Images with combustible cladding are highlighted in orange and without combustible cladding are highlighted in green.

Image	% (count)	Image	%	Image	% (count)
1  *	8.94% (304)	5 	5.68% (193)	9 	6.12% (208)
2  *	9.62% (327)	6 	6.30% (214)	10 	8.88% (302)
3 	7.09% (241)	7  *	9.86% (335)	11  *	9.62% (327)
4  *	9.77% (332)	8  *	9.80% (333)	12 	8.33% (283)

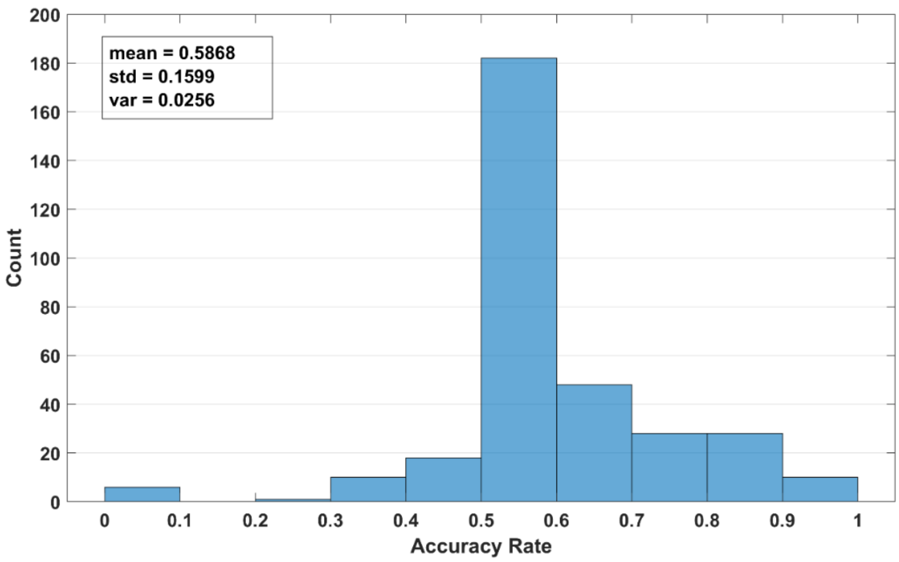


Figure 3: Histogram of the accuracy rate of identifying combustible cladding

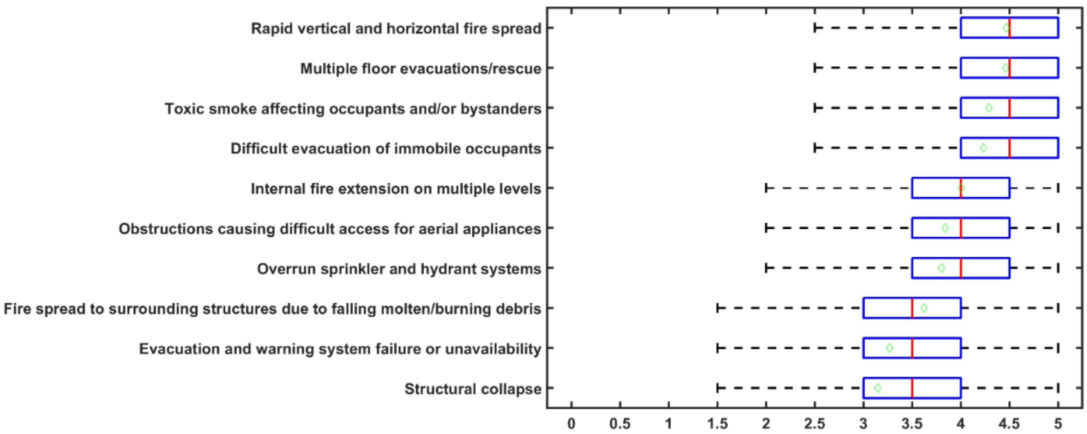


Figure 4: Risk rating for critical factors associated with combustible cladding materials. In the box plots, the boundary of the box indicates the 25th and 75th percentile, the red line within the box marks the median, and the whiskers indicate the 95th and 5th percentiles. The green circle indicate the mean.

Risk Perception of combustible cladding material

As mentioned previously, the participants were asked to rate the likelihood of occurrence and the consequence (severity) for a list of 10 critical factors for a combustible cladding fire in a multi-level building (refer to Table 3). The ratings were given on a 5-point Likert scale (5: Very High, 4: High, 3: Moderate, 2: Minor, 1: Negligible). The responses from both questions were aggregated to calculate an average risk score for each of the factors. The resulting distribution of risk scores was used to rank the list of critical factors in the order of what firefighters perceive as being the most risky. Figure 4 illustrates a box plot of all the critical factors rearranged in the order of the highest mean risk score. As can be seen in figure 4, there are three significant groups of critical factors ranked based on the firefighter’s perception. The most important factors to consider in a cladding fire for firefighters include i) rapid vertical and horizontal fire spread, ii) multiple floor evacuations/rescue, iii) toxic smoke affecting occupants and/or bystanders and iv) difficult evacuation of immobile occupants. The commonality across the top ranking factors are occupant evacuation and safety. Internal fire extension on multiple levels, overrun sprinkler and hydrant systems and evacuations and warning system failure are all rated lower than the first group even though these have a significant impact on occupant evacuation and have found to occur in past cladding fire incidents. For instance, in the tragic Grenfell fire, most of the occupants were reportedly trapped in between levels due to fire extensions on multiple levels.

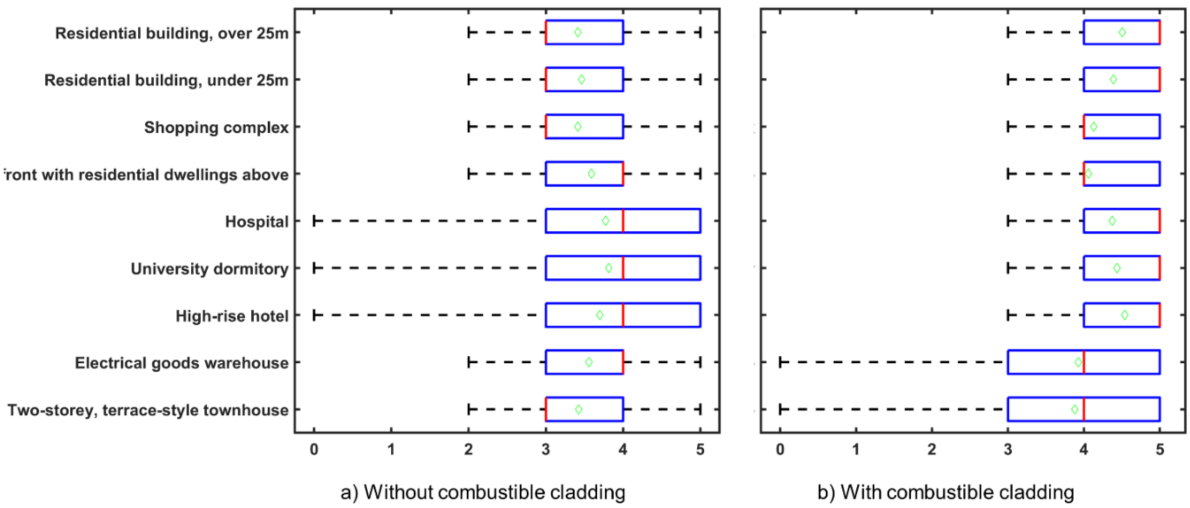


Figure 5: Risk rating for different building types in structural fire with and without involving combustible cladding. In the box plots, the boundary of the box indicates the 25th and 75th percentile, the red line within the box marks the median, and the whiskers indicate the 95th and 5th percentiles. The green circle indicate the mean.

The participants were asked to rate the consequence(severity) of fires with and without involving combustible cladding for different building types. The results showed that for normal building fires, there is no strong significance to suggest certain building types are more at risk. Based on the mean of the responses, hospital, high-rise hotel and university dormitory were perceived to be more at risk than the rest of the building types. When comparing fire with and without involving combustible cladding, there is a significant increase in risk rating across all building category when the structural fire involves combustible cladding. Particularly, the increase is most significant for Residential Buildings (over and under 25m) and High-rise hotels. This can be better highlighted in Table 5, which shows the mean severity value for fires in different building types with and without cladding and calculated the difference. The mean risk rating for residential buildings over and under 25m increase from approximately 3.4157 and 3.4607 to 4.5060 and 4.3886 respectively, which are higher than all other building types. The results suggest that the building type that firefighters perceived as most at risk from combustible cladding are residential buildings and high-rise hotels.

Table 5: Mean severity rating for fire incidents for different building types with and without combustible cladding.

Building Type	Risk Rating without cladding (mean)	Risk Rating with cladding (mean)	difference	std
Residential building, over 25m	3.4157	4.5060	1.0904	0.95
Residential building, under 25m	3.4608	4.3886	0.9277	0.87
Shopping complex	3.4157	4.1295	0.7139	0.88
Single shop front with residential dwellings above	3.5904	4.0602	0.4699	0.88
Hospital	3.7741	4.3735	0.5994	1.08
University dormitory	3.8133	4.4337	0.6205	0.93
High-rise hotel	3.6988	4.5392	0.8404	0.98
Electrical goods warehouse	3.5602	3.9277	0.3675	0.88
Two-storey, terrace-style townhouse	3.4247	3.8795	0.4548	0.87

The participants were asked to rank their priorities in a structural fire, with 1 being your highest priority and 6 being your lowest priority. The results showed that the top priority for firefighters when facing a fire incident is the safety of his/her crew and the firefighter's own safety. This is in line with current Standard Operational Guideline (SOG) which emphasise firefighter safety as the foremost consideration. It is followed by the safety of children and disabled and adult occupants. Note that there is almost no variation in these two categories, which suggests an overwhelming majority of participants ranked the safety of children and disabled and adult occupants third and fourth, respectively. At the lowest priority are protecting property and surroundings from further destructions as a result of the fire and safety of pets and wildlife.

Risk Mitigation Behaviour

In addition to the risk perception and identification questions, a series of questions were also asked to understand what firefighters think about their overall readiness in attending fires involving combustible cladding. From the 439 participants, only 11.57% of the participants that have attended a fire that involved non-compliant/combustible cladding products. 68.55% have not, and 19.88% answered that they don't know. Nevertheless, 85% of participants think they will likely attend a fire involving combustible cladding in the future, with 48.66% of participants think they will counter within the next 5 years. In terms of the level of preparedness in attending incidents involving combustible cladding, figure 7 shows the results on how the participants rated their level of preparedness in attending an incident involving highly combustible cladding. 39.40% of participants rated their preparedness for combustible cladding as less than other types of fire while 57% rated their preparedness as the same for all other fires. Only 3.64% said they were more prepared for cladding fires.

The participants were asked to select which options would help them feel more prepared for fire incidents involving combustible cladding. There is an equal distribution between the options that were given in the question. This suggests that all the approaches are equally important towards improving readiness for cladding fire incidents. There is a significant amount of comments to this question that have specifically highlighted the need for better aerial equipment and tactics. As the fire often extends beyond the reach of firefighters when they arrive. Another issue that has been highlighted among the comments were the current identification procedure relies heavily on outside parties or building managers to report the issue to fire agencies. Once filed, assessors are sent to verify the claim.

Figure 6: Priority of firefighters in a structural fire. In the box plots, the boundary of the box indicates the 25th and 75th percentile, the red line within the box marks the median, and the whiskers indicate the 95th and 5th percentiles. The green circle indicate the mean.

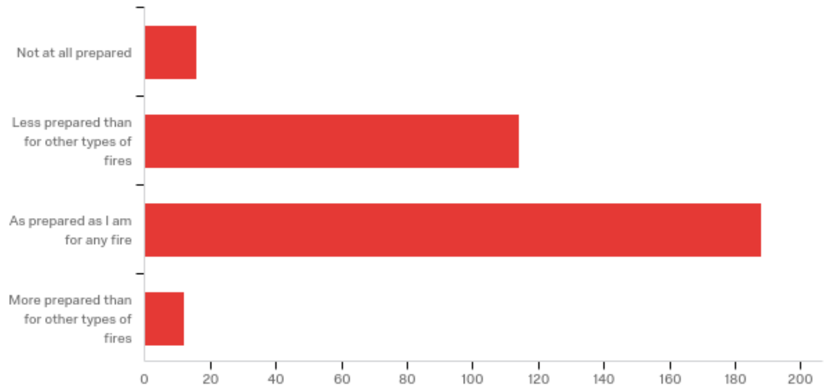


Figure 7: Responses to the question: How would you rate your level of preparedness in attending an incident involving highly combustible cladding?

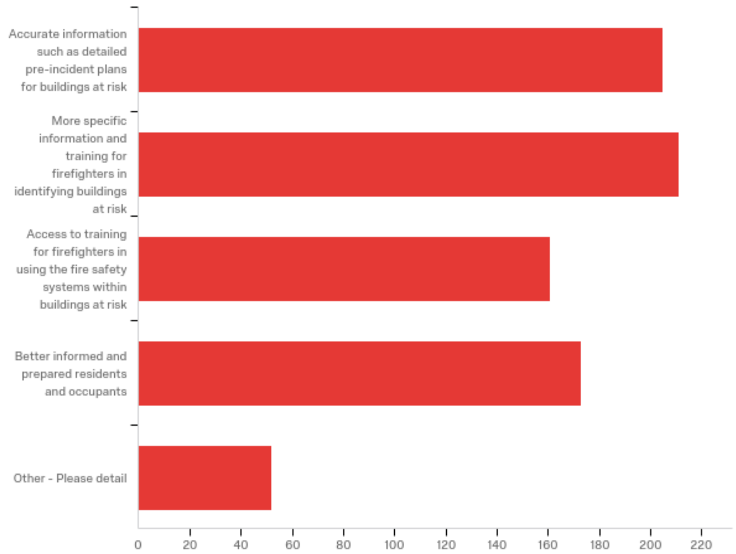


Figure 8: Responses to the question: What do you think would help to make you feel more prepared for an incident involving combustible cladding?

The process has left many unverified buildings with "potential" combustible cladding. The results emphases the importance of accurate information and planning towards effective firefighting operations as it ensures that the most optimal equipment and task crew are deployed. As such, accurate information such as PIP is a top priority to improved readiness and thus reduce the risks of fire incidents in buildings with combustible cladding materials.

Conclusion

Lightweight polymeric materials and composite panels have gained a rapid increase in utilisation due to their low-cost, easy to shape, excellent insulation characteristics and aesthetically attractive. Today, aluminium composite panels are being used in commercial, residential, hospital, and high-profile buildings. However, the polymer materials within the panels such as expanded polystyrene (EPS) and low-density polyethylene (LDPE) are highly flammable and now poses major fire risks impacting people and the economy. Furthermore, it has also become a risk for firefighters and first responders during the operations of such fire events.

In this article, an online survey was formulated to evaluate firefighter' perception and willingness for fire risks associated with combustible cladding material. The aim is to develop a database for the evaluation of risk perception and risk-taking behaviours in firefighters as pertaining to cladding-related fire events. The survey was successfully conducted during the period from March 20 to May 20, 2019 and was completed by a total of 439 firefighters from major state and rural fire agencies around Australia. Based on the results, it was found that that majority of firefighters cannot reliably identify combustible cladding (ACP)s and when attending such event, it is critical to have correct intelligence from pre-incident planning (PIP) reports. Improved PIP will also lead to more effective deployment upon dispatch and ensures appropriate gear is deployed. Furthermore, access to better aerial equipment has been repeatedly brought up in the survey as essential for tackling cladding fires.

Regarding the level of preparedness in attending incidents involving combustible cladding, firefighters in Australia currently have very limited actual experience with combustible cladding fires with only 11.57% of the participants having had attended a fire that involved non-compliant/combustible cladding products. Furthermore, 39.40% of participants rated their preparedness for combustible cladding as less than other types of fire. The results suggest that more specific information and tactical training is still needed the improve the current system of approaches for handling fire incidents in buildings with combustible cladding materials.

Acknowledgements

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Peer-reviewed article

What's wrong and what needs fixing? Stakeholder perspectives on making the future of emergency volunteering

Blythe McLennan, RMIT University and Bushfire and Natural Hazards CRC.

ABSTRACT

The modern landscape of emergency volunteering in Australia is characterised by far-reaching change, converging challenges and emerging new opportunities. In this context, a key concern within the emergency management sector today is how the changing landscape threatens the long-term sustainability of Australia's formal emergency management volunteer capacity. Some volunteer-based emergency management organisations are responding to the changing landscape with new volunteer strategies, models and management practices. While the pace of change has picked up in recent years, overall it has been slow.

This paper posits that greater engagement in frame reflexive learning and practice can help enable further and faster adaption of emergency volunteering models and approaches to better meet the challenges and opportunities presented by the changing landscape. It aims to support frame reflexive learning and practice by articulating the different ways that 'what's wrong and what needs fixing' is framed among a range of emergency volunteering stakeholder groups. The results are based on interviews and questionnaires conducted with over 180 stakeholders, including representatives from emergency service agencies, disaster welfare organisations, volunteer representative groups, volunteering peak bodies, local governments, and community sector organisations. The paper identifies and describes four key frames currently in use by stakeholders: Competition, Professionalisation, Expectation-Capacity Gap, and Culture Clash. It concludes that deeper and wider collaboration at the sector and community level is needed to enable frame reflexive practice through which multiple frames and their implications can be made more visible and a wider range of options for addressing complex cross-boundary volunteering problems revealed.

Introduction

This paper examines ways that the complex problems and uncertainties associated with making a vibrant and sustainable future for emergency volunteering are framed by stakeholders. It defines emergency volunteering as any and all volunteering that supports communities before, during and after a disaster or emergency, regardless of its duration or its organisational affiliation, or lack thereof. While emergency service and disaster welfare volunteering are central forms of emergency volunteering, there is also a significant amount of volunteering that supports communities before, during and after emergencies, which is 'unaffiliated' with emergency management organisations (EMOs). This includes formal volunteering in the wider community sector, as well as informal, emergent and spontaneous volunteering (Whittaker et al. 2015).

The purpose of the paper is not to find a single 'correct' frame through which to view the future of emergency volunteering. Rather, it is to support frame reflexive learning and practice (Schön & Rein 1994; Fischer 2003). This involves relevant actors collectively, systematically and directly exploring different framings of core problems and their solutions (e.g. "what's wrong and what needs fixing", see Schön & Rein 1994, pp. 24-26). The outcomes of this process can make multiple frames and their implications more visible and reveal a wider range of options for addressing complex problems than might otherwise be considered.

The changing landscape of emergency volunteering

The modern landscape of emergency volunteering in Australia is characterised by far-reaching change, converging challenges and emerging new opportunities (McLennan et al. 2016). On one hand, formal volunteering roles affiliated with emergency management organisations (EMOs) are becoming more demanding with greater administrative and training requirements (McLennan et al. 2008; Esmond 2016). Meanwhile, the availability of people for this kind of formal, long-term, high commitment volunteering is declining due to factors such as structural economic change that has increased competition between paid and voluntary work time; and demographic change, particularly an ageing population, greater participation of women in the workforce, urbanisation, and declining populations in some rural areas (McLennan 2008, pp. 15-17).

Background

At the same time, the way people choose to volunteer, and how they seek to fit volunteering into their lives, are also changing. People increasingly eschew the traditional, formal style of volunteering that is most common within EMOs, choosing instead to engage in alternative forms that are more flexible, more self-directed and cause-driven (Hustinx & Lammertyn 2003). The rise of social media and mobile technology has been an important catalyst for change in emergency volunteering, removing barriers to people's participation in all phases of emergency management and increasing people's capacity to self-organise outside of formal organisations (McLennan et al. 2016).

In this context, a key concern within the emergency management sector today is how the changing landscape threatens the long-term sustainability of Australia's formal emergency management volunteer capacity (Reinholtd 2000; McLennan 2008). The picture is not all grim, however. The changing landscape also opens doors onto new and innovative ways to enable and enhance the value of volunteering for communities before, during and after emergencies (e.g. McLennan et al. 2016). For example, there are new opportunities to increase surge capacity and harness local resources and skills in the wake of an emergency event.

Some EMOs are responding to the changing landscape with new volunteer strategies, models and management practices (see for example QFES, 2018, NSW SES, 2019). While the pace of change in this respect has picked up in recent years, overall it has been slow. Compare, for example, the following two statements:

> *Securing a long-term future in the current climate of social and economic change is one of the most significant challenges confronting volunteer-based emergency service and support agencies in Australia and around the world.*
>
> *The emergency management sector is under increasing pressure to develop adaptive emergency management policy and procedures that can respond to current and future challenges. Recent changes to the physical and social landscape in Australia [...] have revealed emerging and veiled volunteer issues.*

Despite their similarity, there is almost a twenty-year gap between when these two statements were published: the first in 2000 (Reinholtd 2000, p. 16) and the second in 2017 (BNHCRC 2017, p.18). This paper posits that greater engagement in frame reflexive learning and practice can help enable further and faster adaption of emergency volunteering models and approaches to better meet the challenges and opportunities presented by the changing landscape.

Framing and its impacts

As Entman (2015) explains in the context of communication, "to frame is to select some aspects of a perceived reality and make them more salient in a communicating text, in such a way as to promote a particular problem definition, causal interpretation, moral evaluation, and/or treatment recommendation"(p. 52). Schön and Rein (1994) describe frames in the context of policy-making as "underlying structures of belief, perception, and appreciation" that determine policy positions (p. 23). They too explain that a core function of framing is to articulate a story or narrative about 'what is wrong' (problem diagnosis) and 'what needs fixing' (solution prognosis) (see also Fischer, 2003). Thus, frames shape how stakeholders and decision makers make sense of complex and multifaceted issues in order to chart ways forward for addressing those issues despite conditions of uncertainty.

Frame analysis has been widely used to better understand how politicians, policy makers and policy entrepreneurs shape policy agendas (Schön & Rein 1994; Fischer 2003), how organisational managers design and enact strategy (Kaplan 2008), how the media shapes public opinion (Entman 1993), and how social movement leaders mobilise collective action for a cause (Benford & Snow 2000). It also shows how overly narrow or contested frames can stall action to address key policy and strategic issues. In the context of emergency and disaster management, for example, Boin and t'Hart (2009) examined the impacts of frame contests in post crisis settings, in which political and policy actors fight to frame the nature of a crisis, responsibility for its consequences, and its implications for the future. Which crisis frame wins determines whether the event is followed by policy stalemate, incremental adjustments or a major paradigm shift. Meanwhile, Aldunce et al (2015) analyzed how practitioners frame resilience ideas under institutional change in Australian disaster risk management. They found three different storylines about resilience that, whilst overlapping in some respects, contained distinctive diagnostic and prognostic elements. This frame divergence has led to confusion over how to implement disaster resilience and created implementation barriers in areas such as public education and community capacity building.

A key similarity across this frame analysis research is its focus on the importance of frame reflexive learning and practice for resolving the framing contests and policy inertia that can be caused by divergent and narrow frames. As Bosomworth (2015) argues, "A frame reflexive practice could provide sectors the type of learning capacity needed for adaptive planning and management" (p. 1461). It is the contribution of frame reflexive learning and practice to enabling adaptive planning for the future of emergency volunteering that this paper seeks to support.

Research approach

The data used to examine how stakeholders frame 'what's wrong and what needs fixing' for emergency volunteering comes from over 180 interviews and qualitative questionnaires administered in 2018 and 2019 as part of a wide Environmental Scan of the current and emerging landscapes of emergency volunteering. Table 1, below, provides an overview of who participated in the Environmental Scan, and how. (Note that participant numbers are higher for stakeholder groups where responses where collected by questionnaire as this data collection method does not allow for such in-depth exploration of issues as interviews.) All participants were asked the same series of open-ended questions to elicit their perspectives on recent changes and current issues in emergency volunteering, and on what needs to happen to move towards a preferred future for emergency volunteering. Responses from each stakeholder group were thematically analysed, and the results of each analysis were separately captured (see for example McLennan & Kruger 2019; Kruger & McLennan 2018; Kruger & McLennan 2019 for the first four groups). Results were then compared across the groups.

What's wrong and what needs fixing' in emergency volunteering

The analysis revealed four main ways that the core problem for emergency volunteering is framed amongst stakeholders. They are labelled here as: 1) Competition, 2) Professionalisation, 3) Expectation-Capacity Gap, and 4) Culture Clash. These frames were predominantly revealed in interview and questionnaire data through descriptions of problem symptoms and their causes ('what is wrong'), and descriptions of the change required to enable a preferred future for emergency volunteering (e.g. 'what needs fixing').

Before expanding on the frames further, it is important to highlight that another key area where participant perspectives were sought, their views on what a preferred future for emergency volunteering should look like, produced quite similar and consistent views across the groups. This shows a high degree of agreement amongst stakeholder groups about the desired outcomes of any policy or strategy change in this area, despite multiple interpretations of the core, underlying problem and changes needed to address it. Key elements of a preferred future highlighted by the participants included (see for example McLennan & Kruger 2019; Kruger & McLennan 2018, Kruger & McLennan 2019): a vibrant, sustainable volunteer capability to deliver emergency management services to communities; formal volunteering that is easy to engage in, accessible, and well-supported by organisations; wide collaboration and capacity-building for emergency management and community resilience goals that reach well beyond emergency service agencies; organisations with strong shared cultures of volunteerism and inclusion; and organisations that are agile, innovative, and future-focused. Two areas where some differences existed were in the degree of participant's commitment to the importance of strong community leadership and ownership in emergency management, and the degree to which involvement of 'spontaneous' volunteers should be risk managed versus enabled. Notably, these differences cut across the stakeholder groups rather than constituting key differences between them. Some participants, most notably those associated with local, community-based community sector organisations, strongly advocated for community leadership and empowerment, and for enabling spontaneous volunteering as a legitimate and valuable component of a societal response to emergencies. Others, particularly from larger and more structured organisations, either placed less importance of these or emphasised associated risks and uncertainties more highly than potential benefits.

Each of the four frames identified are described in turn below. Table 2 provides an overview of how strongly each frame was evident among the various stakeholder groups. It is noteworthy that each of the frames were present across all the stakeholder groups, reflecting the interacting nature of volunteering trends, issues and uncertainties. However, there were clearly discernible differences in the importance and prevalence of the different frames between the groups.

Table 1: Emergency volunteering 2030 Environmental Scan participants.

Stakeholder groups	In-depth interviews	Survey questionnaires	Other	Total
Managers in emergency service volunteerism	18	-	-	18
Managers in disaster welfare & recovery volunteerism	16	-	-	16
Local government managers	17	-	-	17
Community sector representatives	2	46	-	48
Volunteering peak bodies	6 (group interview)	-	7 (direct report input)	13
Emergency service volunteer group representatives	1	75	-	76
Total	60	121	7	188

Table 2: Presence of frames amongst Environmental scan participant categories (red=strong; yellow = moderate presence).

	Competition	Professionalisation	Expectation-Capacity Gap	Culture Clash
Managers in emergency service volunteerism	red	red	yellow	yellow
Managers in disaster welfare & recovery volunteerism	red	yellow	red	yellow
Local government managers	yellow	yellow	red	yellow
Community sector	yellow	yellow	red	red
Volunteering peak bodies	yellow	yellow	red	yellow
Emergency service volunteer representatives	red	red	red	yellow

Competition

Looking through the Competition frame, the core problem for emergency volunteering is mounting difficulty in recruiting and retaining formal volunteers in the face of the changing landscape of volunteering. According to this perspective, changes in how people want to volunteer, social changes impacting people's availability and desire to volunteer, and growing numbers of - often digitally-enabled - alternatives to traditional volunteering with formal organisations, all work to 'pull' people away from formal, long-term volunteering with organisations and threaten the long-term sustainability of the volunteer workforce:

> *People are less likely to commit to long term volunteering. They are time poor. They have a much more expanded list of opportunities [for] where to commit their time.*
>
> Emergency service volunteer representative

> *It's come from an understanding of where the national and international trends are going around sustainable volunteerism models and the emergence of new volunteerism groups and what makes them attractive. You look at that and go, 'okay, here's what we're up against. Our traditional models will not survive in this area.*
>
> Manager in emergency service volunteerism

This is certainly a dominant frame within the emergency services, and the wider emergency management sector, being strongly reflected in descriptions from managers and volunteer representatives with emergency service (response) organisations, and from managers working in disaster welfare and recovery volunteerism. The symptoms of this problem were widely discussed by these participants, and to a lesser extent by participants in the other stakeholder groups. They include, for example, the rise of short-term volunteering, declining volunteer numbers, high volunteer turn-over, and ageing volunteer bases.

Two priority areas of action arise from this frame. First, redesigning volunteer models, management and engagement practices to make formal volunteering more competitive, attractive, flexible and accessible to a wider and more diverse range of (particularly younger) people. Second, developing deeper engagement and connection with communities to increase both organisational understandings of communities as well as community understandings of emergency management, risk, and emergency volunteering.

Professionalisation

The core problem viewed through the Professionalisation frame arises from formal volunteering becoming more professionalised in line with corporatisation, bureaucratization and growing government regulation. While this shift has improved safety and service quality, it has also created additional and significant barriers and disincentives to volunteering. Moreover, some participants described a growing disconnect between the bureaucratic and structured procedures of organisations and the more organic ways that communities prepare for, respond to, and recover from emergencies. Key symptoms of this problems include increases in red tape and organisational control of volunteers, higher volunteer training requirements, 'scope creep' in volunteer roles and higher volunteer workload, greater numbers of volunteers feeling undervalued & dissatisfied, and bifurcation of the voluntary sector more widely between 1) highly professional and 'business-like' organisations, and 2) local, informal, grassroots organisations:

> *Increased corporatisation, substantially more direction and orders from career bureaucrats, ...as a result it is no longer as relevant or connected to community. [The organisation's] key strength as a community-based and driven organisation is being replaced by the notion that it's a professional emergency response service. It is both, but the pendulum and momentum is all focused on the latter and not the former.*
>
> ES volunteer group representative

> *With professionalisation comes a disconnect between the leadership and the community.*
>
> Community sector representative

This frame was most evident among emergency service managers and volunteers, who reported that these shifts were particularly strong in their organisations. There are, of course, strong interactions between the forces emphasised under this frame and those of the Competition frame. The external changes highlighted under the Competition frame operate as "pull" factors that draw people away from more traditional, formal volunteering roles. Meanwhile, the changes emphasised under the Professionalisation frame are "push" factors that further exacerbate recruitment and retention challenges by undermining volunteer motivations and satisfaction and driving people away from volunteering.

Interestingly, while both managers and volunteer representatives used these two frames, managers tended to emphasise negative recruitment impacts of "pull" factors more strongly, while volunteer representatives tended to emphasise the negative retention impacts of "push" factors. In line with this, there are also differences in the solutions arising from the Professionalisation frame compared to Competition, even though both focus attention on making formal volunteering easier and thus more sustainable. The Competition frame emphasizes changes to make formal volunteering more attractive and accessible to a wider range of people (i.e. making emergency service volunteering more competitive with alternatives to improve recruitment), while the Professionalisation frame emphasizes a a need for organisations to provide greater support to existing volunteers and reduce the administrative and training demands placed on them (i.e. to improve volunteer satisfaction and therefore retention). Indeed, some volunteer representatives directly critiqued what they saw as a management overemphasis on recruitment to the detriment of retention.

Expectation-Capacity Gap

The third problem frame, Expectations-Capacity Gap sees the core problem as a widening gap between rising political, social and organisational expectations of volunteer-based services in emergency management and declining or inadequate resourcing and support to build capacity to meet these rising expectations. This gap leaves volunteers and organisations struggling with high workloads, rising numbers of callouts (emergency services) and declining service quality, most noticeably in rural areas that have smaller volunteer bases. This frame was evident across all the stakeholder groups; however, it was moderately present among managers of emergency service volunteerism, and strongly present amongst the other groups.

There were also differences in the kinds of capacity gaps described. Emergency service volunteer representatives emphasised shortfalls in organisational capacity to lead, manage, engage, equip and otherwise support volunteers. Meanwhile, representatives from non-government organisations, volunteering peak bodies and local government emphasised a lack of access to funding, particularly prior to emergency events occurring, as well as shortages in human resources and organisational planning, and a lack of recognition for the contribution of the community sector and community development to emergency management and community resilience goals:

> *There is no recognition in the formal arrangements as they currently stand for spontaneous volunteers, local community groups, local community sector organisations and so on. [...] there is no recognition or resources to 'support the supporters' - and this inevitably takes a toll on the individuals and organisations involved.*
>
> Community sector representative

There are three key priority action areas associated with this frame that were highlighted by participants. First, involving a wider range of emergency management stakeholders in planning, including community sector organisations both large and small. Second, reviewing and redesigning formal emergency management funding arrangements to be more equitable and inclusive, recognising contributions from a wider range of organisations and volunteers. Third, building greater community-wide capacity for emergency management through access to training and other capacity-building programs.

Culture Clash

The Culture Clash frame, while not the most prominent in participant responses, was commonly portrayed as underlying and exacerbating the problems highlighted under the other three frames as well as presenting a problem in itself. According to this frame, command-and-control culture and structures, and traditionalistic attitudes in the emergency management sector are persistent barriers to the innovation, collaboration and adaptive capacity needed to respond to the shifting landscape of volunteering:

> *I think entrenched attitudes, vested interests and an 'old guard' unwilling to innovate are the greatest challenges to this [emergency management] sector at present.*
>
> Community sector representative

> *[The key challenge around volunteer sustainability is] culture; changing the emergency service organisation culture to be inclusive and collaborative [..] some of this stuff around that cultural arrogance.*
>
> Manager in emergency service volunteerism

Key symptoms of this problem described across the different stakeholder groups were resistance to change, insular decision-making, presence of siloes, risk aversion, poor youth engagement, failure to innovate, low volunteer diversity, and persistence of out-of-date models and practices. A symptom shared between this and the Professionalisation problem is a g widening gap between the goals, values and practices of bureaucratic, and increasingly corporatised and professionalised, emergency management organisations on one hand, and the more community-centric values and motivations of volunteers and communities:

> *Whilst it used to feel like you worked for the community wearing [an organisational] uniform and doing what the community needed, it now feels like you wear a uniform and do the work of the [organisation].*
>
> Emergency service volunteer representative

> *I believe it is highly likely that communities may start to self-organise and once again create their own response capacity outside of the corporate brand. [...] Self-organised through social media, it is likely that communities will say "enough of your crap!! We want a local brigade that can respond when we need, and for the reasons we need it.*
>
> Emergency service volunteer representative

Solutions for addressing the Culture Clash problem were harder for participants to articulate and were more often implied than directly described. Careful, active and purposeful change management at organisational levels to bring people along with the shifts needed to adapt to the changing external environment was raised. So too was the need to continue and deepen the sector's growing focus on improving diversity and inclusion in emergency management.

A key aspect of change management that will need close attention is to manage impacts of change on organisational and volunteer values so as not to further widen the gap described above. As Calcutt (2019) shows in a recent study of values motivating emergency service volunteers, "values are powerful motivators, and shared values can reinforce volunteer commitment and retention, while conflicting values can contribute to volunteer turnover. Satisfying and managing the different values needs of an increasingly diverse volunteer workforce will require a more nuanced and responsive approach, with a greater emphasis on building an organisational culture founded on the values of encouragement, respect and inclusion" (p.2, abstract).

Frame reflexive learning and practice for emergency volunteering

The underlying purpose of this paper was to support greater engagement in frame reflexive learning and practice (Schön & Rein 1994) that can enable adaptive planning for the future of emergency volunteering. Frame reflexive learning and practice involves relevant actors collectively, systematically and directly exploring different framings of core problems and their solutions (e.g. "what's wrong and what needs fixing", see Schön & Rein 1994, pp. 24-26).This paper contributes to this primarily by articulating the different ways that 'what's wrong and what needs fixing' is framed among a range of emergency volunteering stakeholder groups. Bosomworth and colleagues have studied the need and potential for frame reflexive learning and practice in Australian emergency management and climate change policy (Bosomworth 2015; Bosomworth et al. 2017). As she explains, "an exploration of different framings of a sector's policy 'fundamental problem' could reveal a greater array of policy options than currently considered, and thereby present more robust, adaptive policy suites" (Bosomworth 2015, p. 1452).

Certainly, articulating frames alone is not enough. Processes and forums through which these frames can be explored, and their implications robustly examined are needed. Deep and wide collaboration is a necessary condition for frame reflexive practice through bringing together a wider range of stakeholders with different ways of framing the same policy issue. Bosomworth et al. (2017, p. 318) identify how collaborative or networked governance "could help strategic-level emergency management overcome a tendency to react within narrow frames of problem-solving, and to challenge the traditional occupational identity of reactive 'command and control'".

In the context of emergency volunteering, participants in this research across all the stakeholder groups recognised a shift in the sector towards greater collaboration - including with actors from within as well as beyond the sector. However, they also conveyed that the sector still has a long way to go to achieve the deeper and wider collaboration in planning and governance that many participants posited is a core element for a preferred future for emergency volunteering. This was especially emphasised by participants from local-level community-based and community led groups:

> *We continue to advocate with the authorities and agencies for improved awareness by them of the potential benefits from engaging community-based organisations. This requires that they learn to trust us to know what is best for our community.*
>
> Community sector representative

On ongoing barrier to collaboration and frame reflexive learning and practice is the tendency for emergency volunteering problems and solutions to be framed, discussed and acted on primarily at the level of organisations in the context of workforce planning, and volunteer recruitment and retention programming. While these are indeed important areas of planning and action for volunteer sustainability, by comparison there is relatively little action at the more strategic, sector-wide level. While wider forums do exist for organisations to share learning and discuss shared challenges, e.g. Australian Fire and Emergency Services Authorities Council (AFAC) and the Australian Emergency Management Volunteer Forum (AEMVF), these still have relatively narrow membership and remain focused on organisational challenges and initiatives.

A key development that could enable frame reflexive learning and practice is therefore creation of new and more open, inclusive forums within which emergency volunteering issues that transcend organisational boundaries, such as the coordination of spontaneous volunteering and reviews of funding arrangements, can be collaboratively explored, while also remaining centred on community needs, risk and values:

> *Something that brings the leadership of all the emergency management services together and focuses on the community and supporting each other in the betterment of the community is what is needed. […] How do we develop leadership across all those agencies to focus on the communities and therefore focus on the volunteers […]?*
>
> Manager in emergency service volunteerism

As this quote highlights, a key, unresolved issue is from where leadership and, indeed, responsibility for mobilising collaborative action on boundary-spanning issues. Without this, the same volunteering issues that were being highlighted and discussed twenty years ago, may well remain unresolved and even further entrenched in another twenty years' time.

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Peer-reviewed article

Business involvement in natural disasters in Australia and New Zealand

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ABSTRACT

Catastrophic natural disasters by definition overwhelm the capability and capacity of emergency management organisations, at which times, the business sector can provide additional resources to assist communities. This study analyses the involvement of businesses in disaster management in Australia and New Zealand in three severe disaster events: the Black Saturday bushfires (2009); the Queensland floods (2010-11); and the Canterbury earthquake sequence (2010-11). It finds that businesses are already assisting communities to respond and recover from disasters, but there exists significant potential for further participation given a large number of businesses did not report involvement. Businesses are motivated by commitments to their staff and customers and corporate social responsibility, reflecting more complex business objectives then solely profit generation.

Introduction

In recognising that truly catastrophic disasters will overwhelm emergency management organisations, the Australian Natural Disaster Resilience Strategy (ANDRS) acknowledges the business sector as an important participant in disaster management. ANDRS states:

> *. . . businesses can and do play a fundamental role in supporting a community's resilience to disasters. They provide resources, expertise and many essential services on which the community depends.*
>
> Council of Australian Governments (2011, p. 5)

Businesses are defined here as for-profit organisations that do not comprise part of government. We employ the term business rather than private sector to exclude not-for-profit companies, whose contributions lie beyond the scope of this research.

Disaster management has been typically seen as the preserve of emergency management organisations utilising an all-hazards, all agencies approach (Johnson et al. 2011). The activities and resources of Emergency Management (EM) organisations, however, are generally oriented towards the management of small-scale, relatively frequent events. Maintaining resources for truly extreme events would be prohibitive and unrealistic. As a result, larger scale events will overrun the ability of emergency management organisations to respond effectively at local, regional and even national scales. In reality the role of disaster management is never the sole responsibility of governments and the business sector offers additional capabilities to help support the recovery of impacted communities.

This support can either be by way of direct contributions or through third parties such as non-government organisations. In responding to Hurricane Sandy (2012) in the United States, for example, the business sector was able to move eight times the amount of food into affected areas compared with the combined efforts of government and non-government organisations (Kaufman, Bach & Riquelme 2015). Similarly, after Hurricane Katrina (2005), the retail store, Wal-Mart, frequently outpaced FEMA by several days (Chandra et al. 2016). The business sector can also act with more flexibility than government, making fast decisions and acquiring, moving and disposing of resources rapidly. It can quickly scale its operations to match the need (Busch & Givens 2013).

Partnerships between the public and business sectors need to be tailored based upon the needs and capabilities of the organisations involved. Some are formal in nature and involve regulation or contractual relationships whilst others can be less formal. To be successful both parties need to recognise the value that the relationship creates. Key motivators for government and business sector collaboration include creating public value through building resilience; information sharing to support each other's operations; quicker restoration of essential services; avoiding duplication of effort; the provision of assistance in emergency planning and better decision-making (FEMA 2018).

Examples of business sector engagement in disaster management in the United States demonstrate a need for coordination between the public sector and businesses so that accountabilities and expectations are clear on both sides (Busch & Givens 2013). For example, during Hurricane Katrina relief supplies delivered by Wal-Mart were turned away because FEMA said they weren't needed (Richman 2005). Better coordination reduces duplication of effort and delivers more effective outcomes (Busch & Givens 2013).

Johnson et al. (2011) examined disaster-related activities of large companies in the United States and found that corporations engage in activities related to disasters by way of short-term relief and recovery activities. These were reactive and episodic in nature and included both financial and in-kind activities delivered to employee and customer stakeholder groups. To date there has been little comparable academic research undertaken in Australia and New Zealand, something this study aims to change.

Unlike Johnson et al. (2011), however, we focus on the support that businesses have provided in domestic natural disasters. Specifically, we investigate what role large businesses have played in responding to the 2009 Black Saturday bushfires; 2010-11 Queensland floods; and 2010-2011 Canterbury earthquake sequence. Questions posed include how have businesses undertaken their role? What support did they provide and to whom? And what types of businesses were involved? We conclude with a brief discussion of policy implications.

Background to events

Three severe natural disaster events from Australia and New Zealand were selected, each of which demonstrably tested emergency management organisations and where anecdotal evidence suggests that businesses assisted in response and recovery efforts.

2009 Black Saturday bushfires

The Black Saturday bushfires (7th February 2009) were preceded by a heatwave generating record-breaking temperatures and extreme fire conditions across Victoria and South Australia. Multiple fires ignited across Victoria. Fires spread quickly due to extreme winds, burning in excess of 450,000 hectares of land, killing 173 people, destroying more than 3500 buildings including 2029 homes and resulting in an economic impact of greater than AUD4.4 billion (Teague, McLeod & Pascoe 2010). The insured loss normalised to 2016-17 financial year societal conditions has been estimated at AUD1.8 billion (McAneney et al. 2019).

2010-2011 Queensland floods

Major flooding affected nearly 75 per cent of Queensland and also parts of northern NSW (Chanson 2011). There were 38 fatalities with an additional 6 persons missing presumed dead, widespread damage to housing and infrastructure, and an estimated economic impact in excess of AUD10 billion (Queensland Floods Commission of Inquiry 2012). The normalised insured cost was AUD2.3 billion (McAneney et al. 2019)

2010-2011 Christchurch earthquakes

On September 4, 2010, the first of a swarm of earthquakes impacted Christchurch, the largest city in the South Island of New Zealand; it was a Moment Magnitude 7.1 earthquake with its epicentre at Darfield some 40 km west of the city. The third of five quakes designated as 'insurance' events occurred on 22 February 2011 and was centred 5 km southeast of Christchurch; this Moment Magnitude 6.3 event resulted in seismic motions well in excess of those underpinning the building code. 185 people died and damage to the CBD was such that much of it has now been demolished and some areas of former residential property designated unsuitable for rebuilding due to liquefaction (McAneney et al. 2015). The cost of recovery is estimated at some NZD40 billion or 20 per cent of annual Gross National Product. The total cost of rebuilding has been estimated at more than NZD40 billion (The Treasury 2014).

Methodology

Lists of the top 100 businesses on the Australian Stock Exchange (ASX 100) (as at 1st December, 2016), and the top 100 NZ companies by number of employees from Katalyst Business (as at 12th March 2019) were obtained. Government agencies were removed from the New Zealand list, and merged with the New Zealand Stock Exchange top 50 businesses (NZX 50) (as at 12th March 2019).

Following Johnson et al. (2011), a content analysis was undertaken based on documents found from internet searches for annual reports and press releases of each business. These were examined for any reference to the three events. If any response or recovery related activities were identified, the relevant text was copied to a separate document for subsequent classification.

A classification schema was produced based on descriptions used by Johnson et al. (2011). Information included source of support; beneficiaries; details of cash contributions; subtype of support where the contribution was not in cash; category of business making the contribution based on the Global Industry Classification Standard (GICS) (Australian Securities Exchange 2019) and reasons for making a contribution and any disaster impacts on the business.

Data were then reviewed and classified into a single table for analysis in Excel. The table of records was analysed using a script in R to produce cross tabulation data from which correlations have been drawn.

Limitations

This study has several limitations, the most critical of which are that contributions need to have been reported. 73 per cent of the event-business combinations searched had either an annual report or a relevant press release; however only 25 per cent mentioned support for any of the three events. It is probable that some businesses provided support but did not disclose this in their annual reports or publish press releases and as such our analyses offer a lower bound on the extent of private sector involvement. Some businesses also reported contributions but without enough detail to identify a source or recipient.

Results

From a total of 314 business and event combinations, 233 annual reports and 10 press releases were found and, of those, a total of 75 businesses were found to have made contributions (32%). A mention of the event was found in 31 per cent of businesses searched for Black Saturday (n=24), 51 per cent of the businesses searched for the Queensland floods (n=42), and 73 per cent of the businesses searched for the Christchurch earthquakes (n=54).

Impacts on businesses

A total of 63 businesses mentioned they had suffered impacts from the events (Figure 1).

Changing market conditions i.e. demand for services or products, as a result of the event, was the most common of impacts on businesses (total n=43), followed by immediate financial loss (total n=34), business interruption losses (total n=30), loss of stock (total n=21) and longer term financial losses (total n=8).

Business categories

Figure 2 illustrates the percentage of businesses in each category that were found to have made a contribution.

56 per cent of utilities businesses (n=9) and 50 per cent of the businesses in the metals and mining category made contributions. The latter may not be representative of the wider sector given that it refers to only a single observation.

Contribution types

Overall, 63 per cent of businesses that mentioned one of the events either contributed or had otherwise supported relief efforts (n=75). 79 per cent of businesses that mentioned the Black Saturday (n=19) fires contributed towards the recovery; 64 per cent for the Queensland floods (n=27), and 54 per cent for the Christchurch quakes (n=29). A comparison of the prevalence of cash and in-kind donations for each event can be found in Figure 3.

Cash contributions were more common than in-kind contributions in two of three events (Figure 3). Examples included a biotechnology company that donated to the Victorian Bushfire Fund set up by the Australian Red Cross and the Victorian Government, and a subscription television provider that made multiple contributions to relief efforts including to an NGO following the Christchurch quakes.

Of the 56 businesses reporting a cash donation, 86 per cent of these specified the dollar amount. Table 1 shows statistics on cash contributions.

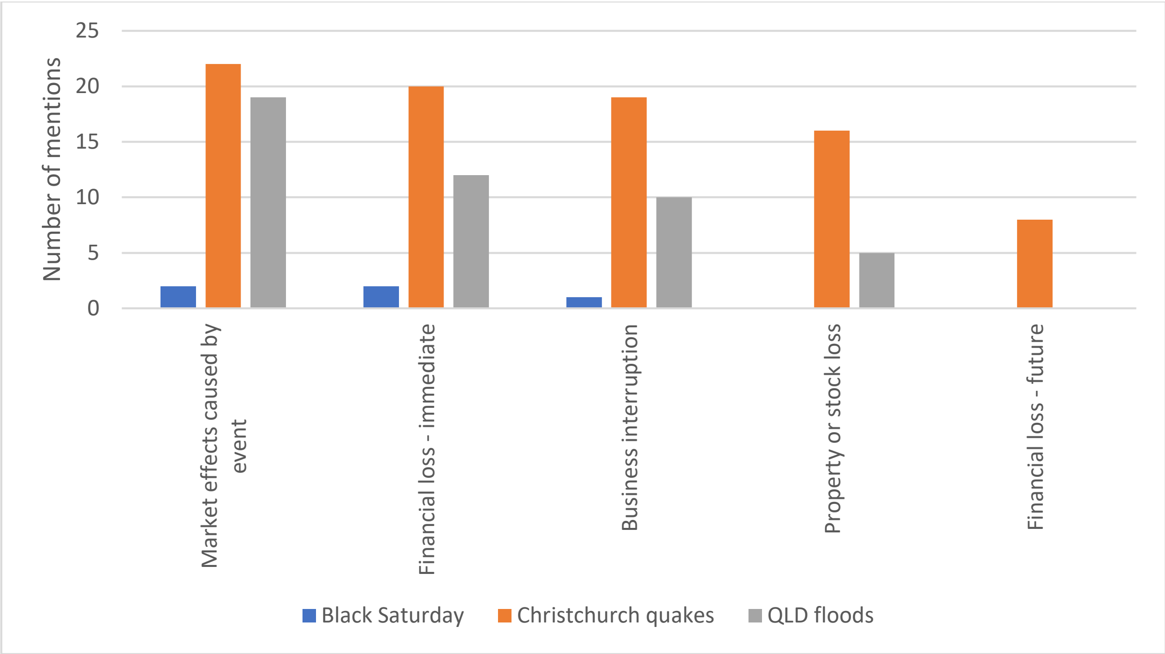

Figure 1: Impacts mentioned by event.

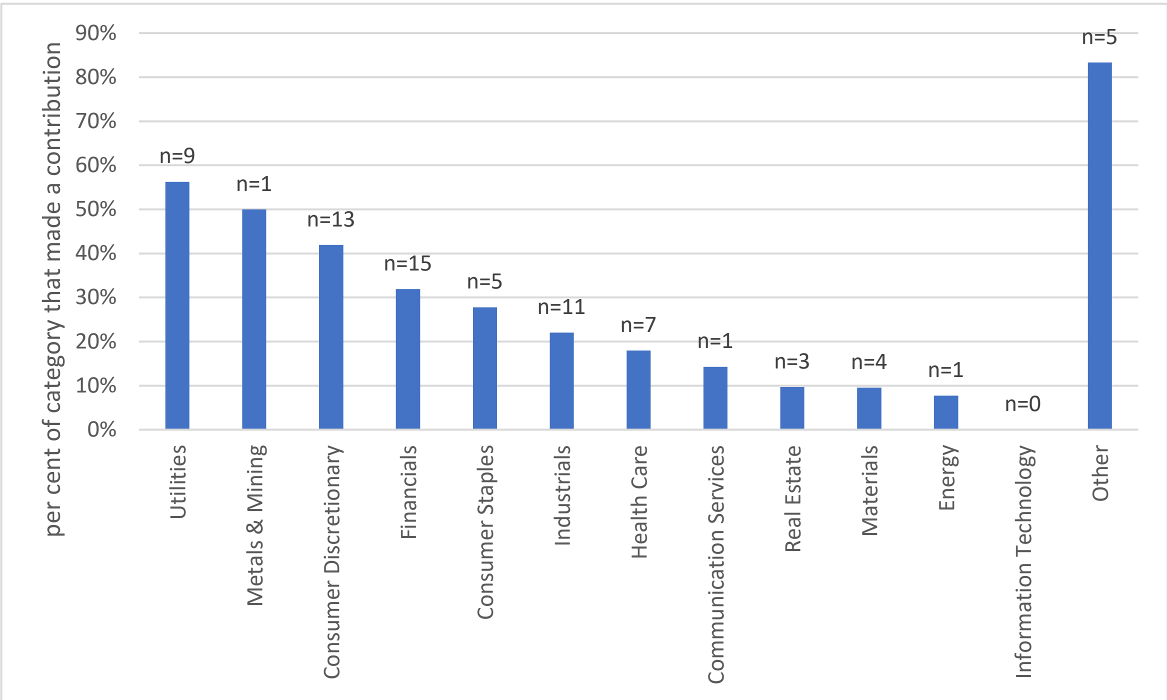

Figure 2: Percentage of businesses that made a contribution by business category.

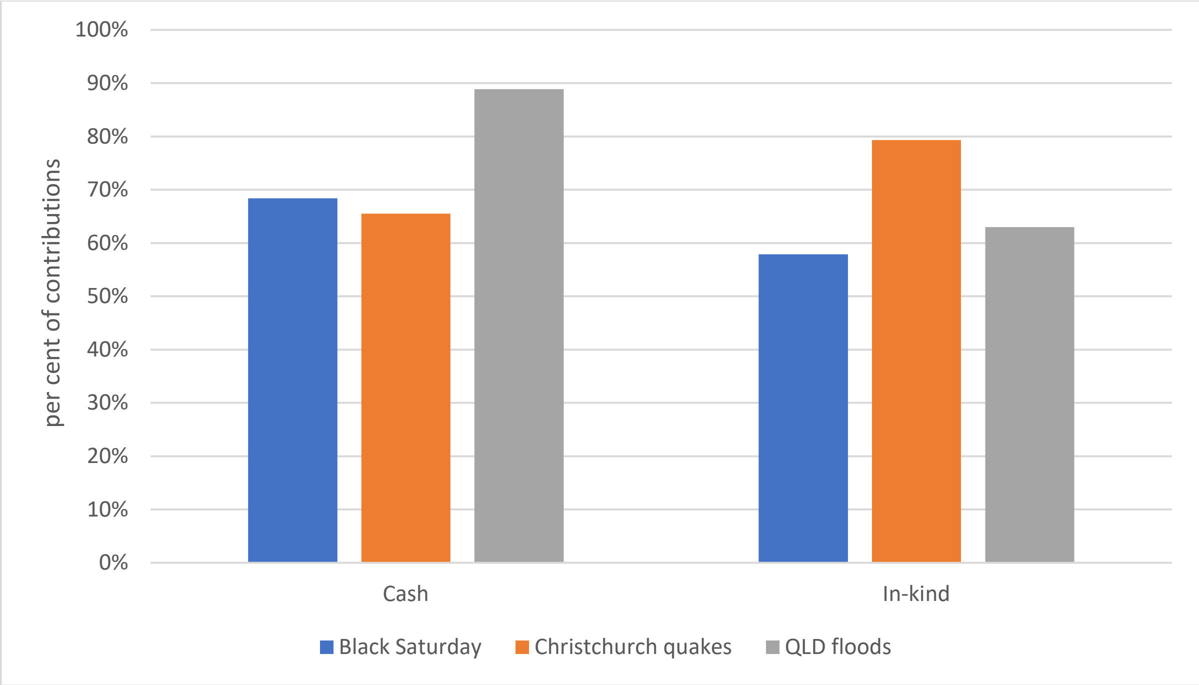

Figure 3: Contribution types by event.

Table 1: Cash contribution statistics by event. All figures are in AUD2018.

	Black Saturday	Christchurch quakes	Queensland Floods
Highest	14,070,800	12,435,634	74,165,000
Lowest	67,928	31,350	22,820
Median	1,213,000	782,367	330,320
Mean	2,161,278	2,283,895	6,083,171

The largest single contribution was AUD74 million following the Queensland floods by a major bank. The largest contribution following the Christchurch quakes was NZD12.4 million and the largest contribution following Black Saturday was AUD14 million, both made by consumer staples retail groups.

43 per cent of businesses made both cash and in-kind contributions (n=32). Overall, 68 per cent of contributing businesses made in-kind contributions: 58 per cent for Black Saturday (n=11), 63 per cent in the case of the Queensland floods (n=17), and 79 per cent for the Christchurch earthquakes (n=23). Examples included an outdoor equipment store that partnered with an NGO to make both cash and in-kind contributions to both the Christchurch earthquakes and Queensland floods.

The most frequent contributions came from financial institutions (20%, n=15). Figure 4 breaks down relative contributions made by different business sectors as a percentage of the total number of any kind of reported contribution.

More consumer discretionary, financial, health care, consumer staples, real estate and energy businesses contributed cash compared to in-kind, while the reverse was true of industrial, utility and materials businesses.

Contribution sources

Over all events, contributions were most commonly sourced directly from the business, followed by contributions from employees. More than one contribution source was identified for 31 businesses. Figure 5 shows the breakdown by event.

Where corporation support was identified, 72 per cent of businesses contributed cash (n=48); 70 per cent contributed in-kind (n=47) and 45 per cent contributed both cash and in-kind (n=30). In contrast, where business employees donated, the most frequent form of contribution were in-kind (83%, n=18). For example, staff and students from a university worked with schools to develop tools to help children deal with trauma resulting from the Christchurch earthquakes.

This was followed by cash contributions (78%, n=18) such as a financial business that contributed to various charities and community partners following Black Saturday, via both in-kind and cash contributions.

Recipients

It was possible to identify recipients of contributions in 88 per cent of all contributions (66 cases). Overall, contributions were most frequently sent directly to affected communities (62%, n=47). This was followed by contributions by way of partnerships with NGOs (43%, n=33), such as the Red Cross Bushfire Appeal after the Black Saturday fires, and in partnership with Government (32%, n=24), such as donating to the Queensland Premier's Disaster Relief Fund following the Queensland floods. After Black Saturday, partnerships with NGOs occurred in 55 per cent of cases (n=11) compared to only 15 per cent where businesses collaborated with Government (n=3). 47 per cent of all contributions had more than one contribution recipient (n=35). Figure 6 compares the contribution recipients identified overall and by event.

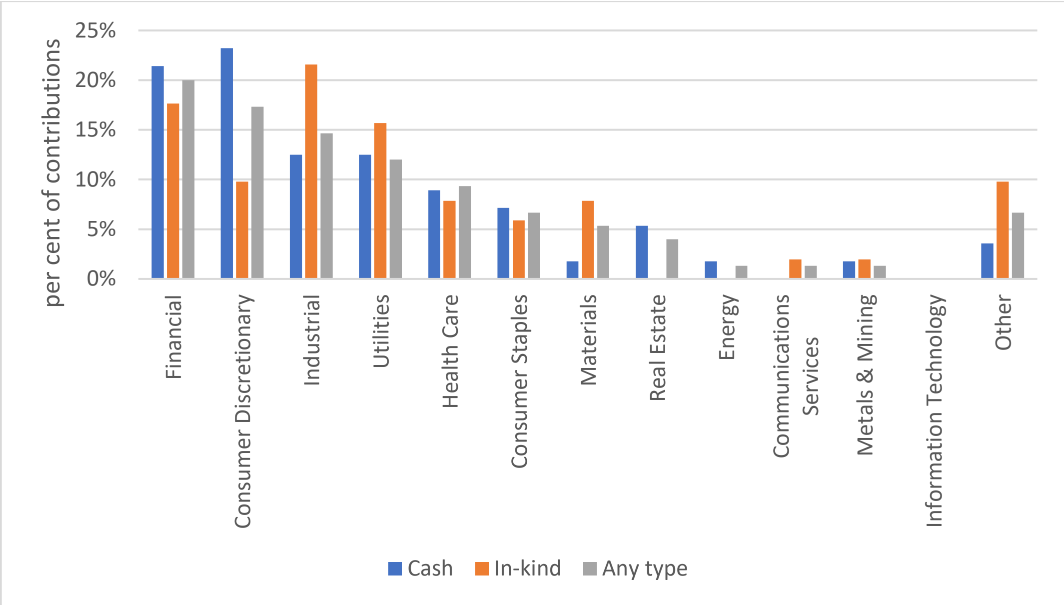

Figure 4: Business categories by contribution type.

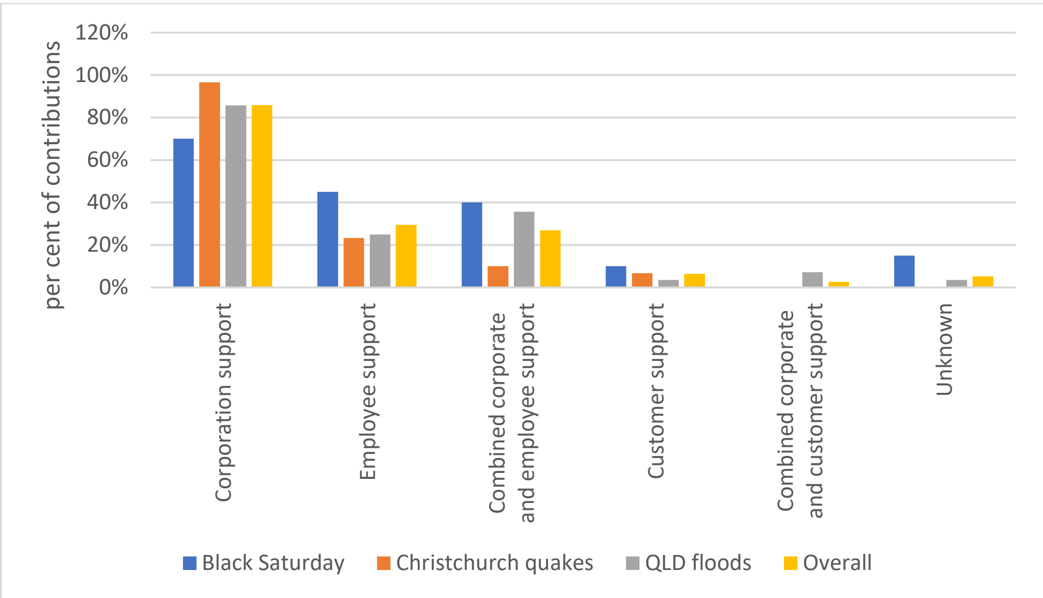

Figure 5: Contribution sources overall and by event.

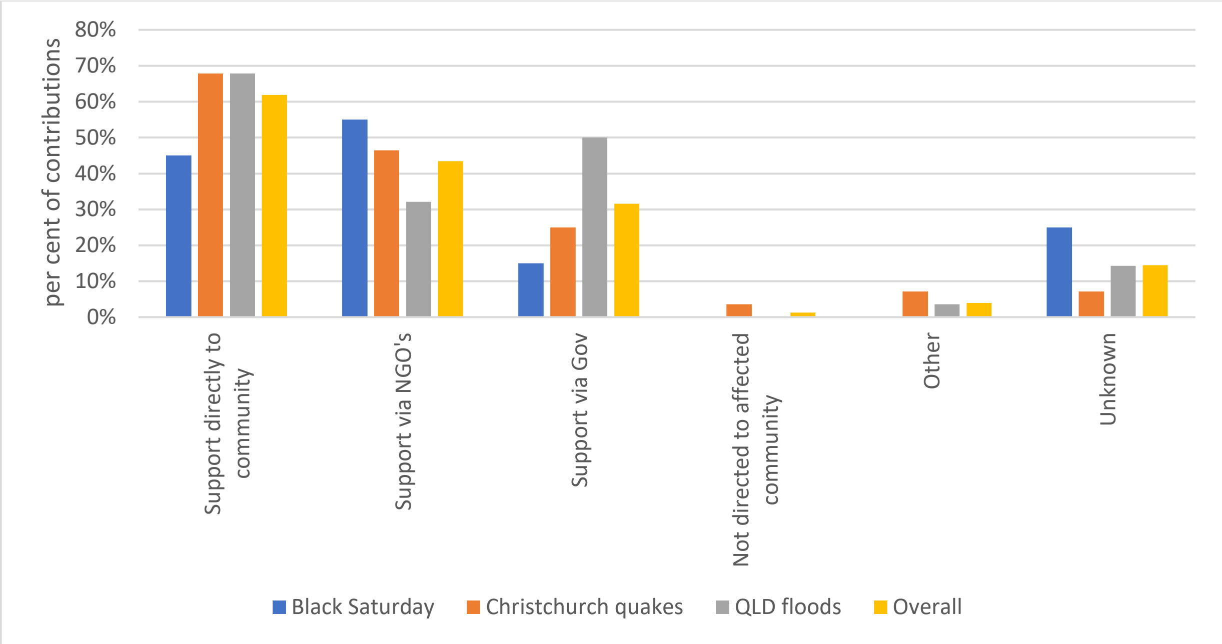

Figure 6: Contribution recipients overall and by event.

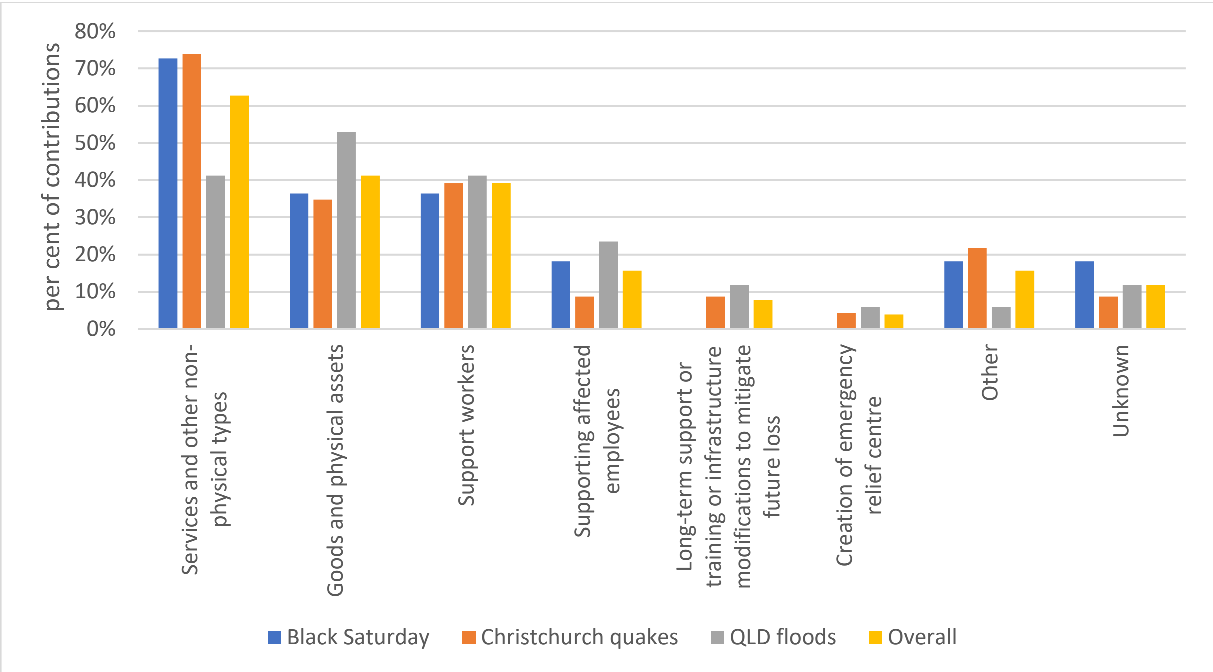

Figure 7: Contribution sub-types overall and by event.

A high proportion of contributions made directly to affected communities included an in-kind component (87 per cent, n=41). In one instance, an airline made in-kind contributions directly to affected communities by launching an initiative to provide care for affected customers. Of those that made an in-kind contribution directly to affected communities, more than half also made cash contributions (63 per cent, n=26), such as a corporation that supported relief efforts for Black Saturday via corporate donations, fundraising, volunteering and donation of goods.

In-kind contribution sub-categories

In-kind sub-types were identified for 88 per cent (n=45) of contributions that had an in-kind element. Figure 7 illustrates the relative prevalence of different sub-types as a percentage of all in-kind contributions by event.

The most common in-kind contribution was services and other non-physical types. For example, an energy business provided confidential counselling services to team members affected and transferred additional workers to assist in looking after customers.

Another energy business supported customers by waiving fees and providing grants for electricity and gas customers. A transportation business discounted fares for passengers and an airline provided flights for emergency services personnel. A common type of support by banks, utilities and communications businesses making non-physical donations was to waive or postpone fees to allow affected customers to deal with more pressing concerns. For example, during the Queensland floods, a telecommunications company waived fees for fixed payphones and supplied free mobile phones and sim cards to evacuees. Goods and physical assets (41 per cent of in-kind contributions, n=21) was next most common such as a building materials company that supplied transport and materials to support affected communities. 59 per cent of contributions had more than one in-kind subtype identified (n=30).

Reasons for support

Few businesses explicitly provided a reason for making contributions. Where reasons could be ascertained, Figure 8 shows the number of mentions.

Looking after customers was the most common intent (overall n=22). Examples were a mining business that paid for its employees to assist in the clean-up following the Queensland floods and a retail chain that justified their contributions to the Queensland Premier's Flood Relief Appeal and Christchurch Earthquake Appeal as a demonstration of its commitment to their employees and customer base in communities where they operated.

Corporate social responsibility was next most common (overall n=21) including an industrial business that itself donated and also encouraged their employees to donate money and supplies to communities most affected. Seven businesses contributed in order to maintain business continuity, such as an energy company that altered their supply chains and worked extended hours to reopen retail sites and truck stops in order to maintain a steady supply of fuel in Christchurch after the earthquakes. No businesses mentioned seeking profit or being required to contribute by regulation.

Discussion and conclusion

For the first time in an Australasian context we identify the degree to which large businesses have been involved in response and recovery efforts associated with severe disaster events. Despite limited efforts by authorities to involve businesses in emergency management, it is revealed that large businesses are already supporting communities. This, however, is not universal, and the potential exists to enhance the role of the business sector as part of a nationwide whole-of-community approach to emergency management.

Like in the United States (Johnson et al. 2011), businesses in Australia and New Zealand have been reactive to disasters and contributed in a range of different ways by way of cash or in-kind means. Businesses can act as conduits to coordinate support from a variety of sources including from their employees and customers. However, the business sector itself is also vulnerable to disruption in a disaster and so strong business resilience is a prerequisite for businesses supporting community needs.

Businesses mostly provided support independently in a variety of ways including directly to communities or via partnerships with NGOs rather than acting as an extension of government. Businesses also supported affected employees to resume their work-related responsibilities.

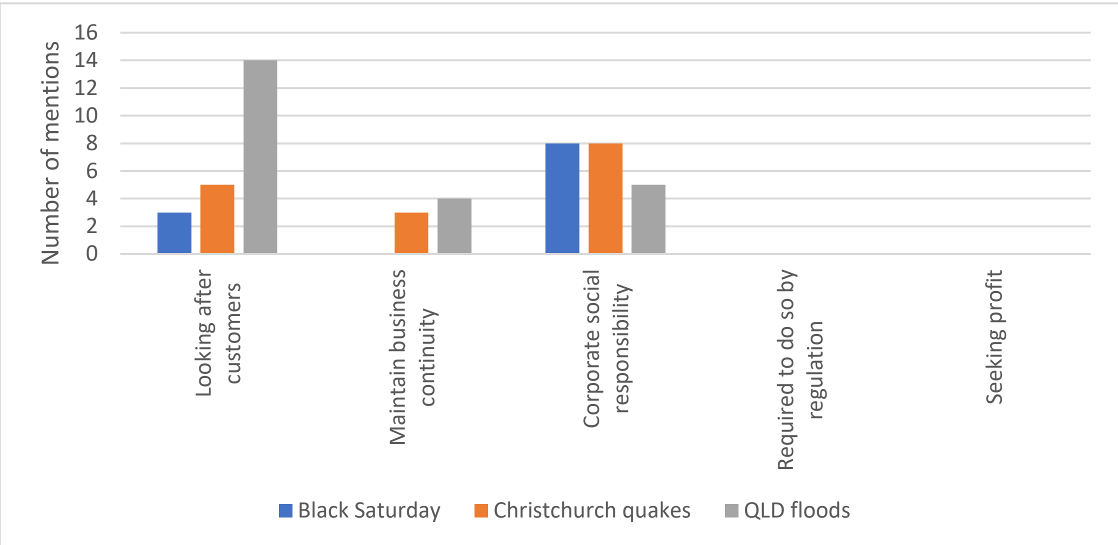

Figure 8: Reasons for support.

Johnson et al. (2011) argue that United States businesses are primary motivated by core financial needs based on business continuity and profitability and values, the norms that society expects of businesses whereas in the Australasian examples examined here, businesses appear to have been largely motivated by a commitment to their employees and customers and by social responsibility objectives. Cash donations by Australian and New Zealand businesses may suggest that motivations are more altruistic, reflecting more complex business objectives then solely profit generation.

Our research highlights the opportunity for businesses to plan their involvement in disasters either through business continuity plans or as part of corporate social responsibility programs. These efforts may include decisions regarding preferred delivery partners and types of support that could be provided, and relationship building to support these activities. The opportunity for Government could be in informing businesses in respect of priority needs, how information may be obtained about such priorities at the time of a disaster and encouraging investment in resilience building initiatives.

Government does not need to formally activate the business sector as businesses will be reactive to the needs of their customers and employees. In this sense the relationship between businesses and government may be best defined as one of collaboration rather than direct control. Nonetheless, information sharing is vital in that it enables the business sector to best direct its efforts and to make critical business continuity decisions. Emergency management organisations can gather information from businesses who have local networks, supply chain vulnerabilities and ideas about how their capabilities can be utilised.

Mechanisms for collaboration should be included within disaster plans. This could include dedicated collaboration centres involving businesses, NGOs and government. In the United States, FEMA has developed a National Business Operations Center that acts to exchange information between Government and the business sector. During disasters, the Center provides real-time situational awareness and ground truthing on the needs of impacted communities. FEMA has also created a business sector role within its National Coordination Center to facilitate information sharing with businesses.

In Australia, Trusted Information Sharing Networks exist to facilitate sharing of information between the Commonwealth Government and critical infrastructure providers but do not provide a wider business forum for collaboration. On the positive side, the capability to work with business has been recognised in the Australian National Preparedness Framework; however, emergency managers may require upskilling to take full advantage of this capability (Gissing et al., 2018).

Further research may reveal more about the activities of businesses immediately following disaster events. Highlighting the contributions of businesses to disaster response and recovery efforts may serve to enhance motivations for business involvement. Finally, this study has focused on large businesses and there is a need to better understand the contributions that small businesses make to disaster management.

Acknowledgements

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ABSTRACT

The key problem faced in preparing for future disasters is a problem of imagination. It is a problem embedded in the stories we tell about what we imagine might happen. These stories tend to focus on a 'bell curve' distribution of disaster events, combining our own lived experience with the stories of others. This combination of personal experiences and the stories of others forms the basis of our perception of risk and vulnerability. This is a dynamic and ongoing process. The story is never finished, nor is it complete, as we selectively incorporate or reject information depending on its source, content and compatibility with the existing narrative.

The existing narrative for natural hazard management incorporates perceptions of probability; generally, 'disaster consequences will tend to hover close to the mean and every now and then we will be tested'. As the volume of hazards grows the narrative is more deeply imbued with concepts of coping and 'lessons learned'. If certain narratives are allowed to flourish uncontested within an organisation an ironic consequence can be a failure of imagination and coping. A failure to be future ready.

This paper is a discussion about the extent to which we're future ready using the Johari window as a heuristic and reflecting on a case study from Indonesia.

Peer-reviewed article

Are we future ready? It depends on who you ask

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Introduction

In February 2002, in a long interview following the Al Qaeda attacks in the US of September 11, 2001, the US Secretary of Defence Donald Rumsfeld famously said:

Reports that say that something hasn't happened are always interesting to me, because as we know, there are known knowns; there are things we know we know. We also know there are known unknowns; that is to say we know there are some things we do not know. But there are also unknown unknowns—the ones we don't know we don't know. And if one looks throughout the history of our country and other free countries, it is the latter category that tend to be the difficult ones.

US Secretary of Defence Donald Rumsfeld (2002)

Among other things Rumsfeld's comments renewed interest in the 'Johari Window' (Luft & Ingham 1961). The Johari window was initially designed as an interpersonal awareness tool but is now used in a range of contexts including organizational redesign and the assessment of hazard risk (Kim 2017; Kim 2017b). In this paper we consider two of the four 'frames' of the Johari window to consider the question of 'future readiness'. The discussion will be illustrated with a case study from Indonesia that has relevance in Australian and international contexts. Donald Rumsfeld identified one of two key issues relating to knowledge and perception of risk which were first presented in the 1950's through the 'Johari window' (Luft & Ingham 1961).

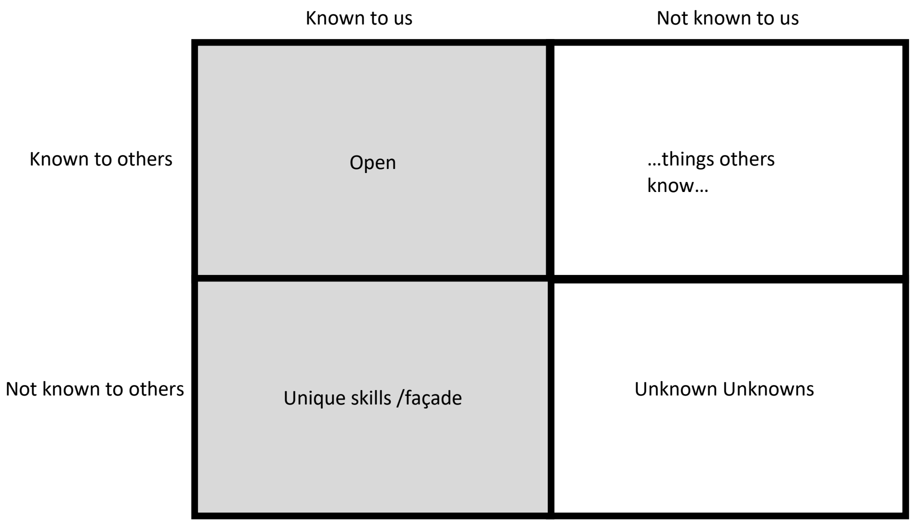

Figure 1: The Johari Window: (after Luft and Ingham 1961).

Rumsfeld draws attention to the problem of the unknown, and not merely to facts that we don't yet have, but events that we can't imagine. Indeed, those events were described by the president of the United States as "unimaginable" (Bush 2001). This inability to imagine the nature and scale of hazards and vulnerability is a major issue in any consideration of whether or not we are 'future ready' (Ballantyne et al. 2000; Paton, Smith & Johnston 2000). To be prepared for a future we cannot imagine seems to be a paradox.

Perhaps a first step is to be aware of the possibility of exercising our imagination. In Australia it is unthinkable that an agency or government might admit that it did not take measures to protect citizens from future hazards. One trend that appears to accommodate the failure of imagination is to label events as 'unprecedented'; never seen before. While not quite a proxy for 'unimaginable', it is applied to many large-scale, high-impact hazards, such as the Black Saturday bushfires (Paveglio, Boyd & Carroll 2012). The hint that it is a fig-leaf for failure of the imagination lies in the fact that it is used even when there is data to indicate that fires of that magnitude might be reasonably expected (McLennan & Handmer 2012). 'Unprecedented' explains the scale of impact of the hazard as well as why we have the sense of being overwhelmed without recourse to admission of our limited imagination. This feeling of being overwhelmed is captured in the video made by Channel Nine cameraman Richard Moran who patrolled with Officer Darrell Thornthwaite of the ACT Fire Brigade District, during the Canberra Bushfires in 2003 (Moran 2003). The footage is disturbing precisely because the viewer has a fly-on-the-wall observation of the personal consequences of a fire beyond Thornthwaite's imagination. The Canberra bushfires were of course unprecedented in the sense that the fire did burn into suburbs and 500 homes were destroyed (McLeod 2003) after 50 years without a single similar loss.

There are ways to investigate unknown unknowns (Kim 2017a; Kim 2017b), but our purpose here is to look through the Johari window category that is much easier to access. This is the frame of the Johari window; 'what others know'. This might also be characterised as 'things we could find out easily but often don't'. If other people know something, particularly something that may prove important to our own survival, how is it that we don't know it? How are these information asymmetries established and maintained? What is it about certain information, or the people who hold it, that has restricted us from accessing the knowledge? One distinct possibility is that we haven't asked. This failure to ask may in turn arise from a failure of imagination, but it is equally plausible that it arises from a culture or social setting that does not encourage the asking of questions and the testing of our knowledge.

What others know: an Indonesian case study

There is a story, possibly apocryphal, that three days after the 2004 tsunami, when Indonesian President Susilo Bangbang Yudhoyono was advised that the whole island of Simeulue had survived, he said one word – "Impossible." The proximity of the island to the epicentre of the earthquake and the scale of devastation elsewhere meant the government had already written off Simeulue as destroyed. But Simeulue locals tell the story of how the military pilots looking for survivors were shocked to see thousands of people standing on the hills waving; big smiles on their faces.

In fact, about 80,000 coastal people on the island of Simeulue had survived the tsunami. With no communication possible with the outside world in the early days, post-event, Simeulueans thought the tsunami had happened only to them. They didn't know the tragic story of loss on the mainland only 150km away. For many it was 10 days before they had any contact with their friends and relatives in Sumatra. They were shocked by the level of carnage in Aceh, because on Simeulue they knew about 'smong', their own word for tsunami and what to do when it threatens. Why didn't their compatriots survive when they did?

The answer to this question, and deeper questions about the operationalisation of cultural knowledge during rare hazard events forms the basis of the current research. Field research was conducted in Simeulue in 2016 and 2017 to examine the cultural context of the survival of the island's inhabitants. The work was conducted as part of a PhD research program in three field seasons from 2015 – 2017 (Sutton et al. 2018). Narrative interviews were recorded with the aid of a translator from 58 individuals across the island. Each interview participant had personal experience of the 2004 tsunami. These interviews reveal a remarkable consistency of understanding of the nature and warning signs of a near-field tsunami.

The people of Simeulue had maintained an emotional narrative tradition about smong. This tradition has been kept alive within families and villages across the island following an even more devastating smong in 1907. When the massive 9.2Mw earthquake occurred on Boxing Day 2004 everyone realised that a smong must come soon. They knew they had very little time to get to higher ground. So, they ran. Of 80,000 people, locals say only one died (and give his name and the peculiar circumstances of his death). Babies and grandmothers were carried, the blind were led by relatives, everyone running to the hills as the sea receded. By the time the smong arrived they were able to look down and thank their grandparents for passing on the cultural knowledge that saved their lives – while watching their homes destroyed.

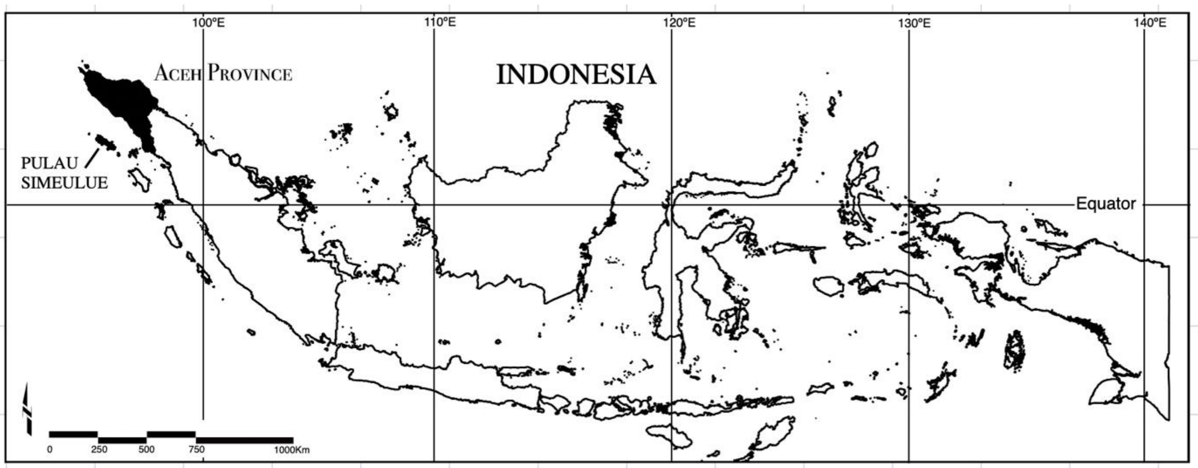

Figure 2: The location of Simeulue Island in Indonesia.

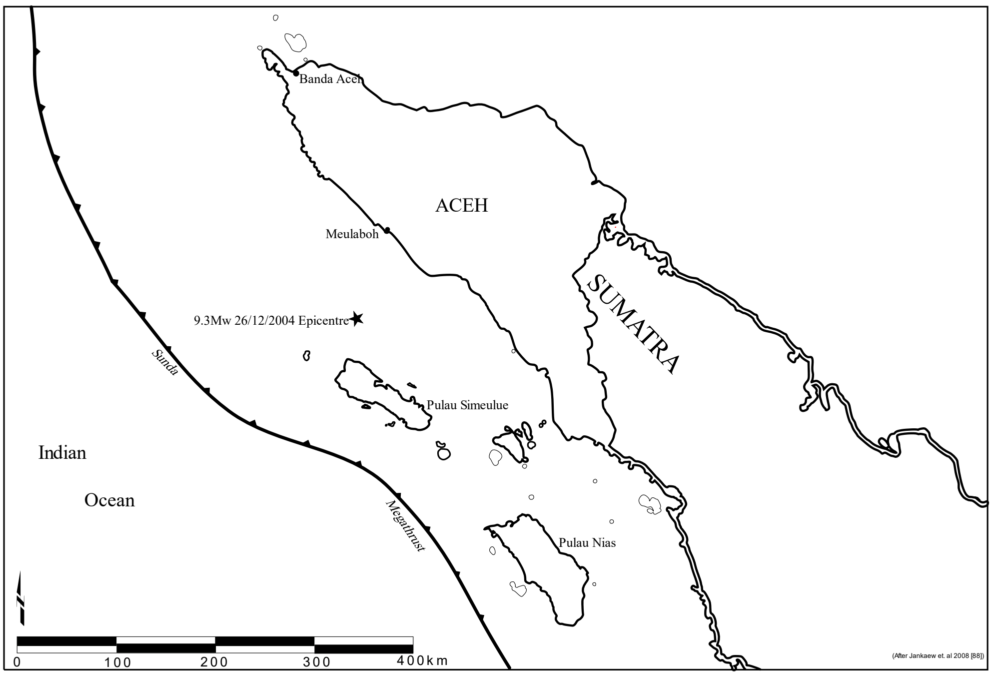

Figure 3: Location of Simeulue relative to the Epicentre of the 2004 tsunamigenic earthquake.

The story of smong is a story that the people of Simeulue knew, but which was not known by others. Amad[1] told of his experience of the tsunami in Banda Aceh. A Simeulue local he was at that time a university student in the provincial capital. He felt the earthquake while crossing a bridge. He looked to the coast and saw the wave and yelled "SMONG" and "RUN. RUN" repeatedly. Locals laughed at him and indicated they thought he was crazy. He ran to a nearby 5-storey building imploring locals to do the same. They did not respond other than to mock him. Less than an hour later Amad was watching bodies wash by in the flood. After graduating, Amad has worked as a journalist and has tried to share the "wisdom of smong" throughout Indonesia.

Accounts similar to Amad's were provided by Simeulue locals Nina[2] and Eni[3], who were in Banda Aceh and Meulaboh respectively when the smong struck. Nina was meeting with a religious organisation near the river when she felt the earthquake. She tried to persuade those near her to run to higher ground, but they rejected her advice. Instead they went down stream to see what the commotion was. They were all killed. Eni was studying nursing. Following the earthquake many people went on motorbikes to the coast to see what was happening. Shortly after Eni saw many bodies tumbling in the surge of water several kilometres inland.

These three stories show how, in close proximity, good information and sound choices can mean life or death. From the macro-scale to the individual, the consequences of the lack of knowledge about smong in Aceh were devastating. Nearly 300,000 people died and the tragic stories of those interviewed in Simeulue suggest that at least some of them had a chance at survival – if only they had "opened the Johari window" and sought to share Amad's knowledge of smong.

Why don't we know what others know?

What are some of the factors that cause information asymmetry and how do these contribute to us not knowing what others know? We indicated (above) that 'not asking' is a potential contributor, but there are likely to be other factors as well. In Simeulue, isolation is one of the factors that contributed to the information asymmetry with the rest of Aceh.

It was compounded by the very long intervals between major tsunami in the region (Rubin et al. 2017; Sieh et al. 2015). Although there is clear evidence that past tsunami were catastrophic (Daly et al. 2019) all memories fade and the emotions attached to tragedy diminish with time. But there are other factors as well and the reaction of Banda Aceh locals to Amad's frantic attempts to warn people is also indicative of a more common contemporary response to the unknown. The rejection of Amad's warning is linked to who we are and where we obtain our information (Westcott, Ronan, Bambrick & Taylor, 2017) and these traits are not confined to Indonesia. One can imagine someone yelling 'tsunami' and 'run' in St Kilda or Bondi receiving similar raised eyebrows to the victims of the Banda Aceh tsunami. Those outside our 'in-group' are likely to be ignored – or, like Amad, mocked!

The proximate cause of a reticence about the knowledge of others is trust (Paton 2007). The warnings of a person yelling 'tsunami' in St Kilda, Bondi or Banda Aceh are ignored because we don't trust them. We are unlikely to trust information from a stranger or a person we identify as outside our group (Mazar, Amir & Ariely 2008). We are also unlikely to trust someone whose behaviour is markedly wrong for the context (you won't be considered crazy yelling at the football, but do it in a public space, on a normal day, and you will).

A lack of trust in the value of information and more importantly in the value of the source of information can contribute to ongoing information asymmetry. This particular failure of imagination is a potential problem in organisations with highly specialised functions and skill sets. Hazard response organisations for example have traditionally been staffed by a highly skilled but homogeneous workforce (NSW Rural Fire Service 2001). In these situations, the recruitment of staff and the roll-out of training programs build capacity to deal with hazards within the normal statistical distribution. The agency program, taken as a whole tends to build organisations with self-reliant cultures which can in turn develop a lack of trust in external sources of information and the wider community.

The recent review of the US Federal Emergency Management Agency (FEMA 2019) found that over the last 20 years, the capacity of personnel within the agency had improved considerably. However, the "Building Cultures of Preparedness" report found that despite improvements in the agency's capacity, there had been no improvement in community resilience over the same period.

The self-reliance and capability of agencies is, ironically, potentially linked to a diminished trust in an outside organisation. Taleb (2007) describes the false security that resides in the 'bell curve' distribution of events. While most hazard events will be managed within the limits of existing resources, training and experience, a few will stretch the capacity of agencies and communities. But each time a hazard is 'managed' the sense of confidence in the capacity to cope will grow. The combination of this confidence in coping and a mistrust of outsiders when combined with universal optimism bias (McKenna 1993; Sharot 2011) can, if not managed, confound the imagining of extraordinary events which will rely on the engagement with networks right across society. Taleb (2007) calls events that are outside the statistical distribution, with a scale and consequence that exceed all capacity, "Black Swans". The problem is that Black Swan events do occur.

[1] Not his real name. Interview recorded 10 December 2016
[2] Not her real name. Interview recorded 8 March 2017
[3] Not her real name. Interview recorded 10 August 2017

The 2004 Boxing Day tsunami was a Black Swan event as was the Canberra bushfire of 2003 mentioned above. But these events were not necessarily 'unknown unknowns' as such, and as the Simeulue case study shows, a dispassionate review of 'what others know' may have extended life-saving timely evacuation to the rest of Aceh.

Technology

The FEMA (2019) report shows how the agency has improved its technical capacity through the adoption of technology. In Australia too EM agencies trust in technology and, as a general rule, emergency management agencies remain positive about their ability to effectively respond to future natural hazard events through the use of technology. Any observation of interactions between agency staff will note a degree of enthusiasm when discussing technologies that is not found in canvassing other program elements. The trade show is dominated by technological solutions to fire and natural hazard management products, with a much smaller emphasis on human or behavioural skills development. The integration of technological improvements to equipment ranging from telecommunications, satellite imaging, PPE and water-bombing aircraft into operations has seen significant improvements the effectiveness of hazard response. There is also encouraging science behind the incorporation of new technologies in both preparation and response to natural hazard events (Edwards, Maier, Hutley, Williams, & Russell-Smith 2013; Provitolo 2012; Jeremy Russell-Smith, Whitehead, & Cooke 2009; Shaw, Izumi, & Shi 2016). In the context of conversations about technology then, some will say that we are, or we will soon be, future ready.

However, there are many reasons for a more cautious assessment of the capacity of technology to accommodate the unknown events of the future. The first is that there does not appear to be a correlation between accelerating technology and decreasing disaster impact (see Figure 4). On the contrary, at a global level the scale of impacts from natural hazards is increasing. As technology increases the value of infrastructure, the economic risk and cost of disasters accelerates.

A second cautionary observation about technology is that it will always include an unreliability quotient. This can relate to design flaws or inappropriate application with sophisticated technology rarely developed by those who will actually use it. As Charles Perrow says, "Nothing is perfect, no matter how hard people try to make things work, and in the industrial arena there will always be failures of design, components, or procedures." (Perrow 2011b:44). In microcosm readers can reflect on their own experience of loss or failure of a smart phone and the devastating and ramifying consequences a failing in a single item of technology can have.

Steingart et al. (2005) demonstrate that even in moderately complex hazard events technological failures are a common occurrence. This is particularly the case with telecommunications and often results in individual agency personnel developing short-term 'work-arounds' to continue operating safely. In these instances, increasing reliance by individuals on electronic communications may contribute to catastrophic failures in some circumstances. For example, communication infrastructure, the use of mobile devices and integration of real-time remotely sensed data are likely to be unavailable to respond with the intense and distributed impacts of an intense solar storm (Riley 2012).

In some cases, technology has failed due to the very hazards they are meant to respond to. For example, the application of aerial fire suppression can be curtailed by new, unprecedented extreme fire weather as occurred in California in 2019 when aircraft were grounded after being unable to fly to the drop zone because of the conditions that made the fire so dangerous (Serna & Kim, 2019).

Other critical technology failures include the Indonesian tsunami warning system (InaTEWS) (Carvajal, Araya-Cornejo, Sepúlveda, Melnick, & Haase 2019; Lassa 2016) and the failure of the Fukushima nuclear power plant following an earthquake and tsunami in 2011 (Perrow 2011a)

Even a simple technology can fail in circumstances if a community does not have a genuine trust in its effectiveness. Such an example was observed during the 2012 earthquake in Banda Aceh (Rahayu 2018). In this instance, vertical evacuation shelters had been built across the city following the 2004 earthquake. However, community mistrust in their structural integrity and their effectiveness during the panic of the quake meant they were largely unused (Rahayu 2018). Instead people crowded into traffic jams trying to get a mobile phone signal. Had there been a tsunami like the one in 2004, the death toll would have been huge – despite the development of escape technology.

As technologies surrounding disaster response are inevitably connected to or operated by people, human factors will remain an ongoing source of concern. This is not so much about 'human error' as Stanton (1996) points out, but rather that social context is rarely taken into account in either the development or the operation of complex technologies. Operational social contexts may exacerbate fatigue, stress, inadequate training or cognitive load in ways that amplify technological inadequacies, often with catastrophic consequences (cf. Hetherington 2006; Flin et al. 2002).

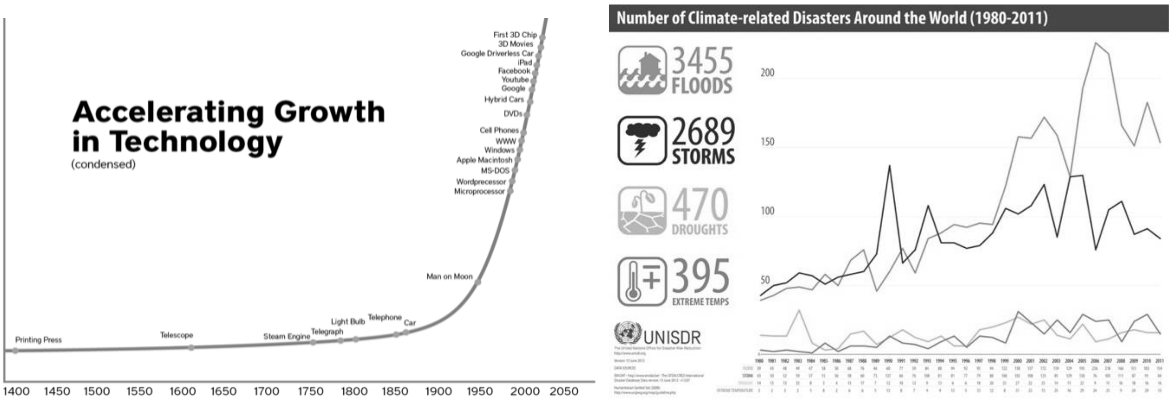

Figure 4: Accelerating growth in technology and rate of climate-related disasters.

A fourth issue with relying too heavily on technology is risk compensation (Adams 2001). In a climate of uncertainty, knowing that response resources exist can reduce the perceived need for vigilance and preparation (Paton & McClure 2013). In a world where rates of preparation for disaster are low (eg. FEMA 2019, Ballantyne 2001) efforts are need to ensure there is no attrition of community resilience. To this end Australian disaster management agencies will often issue overt messages to the effect that ‘there is no guarantee of a fire truck’ responding to a bushfire at your place (Country Fire Service SA n.d.)

While not ‘risk compensation’ per se, reliance on technology may also contribute to an enhanced blindness to other means of improving community preparedness for disaster events. This was perhaps seen in the 2019 Australian federal election, where the two major parties had something of a technology bidding war (Morrison 2018; Shorten 2019), which tends to perpetuate the focus on the technology and skills of response.

Technology is without doubt a part of any future readiness, but a) it does not of itself build community resilience and b) the propensity for technological failure in critical incidents means we should cast a wide net in our search for solutions The question of ‘future readiness’ for Banda Aceh is likely to have changed through time; for example, following the construction of the vertical evacuation shelters, city planners and emergency agencies may have said ‘yes – we are ready’, however following the debacle in 2012 the answer is probably ‘no’.

What others?

In order to keep our imaginations active, we need to move out of our comfort zones and constantly seek new narratives. This is challenging for bureaucracies whose bounded responsibilities in turn place limits on research and researchers (Hewitt 1983:8). New narratives can be informed by science including in the area of bushfire management where we need to think more about the human contributions to the problem. However, Stephens (2019) makes the observation that of 6738 research papers about wildfire between 1990 and 2018, only 194 or 2.9% focussed on psychology or human behaviour. This is despite the fact that anthropogenic ignitions remain a major problem in wildfire management (Collins, Price, & Penman, 2015; Russell-Smith et al. 2007) and human behaviour is a major contributor to bushfire casualties (Victorian Bushfires Royal Commission 2010; 2009).

More intimate, and perhaps effective, narratives can be achieved through dialogue with a more diverse community. Australia is fortunate in having a different, but quintessentially Australian, narrative about fire resident within our indigenous people’s traditional knowledge (Garde et al. 2009; Sithole et al. in Press; Whitehead et al. 2014). This world view does not mean merely learning to cope with destructive wildfires, minimising deaths during conflagrations, but to create a fire regime that obviates wildfires altogether (cf. Gammage 2011). The perspectives this world view offers, including a new way to ‘learn to live with bushfire’ is becoming more widely accepted (Ellis, Kanowski & Whelan 2004). For many Australians this perspective is contrary to a deep sense of concern about bushfire. Increasingly efforts are being made by the mainstream to gain a sense of what aboriginal people know about fire. There are now many formal and informal dialogues contributing to the sharing of the ancient fire narrative of Australia. Should this narrative emerge in a consistent re-telling across the country then perhaps we may say, in respect to fire at least, that we are future ready.

Diversity and inclusion are actively being pursued through research and within agencies (Mackintosh 2019; Martin & Mounsey 2019; Young 2019). In addition to engendering a workforce that is reflective of the demographics of the community they serve, agencies are developing community resilience and learning through dialogue. New narratives are emerging that shed light on what we don’t know and offer the potential to fulfil the objective of the national strategy (COAG 2011) to have a ‘shared responsibility’.

Conclusion

The issues touched on in this paper are not new. Nearly forty years ago Kenneth Hewitt explored the way in which the “dominant perspective” of natural hazard management was focussed on maintaining a status quo rather than exploring new solutions (Hewitt 1983). Among other things Hewitt argued that this dominant perspective held “as an article of faith …that… the further removed people are from urban-industrialism and its technocratic forms, the more completely they are at the mercy of an elementary biophysical struggle with the habitat." (Hewitt 1983; 18). In this context "the technocrat may presume to speak for these people, but can find little value in dialogue with them or learning from them." (ibid).

The current spread of research interests (Stephens 2019) and the belief in 'relief by technology' diminishes our asking of questions, particularly of less technocratic elements of society. Before 2004 virtually no-one outside Simeulue was in any way interested in the stories, songs or lullabies grandmothers told their grandkids. Apparently poor, powerless people on a remote island held little interest for researchers, emergency management agencies or even government in general. But what those old people knew saved lives. The answer to the question "Are we future ready?" really depends on who you ask. Asking communities about their lives and their hazards is a first step to building community resilience.

Acknowledgements

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ABSTRACT

We explore the effects of a small bushfire on the income trajectory of employed residents of Toodyay, a regional town in Western Australia. Our study reveals how detailed profiling, using public data, can overcome statistical limitations in disaster risk reduction exercises and better direct post-recovery interventions to minimise disruptions to important income streams in small regional towns.

Peer-reviewed article

Disasters and economic resilience in small regional communities: the case of Toodyay

Mehmet Ulubasoglu and Farah Beaini, Deakin University and Bushfire and Natural Hazards CRC.

Introduction

Natural disasters in Australia are very costly, and often have devastating socio-economic effects on impacted communities. Recent devastating examples include the Victorian Black Saturday Bushfires 2009 and the Queensland Floods 2010-11, which caused significant loss of life, losses across multiple sectors (including mining and agriculture), and damage to countless homes and properties. With the severity and frequency of natural disasters expected to increase (Kitching et al., 2014), there is growing academic and policy effort towards better understanding: the risks such disasters pose on Australian communities; the impacts they have on different industry sectors and community groups; and the role that disaster risk reduction can play in minimising such impacts and building disaster resilience.

Estimating the total economic costs of natural disasters can be difficult, owing to the lack of complete and systematic data, conceptual difficulties (Kousky 2014) and divergent predictions from growth theory about the effects of natural disasters on economic growth (Loayza et al. 2012). While the literature is inconclusive, with some studies reporting negative effects and others positive or insignificant effects (Loayza et al., 2012), a recent meta-analysis of the literature showed evidence of negative impacts in terms of direct costs (Lazzaroni and van Bergeijk 2014), with more severe disasters causing the highest damage and increasing the likelihood of long-term and/or negative consequences (Boustan et al. 2017; Kousky 2014).

There is also evidence of distributional effects. Economic and human losses shown to be more pronounced in poorer countries (Schumacher & Strobl 2011), and institutional factors and educational attainment levels found to be important determinants that influence resilience and recovery (Kousky 2014; Felbermayra & Gröschl, 2014). Economic diversity also matters. Relying on a single economic sector for income heightens community vulnerability and elongates disaster recovery time compared to diversified economies (Cutter et al. 2008). The type and interlinkages of economic sectors also play a significant role. Due to its land-intensive nature, the agricultural sector is often adversely affected (FAO 2015). Locally, a study of major Victorian bushfires found that industries most susceptible to direct or indirect impacts are the Agriculture, forestry and fishing sector and retail trade (Stephenson 2010). Conversely, the construction sector may experience a boom in the immediate aftermath of the disaster as households redirect expenditure towards rebuilding that they otherwise would've deferred, only to experience a lull in the next few years once that expenditure subsides (Kousky 2014). Even with a diversified economy structure, the interdependence of sectors can have knock-on effects (Yu et al. 2014).

Thus, industries more heavily reliant on inputs from the agricultural sector are likely to experience adverse effects to their production. While these broader examinations are useful, aggregated numbers can mask hide very large distributive impacts, as the typical instruments used (GDP and aggregated consumption) can be misleading measures of actual welfare losses (Hallegatte 2014). What's missing is a systematic understanding of how these broader economic impacts of natural disasters translate to the individual level vis-à-vis income effects; how long these effects persist; and which individuals within the community bear the brunt of these costs. Indeed, regardless of a country's economic development, a lower socio-economic status has been consistently associated with greater post-disaster hardship (Norris et al. 2002), with the poor suffering significant disaster losses due to lower financial capacity and limited access to public and private (e.g. insurance) recovery assets (Blaikie et al. 1994; Gladwin & Peacock 1997). For example, while storm damage from Hurricane Katrina was uniform across demographic groups, it was lower income individuals who were less likely to have evacuated or cover for flood insurance (Masozera et al. 2007). Many other known vulnerabilities to disasters, such as being female, old age, or with lower educational attainment (McKenzie & Canterford 2016), are highly correlated or interdependent with income.

The link between income and disasters also extends to mental health outcomes: In the case of bushfires, the longevity of disruptions to income post-disaster has been shown to materially affect the mental health of those affected by bushfires (Gibbs et al. 2016). Thus quantifying the effects of disasters based on these social and economic dimensions can help policymakers better target and evaluate disaster mitigation recovery programs.

To that end, our research program explores the impact of a number of Australian natural disasters, of various types (fires, flood and cyclone), scales (small, large), and locational settings (regional, metropolitan) on the disaster-hit individuals' economic resilience (measured through their income stream). It disaggregates these impacts on individuals based on who they are (their demographic attributes), if they work (unemployed, employed), how much they work (part-time, full-time) and the industries they work for.

This paper investigates the income effects of the 2009 Toodyay bushfire on the income trajectory of residents of Toodyay – a small regional town in Western Australia with a population of 4,450 around the time of the bushfire. The fire conditions were some of the worst seen in Western Australia at the time, and burnt around 2,900 hectares, the equivalent of 2% of the Shire of Toodyay's total area. While no casualties were reported, the total cost of damages was estimated at $100 million (FESA 2010b).

From a policy perspective, this paper contributes to a greater understanding of the potential economic effects of natural disasters on individuals and communities living in regional towns within Australia (Figure 1). Toodyay is fairly typical of such small, regional Australian towns, having an ageing population within the 1,000–4,999 population range, and an economy historically linked to agriculture, mining and manufacturing; industries which are known to be sensitive to natural disasters (Ulubasoglu et al. 2019). Such towns (~1,700 in 2016) form 9.7% of Australia's population and are mostly concentrated around Australia's eastern seaboard (ABS, 2018).

For Western Australia in particular, it is expected that agricultural businesses in currently marginal areas, such as the Wheatbelt region (in which Toodyay is located) are most at risk from climate change (Sudmeyer et al. 2016), and so deserve particular attention when considering disaster resilience in the state.

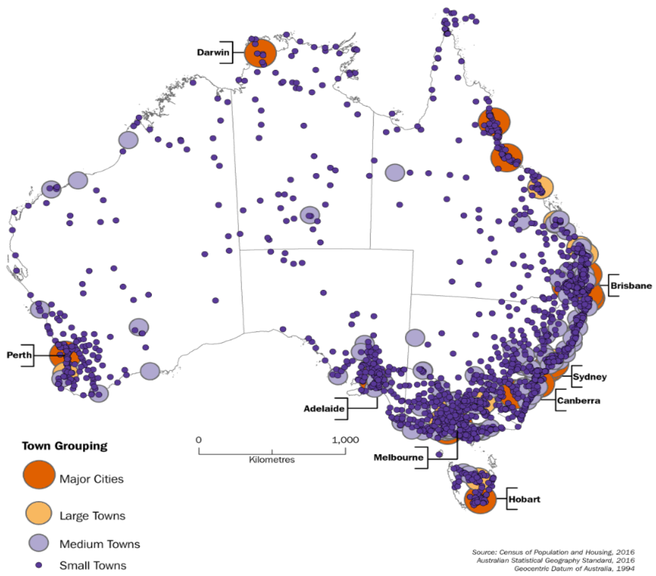

Figure 1: Australian towns, by population size groupings 2016. Source: Australian Bureau of Statistics 2018.

The rest of this paper is organised as follows. We set the scene by providing an overall socioeconomic profile of Toodyay and contextual information on the Toodyay fires 2009. We then outline our methodology, incorporating our sample construction and descriptive statistics. Following our results, we offer conclusions on how this study can be utilised to inform disaster mitigation and recovery activities.

Toodyay profile

Socioeconomic profile

Toodyay is a regional town located in the northern Wheatbelt region of Western Australia, approximately 80km North/East of the state capital Perth. It is characterised by agricultural activities and low population density, with 2.7 persons per square kilometre.

Toodyay has a small population, which grew from 4,330 in 2006 to 4,707 in 2013, before declining to 4,500 in 2016, placing it within the ~1,700 small towns scattered across Australia. The population is relatively older and ageing – Toodyay's median age reached 51 years in 2016, with the share of residents aged 65 or older increasing from 12.8 per cent to 23.3 per cent over the decade.

Since 2006-07, there have around 400 businesses on average located in the Shire of Toodyay (Figure 2). A significant share of these businesses are non-employing (i.e. either sole-proprietorships or partnerships with no employees; Figure 3), and are mostly concentrated in the agricultural and construction sectors (Figure 4). Owing to this, over 60% of Toodyay's employed residents typically work outside the Toodyay Shire (Figure 5), mostly in Perth (~28%) and neighbouring Northam (~16%).

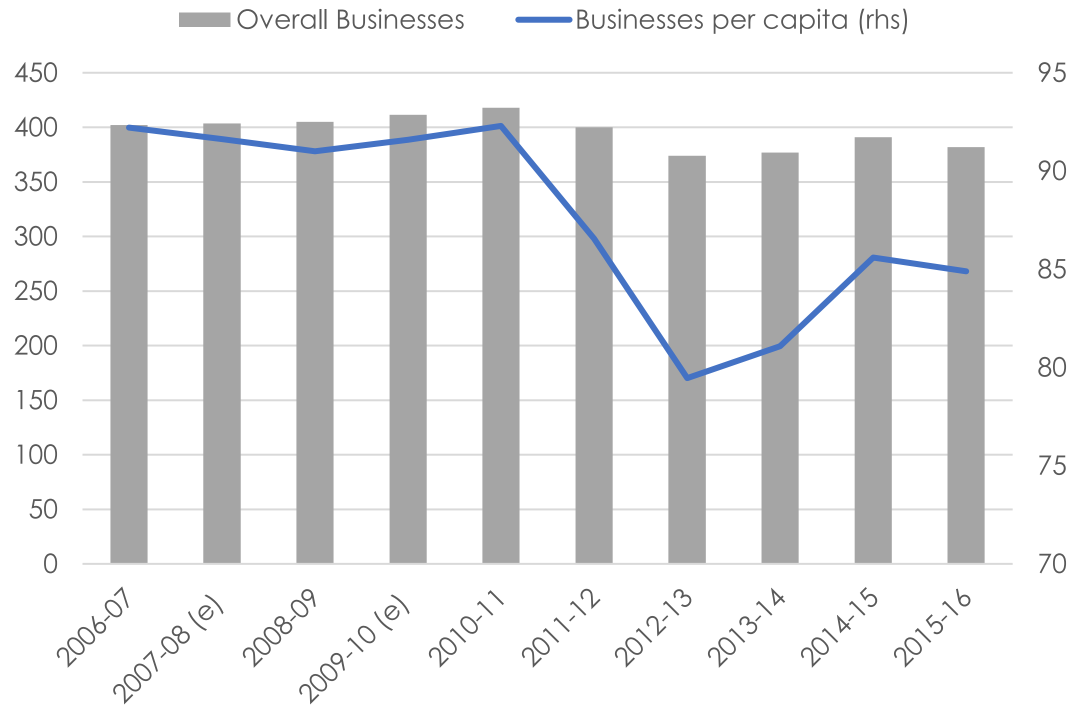

Figure 2: Toodyay Shire businesses, overall and per 1000 persons. Source: ABS, CAT 3218.0 Regional Population Growth; ABS, CAT 8165.0 Counts of Australian Businesses, including Entries and Exits.

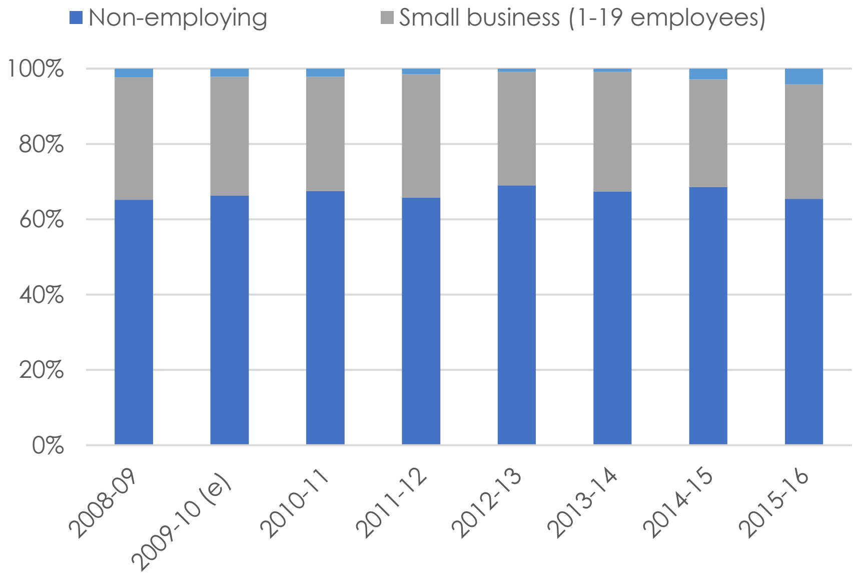

Figure 3: Toodyay Shire businesses, overall and per 1000 persons. Source: ABS, CAT 8165.0 Counts of Australian Businesses, including Entries and Exits.

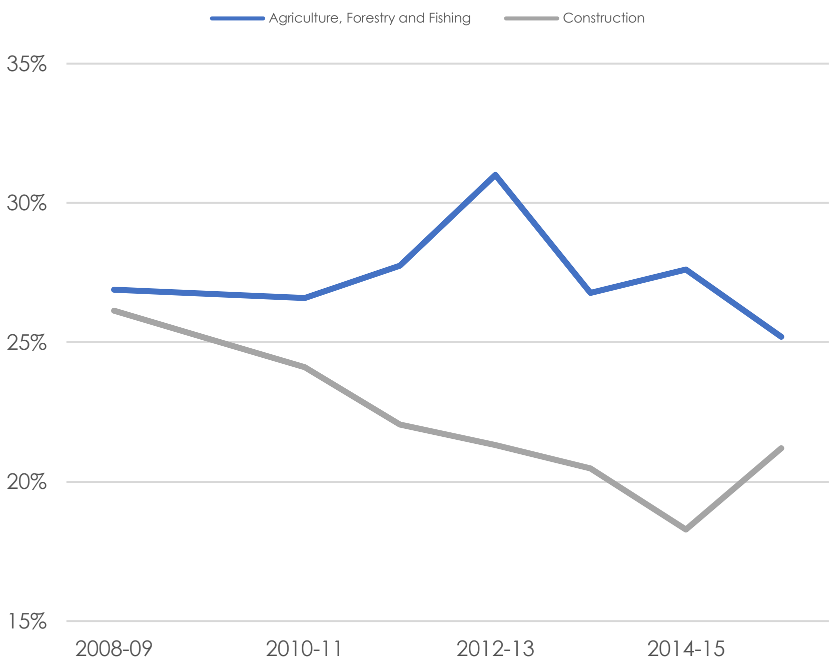

Figure 4: Toodyay Shire non-employing agricultural and construction businesses (% of total non-employing). Source: ABS, CAT 8165.0 Counts of Australian Businesses, including Entries and Exits.

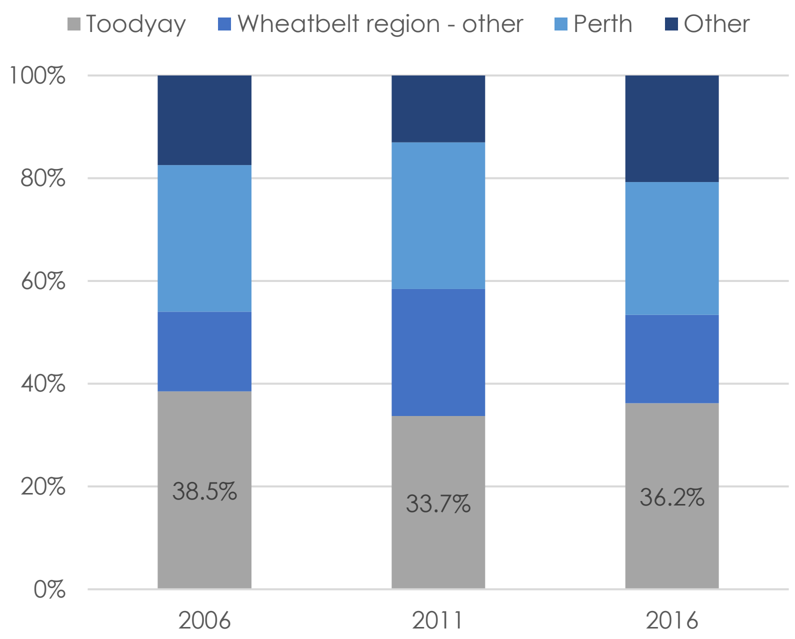

Figure 5: Toodyay Shire residents place of work (%). Source: ABS Census of Population and Housing (2006, 2011, 2016) (Usual Residence Data) retrieved via Table builder. Figure 5 excludes Place of Work "Not Stated" Or "Not Applicable".

Top 5 Industries of Employment	2001	2006	2011	2016	Trendline	2001-2016 Annualised ∆
Toodyay						
Agriculture, forestry and fishing	12.56%	11.10%	7.73%	7.69%		-3.22%
Construction	10.22%	10.97%	10.81%	9.84%		-0.25%
Manufacturing	9.16%	8.17%	6.28%	5.88%		-2.91%
Health care and social assistance	9.01%	9.48%	11.40%	10.06%		0.74%
Public administration and safety	8.52%	8.04%	8.60%	9.89%		1.00%
Retail trade	8.02%	9.10%	9.53%	7.86%		-0.14%
Education and training	7.45%	8.35%	8.02%	8.42%		0.82%
Mining	1.99%	3.62%	6.22%	8.59%		10.25%
Wheatbelt region						
Agriculture, forestry and fishing	29.19%	25.70%	20.28%	20.78%		-2.24%
Retail trade	9.25%	10.01%	9.54%	8.82%		-0.31%
Education and training	7.78%	8.00%	8.54%	8.97%		0.96%
Health care and social assistance	7.19%	8.36%	9.21%	10.02%		2.24%
Construction	6.33%	7.03%	8.28%	7.72%		1.34%

Figure 6: Top 5 industries of employment 2001-2016. Source: ABS Census of Population and Housing (2006, 2011, 2016) (Usual Residence Data). Generated 17 December 2018 using Australian Bureau of Statistics Table Builder.

More broadly, and compared to the Wheatbelt region, Toodyay's overall employed workforce has seen a greater shift away from manufacturing and the agricultural sector, which dropped from the largest employer in 2001 and 2006, to become the sixth largest employing industry in 2016 (Figure 6). Health care and social assistance became the top employer in 2011, while mining also exhibited the strongest gain, most notably over the 2011-2016 period. Based on ABS Census data (at the SA2 level), the top 5 employing industries have typically accounted for 49 per cent of employment. While the overall rankings are different, the common top industries of employment between 2001 and 2016 were Health care and social assistance and Construction.

Toodyay fires 2009

The 29 December 2009 Toodyay Bushfires burnt around 2,900 hectares, the equivalent of 2% of the Shire of Toodyay's total area. According to 2008-09 ABS estimates, 4,450 residents and 405 businesses would have been residing/located within the Shire at the time of the fires.

The fire conditions were some of the worst seen in Western Australia at the time. The total cost of damages was estimated at $100 million (FESA 2010b), though no breakdown is provided. The fire's ignition point was close to the urban interface, destroying 38 houses and damaging over 170 properties (FESA 2010a; FESA 2010c). Some of the properties lost were holiday or second homes (Barnett 2010). One-thirds of affected residents did not have adequate insurance (Parliament of Western Australia 2010). The fires caused material damage to the agricultural sector. 18 cows (Lampathakis 2011) and 100 sheep were killed (FESA 2010b), with damage to 20 sheds, fencing, farming machinery, crops, orchards, vineyards, dairies and olive groves (Moylan, 2010). There was also considerable damage to electricity distribution lines, with repair and restoration of public assets totalling around $443,000. While costly, the Toodyay fire was relatively small (FESA, 2010a), with no fatalities and only 4 injuries recorded (FESA 2010b).

The Toodyay fire was declared a natural disaster, with Category A and B assistance provided by the Federal Government totalling $1.7 million. Over half of this assistance was provided within six months of the disaster (Table 1).

Apart from the federal assistance, the State Government, in conjunction with Western Energy, announced a $10 million financial assistance package for affected individuals on 11 October 2010 (Table 2).

Table 1: Federal Government Assistance (NDRRA).

NDRRA Measure	2009-10	2010-11	2011-12	Total
Category A assistance	$ 299,285	$ 139,065	$ 208,414	$ 646,764
Emergency Food, Clothing or Temporary accommodation	$ 2,343	$ 37,431	$ 3,065	$ 42,839
Removal of debris from residential properties	$ 170,699	$ 3,880	$ 29,228	$ 203,807
Counter Disaster Operations assistance to individuals	$ 87,593	$ 32,478	$ 11,477	$ 131,548
Personal and financial counselling	$ -	$ 616	$ 3,247	$ 3,863
Extraordinary costs of delivering Category A assistance	$ 38,650	$ 64,660	$ 161,397	$ 264,707
Category B assistance	$ 646,205	$ 370,878	$ 46,370	$1,063,453
Restoration or repair of essential public asset	$ 131,452	$ 311,392	$ —	$ 442,844
Counter Disaster Operations assistance to the general public	$ 514,753	$ 59,486	$ 46,370	$ 620,609
Annual totals	$ 945,490	$ 509,943	$ 254,784	$1,710,217

Source: DFES, supplied.

Table 2: Toodyay Financial assistance package. Source: Barnett (2010).

Category	Description	Maximum payment	
Residential buildings	**Established homes which were damaged or destroyed**	**$ 150,000**	
External Structures	**Sheds, fences and other external structures**	**$ 15,000**	
Site Clean-up	**Cost of site clean-up and rubbish removal**	**$ 5,000**	
Home Contents	**Home contents**	**$ 30,000**	
Tools of Trade	**items used for employment purposes (tools and equipment)**	**$ 5,000**	
Private Motor Vehicles	**private motor vehicles including cars, motor homes and motorbikes.**	**$ 10,000**	**$190,000 total payment for each property**

Table 3: Toodyay bushfire disaster assistance.

Assistance	Total allocated	Total distributed			As at October 2012
		2009/10	2010/11	2011/12	
NDRRA (a)	**$ 1,710,217**	**$945,490**	**$509,943**	**$254,784**	**$1,710,217**
Toodyay Financial Assistance Package (b, c)	**$10,000,000**	—	**$4,084,280**	—	**$4,084,280**
Lord Mayor Disaster Relief Fund - Toodyay Bushfires (d)	**$193,000**	**$193,000**	—	—	**$193,000**
Salvation Army Toodyay Bushfire Appeal (e)	**$1,626,000**	**$1,100,000**	**$526,000**	—	**$1,626,000**
Western Power settlements (f)	**$3,000,000**	—	—	—	**< $ 3,000,000**
Total	**$16,529,217**	**$2,238,490**	**$5,120,223**	**$254,784**	**~$10,612,497**

Source: (a) DFES, supplied; (b) Barnett, 2010; (c) Parliament of Western Australia 2011; (d) Lord Mayor Disaster Relief Fund, 2010; (e) Salvation Army, 2010; (f) Parliament of Western Australia 2012.

It is noted that the payments were provided regardless of insurance cover (Parliament of Western Australia, 2010) and were directed at assisting with residential rather than commercial losses. The first payments were reported in December 2010 (Farm Weekly, 2010), with less than half of the funds paid as at 24 October 2012 (Parliament of Western Australia, 2012). Combined with public bushfire appeals and Western Power settlements, monetary assistance for the Toodyay bushfires totaled $16.5 million, with up to $10.6 million distributed as at October 2012 (Table 3).

Methodology

At its core, the research aims to determine the disruptive effects a natural disaster has on an individual's income trajectory. We use a statistical technique called difference-in-differences (DID) model to analyse the Toodyay fire's effect on the income of individuals in the workforce who would have been residing in Toodyay at the time of the fires. The model mimics experimental research design by comparing the differential effect of a treatment (i.e. natural disaster) on a 'treatment group' versus a 'control group'. It calculates the effect of this treatment on an outcome (individual income) by comparing the differences in average changes over time between the treatment and control groups (hence difference-in-differences).

We exploit the rich individual-level Australian Census Longitudinal Dataset (ACLD) available through ABS Datalab which allows us to explore the heterogenous effect of the disaster and provides a convenient 'baseline' (2006) and 'end-line' (2011) surveys for our DID design. As we're interested in impacts on income, we refine our sample to incorporate only Toodyay residents who were in the labour force and reported non-negative income (n=889).

We further restrict our sample to those who did not move between the census years (non-movers; n=447). This is because, In the absence of a full analysis of the migration decisions (which is difficult with the ABS Census being conducted only once every five years), we cannot understand what motivated this movement and what happened to movers.

We compare the difference in incomes of the Toodyay residents (treatment group) and two of its immediate neighbours (Northam and Chittering) as our control group, as their socio-economic characteristics closely resemble those of Toodyay, thus meeting a necessary condition of this model, and enabling us to pinpoint any bushfire-driven effects. Added to the overall income effects, we further explore four key dimensions across which one might expect to observe differences in impact of the fire on individuals:

- gender
- income level
- education
- age.

While our model usually disaggregates sectoral and demographic effects, Toodyay's small population constrained the sample size, making it difficult to achieve statistical power and limiting what we could report on for ABS confidentiality reasons. The small, regional nature of Toodyay is challenging for statistical computations as the non-mover sample size is less than 1000, meaning that achieving statistical power will be difficult. The small sample size also meant that not all variables could be reported due to ABS confidentiality constraints. For these reasons, analysis was limited to demographic attributes that had a sample size of 200 or greater (represented by the horizontal blue line in Figure 7) and met ABS confidentiality constraints. Unfortunately, these restrictions meant that we could not disaggregate at a sectoral level (i.e. by an individual's industry of employment), which we have done for other case studies in our research program.

We present the descriptive statistics for our non-mover sample in Tables 4 and 5.

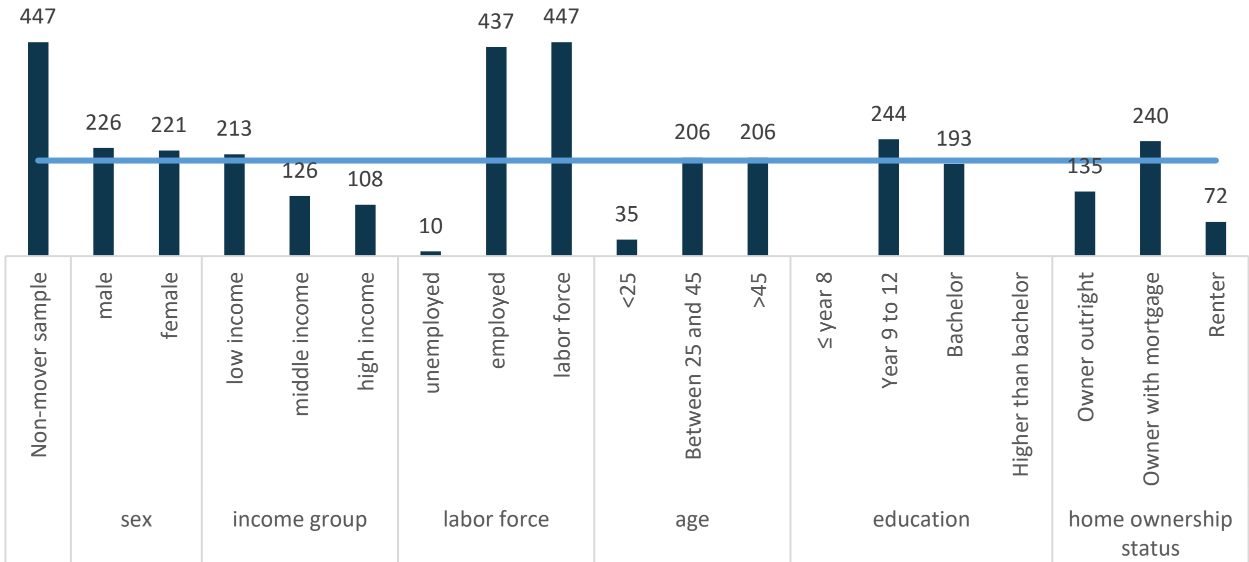

Figure 7: Toodyay non-mover sample sizes (no.), by demographic attributes.

Table 4: Non-mover sample summary statistics (2006).

	(1) Toodyay			(2) Control			(3) Non-mover sample		
	mean	median	std. dev.	mean	median	std. dev.	mean	median	std. dev
Income	$38,070	$36,400	$25,056	$38,298	$36,400	$24,733	$38,204	$36,400	$24,840
Age	39.4	41.0	11.7	38.7	41.0	12.2	39.0	41.0	12.0
education level									
year 8 or lower	0.000	0.000	0.000	0.010	0.000	0.101	0.006	0.000	0.078
year 9 to 12	0.460	0.000	0.500	0.555	1.000	0.498	0.516	1.000	0.500
bachelor degree	0.470	0.000	0.500	0.377	0.000	0.485	0.414	0.000	0.493
higher than bachelor degree	0.141	0.000	0.349	0.099	0.000	0.300	0.116	0.000	0.321
employment status									
unemployed	0.046	0.000	0.209	0.034	0.000	0.182	0.039	0.000	0.193
employed	0.955	1.000	0.209	0.966	1.000	0.182	0.961	1.000	0.193
home ownership status									
owned outright	0.232	0.000	0.423	0.243	0.000	0.430	0.239	0.000	0.427
owned with mortgage	0.429	0.000	0.496	0.548	1.000	0.499	0.500	0.500	0.501
rented	0.293	0.000	0.456	0.158	0.000	0.365	0.212	0.000	0.409

Results

Overall results

We find that the Toodyay disaster did not adversely affect the overall income trajectory of workforce residents within Toodyay; i.e. the difference in incomes of the bushfire-hit residents and our control groups is not significant (Table 6).

While this is likely due to our small sample size (n=447), we note that the fire was relatively small and quickly contained (2% share of burnt area). This is in contrast to another regional bushfire study of the Victorian BSB which occurred over a longer period (7 February – 14 March 2009), with the share of burnt area ranged from 0.1 to 72.2 percent, and for which we found significant and persistent negative effects on the overall income trajectories of individuals residing within the bushfire-hit areas (Ulubasoglu 2019).

From our profiling of the fire and demographic profiling of the Toodyay region, we note that the degree of economic exposure and speed of recovery activities are likely to have also influenced economic resilience to the fire:

- Recovery assistance: Combined with public bushfire appeals and Western Power settlements, available monetary assistance for the Toodyay Bushfires totaled $16.5 million, with up to $10.6 million distributed as at October 2012
- Degree of economic exposure: With a significant number of non-employing local businesses, employed residents mostly work outside Toodyay. This fact, and the historical shift away from disaster-sensitive industries like agriculture naturally limits the fire's effect on the overall income trajectory
- Speed of recovery activities: Compared to bushfires with significant effects (e.g. VIC Black Saturday bushfires), the Toodyay fire was relatively small and quickly contained (14 hours), with 29% of public assistance distributed within first three months.

Thus while individuals, particularly sole traders, within this community may have suffered significant income losses, this does not appear to have translated into any persistent changes to the income trajectory of the broader Toodyay community (in comparison to our control groups).

Arguably, Toodyay residents' continued access to neighbouring unaffected areas they were economically dependent on is likely to have significantly contributed to reducing or eliminating any persistent income losses they could have experienced. This also has an added and material benefit: in the case of bushfires, the longevity of disruptions to income post-disaster has been shown to materially affect the mental health of those affected by bushfires (Gibbs et al. 2016).

Table 5: Non-mover sample summary statistics (2011).

	(1) Toodyay			(2) Control			(3) Non-mover sample		
	mean	median	std. dev.	mean	median	std. dev.	mean	median	std. dev
income	$41,458	$40,610	$25,722	$41,603	$40,610	$25,704	$41,553	$40,610	$25,679
age	361.6	53.0	451.9	45.0	47.0	11.3	184.6	49.0	338.5
education level									
year 8 or lower	0.005	0.000	0.068	0.015	0.000	0.120	0.010	0.000	0.101
year 9 to 12	0.569	1.000	0.496	0.562	1.000	0.497	0.565	1.000	0.496
bachelor degree	0.495	0.000	0.501	0.518	1.000	0.501	0.508	1.000	0.500
higher than bachelor degree	0.120	0.000	0.326	0.113	0.000	0.317	0.116	0.000	0.321
employment status									
unemployed	0.046	0.000	0.211	0.033	0.000	0.179	0.039	0.000	0.193
employed	0.954	1.000	0.211	0.967	1.000	0.179	0.961	1.000	0.193
home ownership status									
owned outright	0.245	0.000	0.431	0.234	0.000	0.424	0.239	0.000	0.427
owned with mortgage	0.482	0.000	0.501	0.515	1.000	0.501	0.500	0.500	0.501
rented	0.208	0.000	0.407	0.215	0.000	0.412	0.212	0.000	0.409

Figures based on use of Australian Bureau of Statistics Microdata.

Table 6: Impact of Toodyay Bushfires on individual income trajectory.

	(1) Non-mover sample
post $\times D$	0.1281
	(0.2077)
Observations	447
R-squared	0.013

*post $\times D$ is the difference-in-differences estimate. Standard errors in parenthesis. For significant results, significance levels are denoted by: *p <0.10, ** p <0.05, *** p <0.01. Findings based on use of Australian Bureau of Statistics Microdata.*

Demographic results

Turning to our demographic modelling, while our point estimates suggest that we have some heterogeneities, their standard errors are high due to the small sample size (n=447). As such, we do not report these point estimates.

Nevertheless, the signs of the point estimates are likely to inform us about the potential impacts of the bushfire on different groups within the Toodyay community had the sample size been larger. Here, we do find some differences between these demographic groups, which largely coincide with our observations in other case studies within our research program:

- Gender: Males experienced some income increase, while women's income changes were close to zero. This is a similar pattern to our Victorian BSB case study, where we found females lost on average (-7%), whereas the income trajectory of males was not affected (Ulubasoglu 2019).
- Income group: Low-income individuals also experienced some income decrease, consistent with results obtained in the Victorian BSB case study (Ulubasoglu 2019).

- Education: Another group that seems to have lost is those with high school education only, whereas those with a university degree seem to have experience some positive income change.

These groups largely coincide with those noted in the literature as being more vulnerable to natural disasters (McKenzie & Canterford 2016) and are likely to be more sensitive to disruptions in income generating activities, particularly if they are working in part-time or seasonal occupations in the agricultural sector. Unfortunately, due to the small sample size and confidentiality constraints, we are unable to explore sectors of employment to determine this.

Conclusions

Overall, we find that the Toodyay fires did not have a significant effect on the income trajectory of individuals residing in Toodyay who were in the labour force in 2006 and did not move between the census years, largely due to sample size limitations, noting that there was also significant public assistance provided.

While the large standard errors means we cannot report point estimates, the signs of the point estimates inform us that there are likely to be heterogenous impacts on different demographic groups, with females, low-income individuals, and those with lower education levels (high school only) relatively more disadvantaged than others within their demographic groupings. These patterns not only coincide with our other regional bushfire case study (Victorian Black Saturday Bushfires 2009), but also with groups noted in the literature as being more vulnerable to natural disasters (Masozera et al. 2007; McKenzie & Canterford 2016). These results are therefore informative for policymakers interested in better understanding the distributive effects of disasters.

From the literature we know that limiting the longevity of income disruptions post-disasters is incredibly important for the mental health of individuals within disaster-affected communities (Gibbs et al. 2016). From our demographic profiling, we observed that a significant number of Toodyay residents commuted to Perth and neighbouring areas for work, which likely helped mitigate overall income losses. Ensuring that these areas remain/are quickly made accessible to community members if such disasters were to strike is critical not only for survival, but also for their longer-term health and economic prosperity.

For regional communities in particular, where there are challenges in obtaining sufficient sample size for statistical computations, our study reveals that detailed demographic profiling, using publicly available data, could be undertaken as part of disaster risk reduction exercises to help policy makers build disaster resilience and better direct post-recovery interventions to minimise disruptions to important income streams.

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Peer-reviewed article

Fit for Duty pilot: ensuring the safety of CFA members and increasing access to health services

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ABSTRACT

The physically and psychologically demanding nature of the tasks performed by operational firefighters in fire and rescue agencies across Australia place greater risks to health of personnel than in usual circumstances. Evidence demonstrates that individuals with underlying health issues are at greater risk of experiencing a cardiovascular event (heart attack, cardiac arrest, stroke etc.) or physical injury when performing activities of moderate to vigorous intensity. A recent Beyond Blue and Bushfire and Natural Hazards CRC survey of emergency services members highlighted a greater number of mental health issues than the average for other areas of employment. Therefore, ensuring that all employees and volunteers are physically and psychologically capable of performing their roles in a safe manner is imperative.

Guaranteeing that individuals have support and access to services that could act to identify early signs and symptoms is critical to this process. The Fit for Duty Program acknowledges that it is not known whether CFA volunteer firefighters are safe to carry out their operational roles from a holistic health perspective and as a result, intervention is required. In the pilot phase of the Fit for Duty program, several approaches were trialled for medical assessments. CFA have partnered with Deakin University to develop task-based physical assessment activities that represent the wider range of tasks required for wildfire firefighting. These activities were reviewed by volunteer members who set the benchmarks for the assessment. It is envisaged that the physical assessment component will be broadened to include other higher risk areas of structural firefighting and technical response. An awareness, education and support approach was adopted for the psychological component which incorporates new and existing CFA Wellbeing education and support programs.

This paper provides some fresh insights into opportunities for fire and rescue agencies to better support the health and safety of their members through presenting the approach, outcomes and lessons learned from the Fit for Duty Pilot Program. Benefits to members have already been realised in this approach which challenges our agencies and industry to re-examine the role of duty of care and suggests that such initiatives are well-founded.

Background

Firefighting is an inherently high-risk job with significant physical and psychological demands that lead to increased risks to the health and wellbeing of firefighters compared to the general population (Banes 2014; Elpidoforos et al. 2011; Wolkow et al. 2013). Supporting this, Walkow et al., (2013) found that volunteer firefighters in Victoria do not benefit from the "Healthy Worker Effect" (HWE) that career Firefighters do, meaning the physical nature of the job does not translate to healthier lifestyles among volunteer firefighters.

Volunteer firefighters have similar cardiovascular risk factors to that of the general population (Banes 2014; Elpidoforos et al. 2011; Wolkow et al. 2013). Risk factors include hypertension, hyperlipidaemia, abdominal obesity, poor dietary intake and physical inactivity (Heart Foundation 2019). Relative Risk data from CFA health monitoring in 2017-2018 reflects this, with 23.2% of a sample of 7,630 volunteer firefighters with a cardiovascular Relative Risk rating of high (17.5%) or very high (5.7%).

Firefighting requires a certain level of health and fitness for safe an effective response, and it is therefore necessary for fire agencies to assess firefighters' fitness for duty in relation to work tasks (Lord, Snow & Aisbett 2013). An entry-level physical selection test to assess the demands of tanker-based firefighting was developed (Lord, Snow & Aisbett 2013). The assessment involves three tasks that represent over 50 firefighting tasks observed among thousands of wildfire firefighters during planned burns across Australia.

Fit for Duty pilot program for volunteer firefighters

Volunteer firefighters are a crucial part of Victoria's Country Fire Authority (CFA), making up approximately 95% of operational members, thus, without them the organisation would not be able to provide its services. CFA does not know whether volunteer firefighters are safe and well to carry out their operational roles at any given time.

This conflicts with organisational obligations and values, particularly in relation Section 21 of the OHS Act 2004, which states:

An employer must, so far as is reasonably practicable, provide and maintain for employees of the employer a working environment that is safe and without risks to health" and CFA's value of Safety First.

The aim of Fit for Duty is to increase the health and safety of volunteer firefighters by identifying and addressing health risks associated with firefighting, to introduce minimum standards to increase volunteer safety. The program was developed and piloted among volunteers from urban fire brigades in CFA's South West Region from 2018-2019. Stakeholder engagement and consultation throughout the pilot contributed to development and adaptations. The program's intent remained unchanged throughout the course of the pilot: to increase health and safety, to increase access to health services, to be easy to participate in and to provide a safe and supportive environment for volunteers. It was a requirement that all program components meet this intention statement to be practical, effective and accepted by key stakeholders.

Methodology

Pilot program development and implementation methods

The South West Region project team worked with subject matter experts across the organisation to develop an initial concept for the program, being a focus on a stepped approach to the identification of health-related risks to operational volunteers. This approach acknowledged the different levels of risk to health that are associated with different firefighting roles.

To develop suitable measurements for risk levels, the project team consulted with operational volunteers from South West Region urban fire brigades and various operational staff members. Consultation took place at local fire stations, whereby the team presented the intent of the program and the concept of a risk-based approach. Feedback from these sessions were compiled. Three program components were developed for piloting among the CFA South West Region urban volunteer firefighter cohort.

Medical component:

The pilot program's medical component consisted of two steps: completion of a medical declaration form and a CFA-conducted health check. The medical declaration form consists of a self-assessment, asking members to declare any known medical conditions. The CFA health check involved cardiovascular health screening, measuring blood lipids and glucose, waist circumference, weight, heart rate and blood pressure. CFA's health team travelled to each individual brigade involved in the pilot to conduct health checks.

If any potential health issues were indicated by completing the medical declaration form or health checks, members were referred to their medical practitioner for further advice regarding their fitness for duty. Participation in the pilot components would not impact a member's ability to remain operational, unless a medical professional advised otherwise.

Completion of the medical component acted as a prerequisite to the physical component.

Physical component:

The physical component consisted of the Tanker-based Assessment, the physical selection test that was developed by researchers from Deakin University. This is the first physical assessment of its kind in Australia and CFA was the first organisation to trial the assessment among a volunteer cohort. Assessment tasks were designed to look and feel like firefighting tasks while assessing role-related physical fitness.

The assessment involved three tasks that were to be completed within the timeframe set by CFA volunteers. Tasks included rake hoeing 1.8 lots of 360L of pine bark mulch over a space of 1.5 metres in less than 2 minutes and 30 seconds; dragging and maneuvering a charged 38mm hose in an M-shaped obstacle measuring a total of 54m in length in less than 90 seconds; using one arm to wind two lengths of 38mm hose in less than 2 minutes and 20 seconds. Assessment equipment was taken to each participating fire station by the project team so that assessments could be run locally for brigade convenience.

Psychological component:

The psychological component involved an awareness-based approach as opposed to setting minimum standards and screening. It included offering mental health first aid training to increase awareness, knowledge and skills to empower local-level support.

CFA's existing wellbeing services were also promoted, such as wellbeing and resilience education for brigades, and various member wellbeing assistance and support programs.

Evaluation methods: data collection and analysis

Medical component:

Data from completed medical declaration forms and CFA health checks were securely recorded and stored by CFA's Health Services Manager. Desensitised data was then stored in spreadsheets to track participant numbers and pilot outcomes.

Physical component:

At each physical assessment session, participants names and scores for each task were recorded. Scores were then entered onto a spread sheet enabling efficient reporting of participation rate and assessment outcomes.

Psychological component:

Courses were coordinated by the project team, with final participant lists established. A follow-up feedback questionnaire was emailed to all participants. The participant list and anonymous feedback provided were recorded on spreadsheets.

Table 1: Outcomes of medical components and GP referrals.

	% cleared by GP	% not cleared by GP	% made non-operational temporarily	% made non-operational indefinitely	% who acquired role restrictions
% of total members referred to GP (n=48)	70.8%	29.1%	4.1%	2%	22.9%

Feedback:

Qualitative data was gathered using online surveys (Survey Monkey), mail-out questionnaires, telephone discussions, focus group-style brigade and group meetings and utilisation of a feedback email address. Feedback that was sought from all stakeholders and included the perceptions on the approach the project team took, the opinions of, and experiences with, the program components, what worked well and what aspects need improvement. Feedback was recorded and compiled into a spread sheet. A thematic qualitative analysis was used to categorise data into themes, generating a feedback summary.

Results & Discussion

A total of 448 volunteer firefighters from classification 4 and 5 brigades in CFA's South West Region participated in the pilot program (434 participated in medical components, 268 participated in the physical component, 14 participated in mental health first aid training).

Medical Component

A total of 434 operational volunteers participated in the medical component (completion of medical declaration form and CFA health check). This component highlighted potential health issues for some volunteers, resulting in referral to medical practitioners for professional advice.

Forty-eight of the 434 participating volunteers (11%) were referred to their General Practitioner (GP) for follow-up. Table 1 presents data on the outcomes for volunteers who were referred to their GP.

Two members were made non-operational temporarily due to existing medical conditions. These members returned to their operational duties once the appropriate medication and health management plans were in place. One member self-nominated to remain non-operational indefinitely due to acknowledgement that they were no longer be fit for duty. Eleven members remained operational, with specific restrictions to duties that are to be maintained long-term with oversight by the relevant Operations Manager and brigade Captain.

Key feedback themes

Members were concerned with the privacy and confidentiality of their medical information. Members were also concerned that brigades would lose many members, potentially resulting in reduced response capacity.

Members believed that their own medical practitioners should conduct their health checks instead of the CFA health team.

Members also believed that only those in high-risk roles should be required to complete medical assessments as their roles are more dangerous and physically demanding.

One member was thankful to the program for acting as a trigger for undergoing further medical assessments:

I hadn't been to the doctor in years. I was diagnosed with high blood pressure and early stage bowel cancer. I am now managing my blood pressure, and the doctor said that if I had waited a few more years, the bowel cancer wouldn't have been as easy to deal with.

Lessons learned

- The current CFA medical forms and processes are outdated and ineffective and due for review.
- The CFA health team do not have capacity to conduct health checks for all members on top of existing CFA Health Programs.
- Medical assessments are best to be completed by an individual's own GP for greater practicality for members, as well as the benefits associated with an individual's GP being familiar with and aware of the patient's medical history.
- Sending members to their own GP is more cost-effective than delivering CFA health checks.

Physical Component

Twenty physical assessment sessions were held, with a total of 268 participants. Five (1.8%) participants did not meet the trialled assessment benchmarks by a small margin. Members of various age, sex and body types could successfully complete the assessment tasks.

Key feedback

Members believed the assessment tasks were too easy, and that current training and skills maintenance drills are more arduous. The assessment was perceived as a waste of time as it did not adequately measure members' physical ability to conduct tanker-based firefighting. The equipment used was of poor quality, not readily available to brigades and therefore reduced practicability of the assessment. While the tasks were designed to look the firefighting tasks, participants still perceived them to be irrelevant, i.e. use of rake hoes was not seen as common.

Table 2: CFA volunteer health and safety data: recorded incident types from 2014-2019

Medical Issues	Physical Fitness Issues	Psychological Issues
62.9%	37%	76%

Lessons Learned

- Those in wildfire firefighting roles (with lower physical demands) may not benefit from a physical screening test.
- The medical assessment component potentially picked up anyone who may not have passed the physical, rendering the physical assessment redundant.
- Physical assessments for firefighters should focus on higher-risk firefighting roles to ensure they are worthwhile.
- Assessment equipment should be readily available to brigades, i.e. regular firefighting equipment held at fire stations or districts.
- Assessments must be able to be delivered at local brigade locations for volunteer convenience.

Psychological Component

Three Mental Health First Aid courses was organised, with a total of 28 course participants. A mix of males and females of different ages attended the courses.

Key feedback

Feedback suggested that the course was worthwhile and participants would recommend it to others. Negative feedback included the perception that the course was draining, with more theory than practical skill development as experienced in regular first aid training. However, it was acknowledged that the support for people with mental health issues is of a different nature than physical health issues.

Lessons Learned

- The course is not suitable for all people as it contains distressing content
- While the course aims to educate Australian adults on mental health and mental illness, it is important that suitable participants are chosen for the course, such as those who are empathetic, approachable and not as likely to be triggered by the content.

Detailed Risk Assessment

Following completion of the pilot program and evaluation, it was acknowledged that further exploration, stakeholder engagement and analysis of organisational risk was required before implementing a program across the state. As a result, a detailed risk assessment was established, measuring organisation health risk as very high, supported by the following data.

Conclusion

The Fit for Duty pilot program addressed health and safety risks faced by volunteer firefighters through the development and trial of risk-based health components.

The pilot identified the potential of positive health outcomes associated with a preventative health program for volunteer firefighters, highlighting positive impacts associated with medical assessments and early detection.

While the physical assessment did not yield intended benefits, it was a positive step in the right direction. Future physical assessments for firefighting may benefit from focusing on higher risk roles. It is important that assessment tasks seem relevant to the role of volunteers and assessments must be able to be held at local fire stations with readily available equipment that is regularly used by brigades.

The pilot yielded a number of learnings, including the need to focus on the different levels of risk of different firefighting roles, the need for a program for volunteers to be as practical and user-friendly as possible, and the importance of including target stakeholders along the program development journey.

Recommendations

- It is important to understand the program's target group, and to include them as key stakeholders throughout program development and beyond.
- It is important when obtaining feedback and suggestions from key stakeholders, that there is evidence of that feedback being taken on board to ensure trust among the program target group.
- Medical assessments are of highest value when it comes to health prevention for volunteer firefighters, as they respond to the higher risk of cardiovascular and respiratory health conditions.
- Medical assessments must be handled with strict privacy and confidentiality.
- Use of thorough, evidence-based processes and partnerships with trusted organisations is crucial for program success and building trust with target groups.
- Ensure sufficient timelines are developed and followed, allowing room for unforeseen time constraints.

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Peer-reviewed article

Denaturalising heatwaves: gendered social vulnerability in urban heatwaves, a review

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ABSTRACT

Heatwaves are dangerous and have killed more people in Australia than all other climate related disasters combined. Urban environments are considered especially vulnerable to heatwaves due to the Urban Heat Island effect. Increasing death rates from heatwaves are predicted to become one of Australia's most detrimental impacts of climate change (IPPC 2014) with major implications for emergency services and public policy development. The catastrophic dimensions of heatwave mortality are not spread evenly across society but are concentrated among specific population groups. Older people, especially women, are overrepresented in heatwave related excess mortality statistics internationally. Using a critical perspective, this paper aims to present a literature review exploring current research on social vulnerability of older women during urban heatwaves. It will illustrate how heatwave vulnerability is largely socially constructed through the intersection of deeply entrenched gender inequality with systemic socio-economic disadvantage. The review will highlight the need for heatwave intervention to be guided by a social justice perspective, to avoid older, poorer women becoming the shock absorbers of the climate crisis.

This paper is part of my PhD research project at Monash University: 'Denaturalising heatwaves: gendered social vulnerabilities in urban heatwaves and the use of public cool spaces as a primary heat health measure'. The research has ethics approval.

Introduction

> *It is not the body-object described by biologists that actually exists, but the body as lived by the subject.*
>
> Beauvoir (1953, pp 69)

Heatwaves are dangerous and have historically been responsible for 95 per cent of deaths of all climate hazards in post-industrial societies (Poumadere et al. 2005). Although heatwaves have killed more people in Australia than all other climate related disasters combined (Coates et al. 2014), they have only recently started to be considered a serious health threat in public consciousness and discourse. Exposure to extreme heat poses a serious health risk to the community and heatwave mortality rates are set to increase dramatically as more climate change related extreme weather events are forecast due to rising greenhouse gas emissions (Forzieri et al. 2017; Intergovernmental Panel on Climate Change [IPCC] 2018; Mora et al. 2017).

Growing heatwave deaths are predicted to become one of Australia's most detrimental impacts of climate change (IPPC 2014) with major implications for emergency services and public policy development. The effects of extreme heat are determined by the unique intersection of geographical, climatic and human characteristics of a given location affected by the hazard. Cities rate particularly high on the heatwave risk index due to the complex interaction of a growing and aging population, the built environment and the Urban Heat Island effect, posing unique challenges to urban populations (Bambrick et al. 2011: Harlan et al. 2006). The negative health impacts of heatwaves are not shared equally across society but are concentrated among specific population groups.

Heatwave vulnerability rises dramatically with age and poverty, with older women overrepresented in international research conducted into heatwave mortality statistics (Borrell et al. 2006; Keller 2013; Poumadere et al. 2005; Staffogia et al. 2006; van Steen et al. 2019; Tong 2015).

In his study on the infamous deadly 2003 heatwave in Paris, of which 64.25 per cent of victims were older women (Poumadere et al. 2005), Keller (2015, p88) draws out physical locations as simultaneous critical settings and sources of disaster. The tiny, badly insulated and marginal apartments many of the poverty stricken heatwave victims occupied, were not simply places where disaster struck but became literally agents of mortality (Keller 2015). The study draws attention to the link between risk in urban geography, such as poor housing, with social biographies of economic disadvantage.

The research presented in this literature review highlights that heatwave vulnerability is to a large extent socially constructed and challenges the proposition that heatwave disasters are 'natural', hence unavoidable and inevitable.

Aim

This literature review has drawn together existing international and national heatwave research from a range of disciplines and aims to contribute to current knowledge and gain important insights on heat vulnerability for older women in urban environments that can inform heat adaptation programs and ultimately help save lives. Although an increased number of studies and publications related to the multidimensional impacts of heatwaves are being generated, there is a need to explore in more detail the lived experience of the most affected and give voice to their concerns.

Scope and methodology

The literature search concentrated on research published in English between 1996- 2019. This review is limited in scope and only focuses on the vulnerability of older women during urban heatwaves in major cities in Australia, Europe and the U.S. Although mental health, disability and homelessness are considered important risk factors in existing heatwave research, they are not explored as separate heat vulnerability factors in the literature presented. Research on how these risk factors intersect specifically with gender in urban heatwaves is in the emerging stages and data very limited.

Information related to gender represented in this review is confined to 'male' and' female' categories only, due to the lack of accessible research available on this topic that is reflective of a non-binary gender spectrum.

The topic was explored across a range of disciplines and practice fields using online searches of Academic Search Premier, ProQuest, Web of Science, Google Scholar, Geobase and keyword combinations included 'climate change', 'urban heatwave', 'social vulnerability', 'gender', 'heat stress', 'adaptive behaviour', 'resilience', 'public health'. The search included reference lists from peer-reviewed articles and books. Grey literature is also included in the form of publications from key international agencies, such as the World Health Organisation and the International Panel on Climate Change (IPCC), Australian government departments and relevant Australian non–government agencies.

Heatwaves, climate change and health

Human existence has been largely shaped and informed by our interaction with nature and our capacity to adapt to changed environmental circumstances, but the biological limit to heat tolerance is narrow. Extreme heat affects the human body on a continuum and while some deleterious health impacts are directly related to heat, it can also function on an indirect level and exacerbate pre-existing health concerns (Costello et al. 2009; Loughnan et al. 2013).

A substantial body of literature has emerged over the last decade warning that climate change is considered the biggest threat to global health in the 21st century and argues that peoples' involuntary exposure to it's multifaceted consequences, such as heatwaves, represents health inequity on a grand scale (Patz et al. 2007; Watts et al. 2018). The Intergovernmental Panel on Climate Change (IPCC) warned in 2014 that increasing deaths from heatwaves could become one of Australia's most detrimental impacts of climate change in the future, with major implications for emergency services and public policy development (IPPC 2014). Current global warming of 1℃ above a preindustrial baseline has already created a 'new normal climate', characterised by more extreme weather patterns, including a dramatic increase in heatwave frequency, duration and intensity (Perkins-Kirkpatrick & Pitman 2018). Over 200 climate records were broken during the Australian summer of 2016- 2017 which was also marked by several high intensity heatwaves across the entire continent (Steffen et al. 2018). In January 2019, the hottest ever recorded month in Australian history, defined by rolling heatwaves unprecedented in duration and geographical reach, Melbourne experienced warmer than average maximum and minimum temperatures (BOM 2019a) and Adelaide recorded its highest ever temperature of 46.6 degrees in the city on January 24 (BOM 2019b). All Australian urban centres are predicted to experience more short-term heatwaves in the future (Papalexiou at al. 2018), with a threefold increase in heatwave days projected for capital cities (Herold et al. 2017).

In 2009 and 2014 over 500 people lost their lives in two major heatwave events in Victoria alone (Coates et al. 2014), well eclipsing deaths from bushfires in the same period. Studies conducted in Europe have mirrored the disproportionate death rate from heatwaves compared to other natural hazards. Research into excess mortality during the notorious 2003 European heatwave recorded well above 35,000 deaths, of which 15,000 occurred in France alone (Keller 2013, Vandentorren et al. 2006). From 1999 – 2003 over 3,400 deaths were associated with extreme heat in the U.S. (Harlan et al. 2006), and the 2010 Eastern European and Russian heatwave was also catastrophic, killing around 55,000 people (Coates et al. 2014). New research is projecting a significant expansion of the global population's exposure to lethal heatwaves (Mora at al. 2017), with global heatwave mortality rates to make up 99 per cent of future climate-related deaths by the end of the 21st century (Forzieri et al. 2017).

Heatwaves and urbanisation

It is argued that climate related phenomena, such as heatwaves, are part of global meteorological processes but that their effect will be felt uniquely on the local level depending on the given ecological and 'human environment'

(Costello et al. 2009; Keller 2013; Klinenberg 2002). For the first time in history city dwellers outnumber people living in rural communities and the UN Framework Convention on Climate Change (2017) estimates urban populations to double by 2050. This is an issue warranting significant attention in the Australian context, where 67 per cent of the population live in capital cities (ABS 2017) and the percentage of people over 65 is expected to double in 50 years, with single households occupied by people aged 75+ set to grow significantly (ABS 2010).

While acknowledging cities to be pivotal sites of innovation, creativity and social connectivity, increasing urban expansion poses challenges and risks to human wellbeing and future ecological sustainability. The loss of natural habitat and green space from growing suburban sprawl threatens ecosystems, diminishes biodiversity and local food production and exacerbates existing health hazards in urban environments (Bambrick et al. 2011). Dawson (2017) argues that urbanisation and its associated environmentally harmful consumption patterns are significant contributors to greenhouse gas emissions and suggests that these interrelated processes are stark embodiments of a growth-centered fossil fuel powered capitalist economy that is compromising human and planetary wellbeing.

Cities are highly vulnerable to the deleterious effects of heatwaves due to a complex interplay of natural factors with the physical and social environments present at a given point in time. Cities are warmer than rural areas, due to urbanisation processes (Harlan at al. 2006; Li & Bou-Zeid 2013; Steffen, W, Hughes, L & Perkins, S 2014). A combination of large amounts of heat absorbing building material combined with heat creation from air-conditioned buildings, a lack of shade and green space, create an 'urban heat island effect' (UHI), which results in higher day time temperatures and less cooling at night (Kovats & Hajat 2008; Li & Bou-Zeid 2013). A range of heatwave studies across continents identified warmer neighbourhoods with little green space and a densely built up environment as risk factors of heat vulnerability (Harlan at al. 2006; Loughnan et al. 2013; Poumadere et al. 2005; Vandentorren et al. 2006).

Social vulnerability: age, gender and poverty

Social vulnerability

Patz et al. (2007) make the point that everybody can feel the impact of heatwaves, but the associated burdens are not evenly spread across society, earning heatwaves the title of 'silent and invisible killers of silenced and invisible people' (Klinenberg 2002). This suggests the existence of underlying disaster risk drivers creating different levels of vulnerability for some population groups.

The IPCC defines vulnerability as '…the propensity or predisposition to be adversely affected. Vulnerability encompasses a variety of concepts and elements including sensitivity or susceptibility to harm and lack of capacity to cope and adapt' (IPCC 2014, p. 5). This definition is an important expansion of earlier versions used by the IPCC and climate change literature which focused on vulnerability in physical systems to also reflect the varied impact of environmental changes on human/social systems. The recognition of the social dimension of differential risks draws attention to the fact that susceptibility to climate events and adaptive capacity of individuals or communities is influenced by a range of factors beyond the actual nature of the climate hazard itself (Alston, Hazeleger & Hargraves 2019; Ford, Smit & Wandel 2006; IPPC 2104). The term 'social vulnerability' is increasingly used to discuss levels of resilience to natural hazards beyond the spatial dimension of location and to analyse the structural and situational aspects that increase risks for certain social groups and communities (Alston 2017).

Age, gender and poverty

Age classification is context specific and has varied over time and between countries, and most of the studies used did not include a precise definition for 'older or elderly people'. In Australia, 65+ is considered the onset of older age as it also correlates to retirement age (ABS 2012). Older people are significantly overrepresented in heatwave related excess mortality statistics internationally, partly due to biological factors, such as reduced thermal regulatory capacity, increased frailty and higher rates of pre-existing chronic illnesses (Kovats & Hajat 2008; Loughnan et al. 2013; Semenza et al. 1996). Age vulnerability is further compounded by poverty, low quality housing and social isolation (Steffen, W, Hughes, L & Perkins, S 2014; VCOSS 2013; Department of Health and Human Services 2018).

A critical orientation, reflecting the intersectionality of systems of power acting upon people's lives, understands human experience to be intensely subjective and at once structured through the existence of discriminatory social relations that create shared experiences among population groups. Greig, Lewins and White (2003, p. 39) suggest that 'although an individual's health is played out as a subjective experience of their own body, the experience itself is a product of social inequalities that inscribe disease on the body'. Heatwave-related multi stress vulnerability seems most prevalent among low-income earners and the socially isolated, as it reduces their ability to access protective resources, such as appropriate housing and affordable cooling options (Klinenberg 2002, Semenza et al. 1996, Vandentorren et al. 2006, VCOSS 2013). A Melbourne research project conducted by the Victorian Council of Social Services (VCOSS) found that seniors in rooming houses and poor-quality public housing had limited social interaction between residents, increasing their vulnerability (VCOSS 2013). The same housing options, which are heavily associated with residents from precarious and low socioeconomic background, were also identified as key stressors during a heatwave, transforming these accommodation options literally into 'hot boxes' (VCOSS 2013, p.16).

Cannon (1994 cited in Neumayer & Pluemper 2007, p 552) also points to low socioeconomic status and class as major risk factors in determining the extent of human vulnerability to climate hazards, claiming that 'there are no generalised opportunities and risk in nature, but instead there are sets of unequal access to opportunities and unequal exposures to risks which are a consequence of the socio-economic system'. This implies that poverty, defined through lack of access to power and resources, becomes a key deciding factor in the circumstances of people's lived experience and their adaptive capacities.

Systemic gender oppression, associated with entrenched discriminatory gender roles, power imbalances and reduced access to economic resources, is identified as a key climate and heat health risk factor for women, who make up the vast bulk of the global poor (Alston 2013a; Burns et al. 2017; Dankelman 2010; Denton 2002; Enarson 1998). Neumayer and Pluemper (2007) found that the lower the socio-economic status of women, the higher their mortality rate, compared to men, in climate disasters. These findings are supported by research into several fatal heatwaves, which uncovered an overrepresentation of women in mortality statistics (Keller 2013; Poumadere et al. 2005; Staffogia et al. 2006; Borrell et al. 2006; van Steen et al. 2019; Tong et al. 2014). Although some authors speculate that physiological reasons, such as menopause related reduced thermo-regulation and hormonal changes, may well contribute to increased female vulnerability (Tong et al. 2014; van Steen et al. 2019), our understanding of the complex interaction of human bodies with heatwaves is still rather limited and warrants further exploration. Women's general longer life expectancy may also account for a higher mortality rate in heatwaves.

Despite Australia's diverse ethnic population, warming climate and propensity to heatwaves, literature on this topic is very limited, creating a serious gap in public health knowledge. One exception is the Hansen et al's 2014 study, using focus groups and interviews across three major Australian cities. It found that older CALD community members might experience increased vulnerability based on language barriers and sociocultural factors. No specific research data is available to date that focuses specifically on the health impacts of urban heatwaves on older women from culturally and linguistically diverse (CALD) or Indigenous backgrounds. Existing studies can be enhanced through in-depth qualitative case studies and interviews and ethnographic work which place underrepresented population groups as key stakeholders in the inquiry process, hereby generating knowledge and meaning for transformative and emancipatory purposes.

Further research into the gendered nature of heatwaves is particularly important as women have a longer life expectancy than men but also less economic recourse in old age. Petersen & Parcell (2014) found that more and more Australian women heading into retirement age are falling into poverty and housing stress, due to low — or lack of — superannuation, high living costs and expensive housing, increasing women's vulnerability to future heatwaves.

Table 1: Excess heatwave mortality risk based on age (75+age group) and gender (male and female only).

Heatwave events	Age (75+ age group) and gender	Source
Australia 1988- 2009	Increase of excess mortality risk:	Tong et al. 2014
Brisbane	Odds ratios for men [95% CI] of 1.33 [1.13 to 1.56] and 1.61 [1.42 to 1.82] for women	
Melbourne	Odds ratios for men [95% CI] of 1.38 [1.19 to 1.61] compared to 1.63[1.44 to 1.85] for women	
9 European cities 1990 - 2004 (excluding 2003)	Increase of excess mortality risk:	D'Ippolite et al. 2010
North- continental cities:	11.55% men compared to 16.65% women	
Mediterranean cities:	25.2% men compared to 34.45% women	
France 2003	82.49% of excess deaths 35.75% men compared to 64.25% women	Poumadere et al. 2006
4 Italian cities 1997 – 2003	Increase of excess mortality risk: odds ratios [95% CI] of 1.28 [1.18–1.40] for men compared to 1.44 [1.30–1.59] for women	Stafoggia et al. 2006
Serbia 2007 Belgrade	90% of excess deaths excess mortality for men rose to 23% compared to 54% for women	Bogdanovic et al. 2013

Intersection of social and spatial vulnerability

International literature critically investigating the intersection of 'physical' space with the lived 'social' space asserts that human vulnerability to contemporary natural disasters is to a large extent the result of the interaction of human decisions with geography and culture, in other words, socially and historically constructed (Harlan et al. 2006; Keller, 2013; Klinenberg 2002; Poumadere et al. 2005; VCOSS 2013). Space and location can then be understood as dynamic processes patterned through the interactions between individuals, human and ecological systems that occur within a set of unequal and oppressive power relations, constraining human development, social functioning and good quality of life (Harvey 2001). Some authors argue that the wide-ranging impacts of extreme heat events have also laid bare the deleterious consequences of ideologically driven welfare policies pursued by the political class that privilege privatisation over community wellbeing and the protection of life affirming social capital (Klinenberg 1999; Keller 2013).

Heatwave studies in the U.S. and Europe have drawn correlations between social and spatial heatwave vulnerability and found that catastrophic dimensions of heatwave disasters are concentrated among the socially isolated and economically disadvantaged elderly (Keller 2013; Klineneberg 1999; Poumadere et al. 2006; Semenza et al. (1996) and higher in suburbs characterised by economic inequality, poor housing, precarious living conditions and weak social connections (Harlan et al. 2006; Klinenberg 1999). In Australia Loughnan et al. (2013) used spatial heat vulnerability mapping in their research design and found that there was a higher concentration of at-risk areas in Melbourne's Western and Northern regions compared to other regions in Melbourne, due to higher population density and increased numbers of poorer older people.

Klinenberg (1999) and Keller (2013) aim to 'denaturalise disaster' with their respective Chicago 1996 and Paris 2003 heatwave studies exposing the largely hidden social conditions that gave rise to the unexpected loss of life of what Klinenberg (1999, p242) called a 'structurally determined catastrophe'. More than heat itself, the non-natural dimensions of the older heatwave victims' existence, such as socioeconomic disadvantage, marginal and badly insulated accommodation, lack of cooling options and social disconnectedness, became critical factors in the level of mortality rates experienced (Klinenberg 2002; Keller 2013). As Keller (2013) argues, the heatwave lifted the veil from the state's inability to care for and protect its most vulnerable citizens and shone a light on the break down in social solidarity, contributing significantly to the high death rate.

Socially just responses: building resilience

Considering the projected increase of heatwave related mortality, the need to understand the nexus between underlying disaster risk drivers, gendered vulnerability, adaptation and building resilience for effective disaster risk reduction is critical (Drolet et al. 2015; Hazeleger 2013).

Although interpretations of resilience are varied, there is consensus that it is best understood as a dynamic process that encompasses the ability to 'bounce back' from crises and difficulties and maintain functioning in the face of stress and disturbance (Alston, Hazeleger & Hargraves 2019; Saniotis et al. 2015). Resilience also reflects the ability to access material and psychosocial resources and take intentional action to strengthen individual, communal and institutional capacity to effectively respond to and influence a dramatic change. How well individuals and communities can cope with crises will also depend on the level of social cohesion towards common outcomes (Saniotis et al. 2015).

On an international level, the Sendai Framework for Disaster Risk Reduction 2015-2030 specifically calls for a holistic approach to combine risk management action with poverty eradication measures to build community resilience and reduce climate vulnerability for marginalised population groups (UNISDR 2015)

Recent initiatives, such as the creation of the National Gender and Emergency Management Guidelines (Parkinson et al. 2018) for Australia are an important contribution to the Sendai Framework's call for an embedded gender perspective in all aspects of disaster practice and policies. Nevertheless, there is still a gap in gender analysis and gender disaggregated data on climate disaster prevention and mortality rates. Even though international initiatives such as the Sendai framework provide a blueprint for governments to play the main role in disaster risk reduction (UNISDR 2015), there is also insufficient evidence on its application and effectiveness with regards to heatwave adaptation in the Australian context.

Feminist environmentalism critically analyses women's systemic oppression as being rooted in the same economic and social structures responsible for environmental destruction and climate change (Dominelli 2012; Alston 2013a). Mellor (1997) argues that although ecological awareness is important in crafting a 'politics of nature' that helps regulate human-nature relations, but to understand that human-nature relations are a living process and historically constructed within human-human relations is essential (p. 148). This suggests that unless structural inequality within human society is addressed and the various forms of domination dismantled, the existential threat posed by environmental destruction falls disproportionately on women and oppressed minorities.

Conclusion

Heat related mortality is expected to rise significantly in the future, posing a formidable challenge to existing public health strategies. Effective adaptation and mitigation measures are required to reduce health risks and protect the community from the multifaceted effects of extreme heat events. This literature review highlights the growing body of knowledge on urban heatwave vulnerability for older people in the U.S., Europe and Australia. The research found that older women who experience multi-stress vulnerability, are most at risk from heatwave related deaths.

The literature identified most of the heat stress factors as socially constructed, illuminating how social systems of power create most heat related vulnerability. It also acknowledges that there are real human limits to being able to absorb the consequences of disasters resulting from a carbon-intensive economy. Although there is a growing body of literature internationally on the intersection of gender and climate change, data on why and how heatwaves disproportionately affect older women is in the emerging stages. Considering women's heightened vulnerability to climate change and heatwaves due to entrenched discriminatory gender relations and 'gender-blind policies and practices' (Alston 2013b, pp. 352), a research focus on women's experiences is warranted.

2019 may well become the hottest year on record yet with rolling and record-breaking heatwaves occurring right across the globe. New research on heatwave vulnerability and socially just adaptation measures that focuses on the marginalised and most affected will be critical in safeguarding life and preparing the community for a hotter future.

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Peer-reviewed article

Joining the dots: using social media to connect with more vulnerable Victorians during emergencies

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ABSTRACT

An ongoing challenge for emergency, government, and community organisations is 'how can social media (social media) be best used to connect with people who may be considered more vulnerable during an emergency event?' This question has three key elements. First, when using the term vulnerable who might we be referring to? Second, how is social media being used by relevant organisations and vulnerable community members? Third, how might we better use social media to connect to the more vulnerable sections of the community? This paper reports on findings from recently completed research funded by Emergency Management Victoria. This research is unique in that it combines insights and perspectives from: interviews with emergency, government and community organisations; analysis of social media postings; and interviews and a survey of community members.

Our research noted that most organisations have developed a more nuanced perspective of the term vulnerable, one which takes account of contextual and temporal factors and recognises that all Victorians are periodically vulnerable. Interviews highlighted that organisations, community groups, and vulnerable sections of the community operate in a complex informational and social media landscape. Moreover, this landscape continues to develop with changing boundaries between actors, and organisations' evolving roles. Analysis of social media highlighted that the messaging was generic, with little content aimed at vulnerable sections of the community. The research also investigated how vulnerable people used social media during emergencies. Findings included a growing expectation from community members on the use of social media by emergency and government organisations and that community members increasingly prefer to obtain information from community groups on social media.

The research provides a range of suggestions to improve effective use of social media to better meet the needs of vulnerable persons during emergencies. These included the use of communities of practice, education of social media users, development of practice guidelines, standard setting, and monitoring.

Introduction

Over the last 15 years use of social media) has rapidly expanded to the point that it is used by millions of Australians every day (Yellow 2018). For many people it is an important way of staying connected with friends, family, and the wider community, and for receiving and sharing news, media and commentary. In response to the growing proliferation of these platforms, organisations have developed increasingly sophisticated social media capability, enabling them to use this channel to communicate and interact with the broader community.

Social media is playing an increasing role in helping government, emergency response organisations (EROs), non-government organisations (NGOs), and community groups share information before, during, and after large scale emergency events. The growing ubiquity of social media means that these platforms are an important 'go to' source of information and communication channel for many Australians during emergencies.

Research has highlighted that community members who may be considered more vulnerable to large scale emergencies are disproportionately and adversely affected by these events (IFRC 2013). Vulnerability is defined broadly as referring to those whose circumstances create challenges to seeking, obtaining, or responding to information, or their ability to respond to the same information as the general population (Nick et al. 2009). This definition is purposely broad and reflects that vulnerability changes over time and is context dependent. Circa one in five (19%) Victorians believe they have limitations which may affect their ability to respond to an emergency (Hoy 2018).

This paper reports on research funded by Emergency Management Victoria (EMV) through the National Disaster Resilience Grant Scheme and addresses the question 'how can social media be best used to connect with people who may be considered more vulnerable during an emergency event?' To address this question the paper will consider three issues. The first is to consider the term vulnerable and who might we be referring to in using this term. The second is to assess how social media is currently being used by relevant organisations and vulnerable community members.

Table 1: Summary of the organisations and individuals interviewed during Phase 1.

Organisation	Example organisation	No. of organisations	No. of interviewees
Government agencies	Central organising agency; fire and emergency services authority	4	10
EROs	Police; fire service	3	8
Local governments	Local councils	5	9
NGOs, CBOs, informal community groups	International NGO; locally focused community organisations; auxiliary response groups; local community groups	14	14
Non-traditional actors (platform-based)	Peer-to-peer accommodation, not-for-profit	2	2
Total		28	43

The third issue is how we might better use social media to connect to the more vulnerable sections of the community. In using the term social media we are referring to Web 2.0 platforms/mobile apps that allow for the creation and sharing of user-generated content.

Phase 1: organisational perspectives

We interviewed 43 people from 28 organisations (see Table 1). The interviewees and organisations were identified through the researchers' professional networks and complemented by a snowballing technique. A semi-structured interview focused on the organisation's role, how it shares information, the tools it used (with a focus on social media), how it reaches out to specific communities, and how it shares information with other organisations.

While most studies considered specific incidents such as a flood, bushfire or hurricane (Choo & Nadarajah 2014; Tim et al. 2016), interviewees in our study were free to reflect on a range of incidents (Allen, Karanasios & Norman 2014). Interviewees reflected on larger scale emergencies that they vividly recollected, predominantly floods, bushfires and heatwaves. Importantly, the reflections accounted for incidents over time, covering multiple instances rather than a single snapshot of an event. Interviewees referred to a range of vulnerable groups such as older persons, socially and geographically isolated persons, recent migrant/refugee communities, and transient persons such as tourists. Interviews were conducted face-to-face or over the phone. One interviewee participated via email. Most interviews were audio-recorded with the permission of the interviewee, or comprehensive notes were taken, allowing the discussion to be reconstructed immediately after.

The interviews and notes were transcribed and entered into NVivo qualitative software for analysis. In total, 620 pages of qualitative data were analysed. Data collection and analysis were conducted simultaneously so understanding could emerge from the theoretical concepts and empirical content. Saturation point was reached when no new themes emerged from the data.

Our coding sequence followed the logic of open coding, axial coding, and selective coding, and the constant comparative method (Charmaz & Mitchell 2001). To ensure a systematic and reliable coding process, two authors analysed each transcript; after analysis of each transcript we compared and contrasted codes to negotiate a consolidated yet evolving code book. Through multiple rounds of axial coding we identified relationships among the open codes. As our analysis developed, we applied selective coding to focus more on conceptual abstraction (or the 'story-line') based on our insights into the research (Charmaz & Mitchell 2001). This allowed us to manage the volume of data and constantly organise codes into a coherent structure. Alongside the analysis we compared our findings to the literature and this helped us create insights from our research.

In addition to the interviews, study participants were forthcoming with numerous additional materials regarding their work. Illustrative examples include both an NGO and local government disaster guide and preparation manual, and ERO and government strategic reports. These materials contributed to our understanding of organisational strategies and procedures.

Phase 2: social media analysis

In Phase 2 a qualitative review of social media content was undertaken to understand how social media is currently being used by relevant organisations and vulnerable community members. In particular, we were interested in whether organisations provide social media information that engages vulnerable groups or, rather, they focus on delivering general information to the wider population.

The social media analysis focused on Facebook posts with content related to extreme weather events. Data was collected from the public pages of 13 organisations based in Victoria. Three of these—Country Fire Authority (CFA), VicEmergency (EMV), and State Emergency Service (SES)—are state organisations dealing with emergency and extreme weather events. The other 10 organisations are local community groups from regional areas in Victoria. These local groups use their Facebook pages to share alerts on weather events with their members. Netvizz was used to extract data from public Facebook pages and groups for this research. A total of 1,864 posts was collected from the CFA, VicEmergency and SES Facebook pages (713, 828, and 323 posts respectively) for the period 03/01/2018 to 28/02/2018. Likewise, a total of 3,246 posts was collected from the 10 community groups. The Facebook content was filtered using a set of keywords potentially related to vulnerable populations.

The subset of posts containing the keywords were further analysed to identify the common patterns of target audience, content, message, language use, and structure. The social media analysis was undertaken to assess the degree to which specific messaging and information was targeting the more vulnerable sections of the community.

Phase 3: individual perspectives

This phase focused on community member accounts of how they accessed information during times of emergency. First, we undertook interviews and focus groups with individuals in Victoria. The purpose was to obtain an understanding of how different groups use social media in emergencies. The sampling process for individual interviews/focus groups occurred in two ways. First, we reached out to a range of community groups whose member bases constituted a base of vulnerable persons (e.g. Counsel of the Ageing). Second, participants were recruited by selecting from respondents to posters placed on community noticeboards and through the use of snowballing. We included a wide range of participants including persons aged over 60, with physical limitations as well as socially isolated people and travellers (identified in Phase 1 as a potential at-risk group). In total, 47 Victorian participants were included in two focus groups and individual interviews from mainly rural and regional areas, and a smaller number from metropolitan cities. Similar to Phase 1, a semi-structured interview protocol was used to guide the interviews and focus group sessions. The initial part of the interview sought demographic and background contextual information before asking participants questions about how they obtained information (including social media) during severe weather events or larger scale emergencies. There were also questions asking about the types of information sought and shared, and participant attitudes towards various information providers and channels. Most interviews were audio-recorded with the permission of the interviewee(s), or comprehensive notes were taken, allowing the discussion to be reconstructed immediately after. The simple interview protocol enabled straightforward coding of the transcripts to identify the current use patterns and attitudes towards social media. Analysis of the coding generated simple frequencies, respondent rankings of media channels usage, and preferences and sources for information.

The findings from the interviews and focus groups were used to help develop questionnaire items. The survey aimed to identify the attitudes of vulnerable persons in Victoria towards the use of social media in extreme weather events. The term 'extreme weather events' was used in the survey rather than 'emergencies' as it is clearer to a general audience. We built on the interviews and focus group discussions and adapted the Reuter and Spielhofer (2017) survey instrument to generate descriptive statistics and to elicit reasons for respondents' answers. The survey was administered by Qualtrics (www.qualtrics.com). A link to the online survey was sent out to people residing in Victoria who report to have used social media to search or share information during an extreme weather event and who also identify as belonging to different vulnerable groups (i.e. over 60 years old, geographically or socially isolated, suffering from physical limitations and/or of low socioeconomic means). Only respondents who committed to providing their best answers were eligible to complete the survey. The survey contained 34 questions.

We collected 215 survey responses from Victoria residents who reported they use social media to search or share information during an extreme weather event, and who also identify as belonging to different vulnerable groups (i.e., over 60 years old, geographically or socially isolated, suffering from physical limitations and/or of low socioeconomic means). A summary of the demographics for the survey participants is shown in Table 2.

Results

In this section the findings from the three phases of research are discussed.

Phase 1: organisational and community group interviews

Table 3 summarises the role of the organisations, how they address the informational needs of vulnerable persons, how specific information was, and the directional flow. While Table 3 presents the activities of organisations and groups as silos, clear interdependencies exist amongst them. Victoria's mandated Joint Standard Operating Procedure guides hierarchical flow of information from central government actors to EROs, local governments and filtering through to NGOs and CBOs and informal community groups. While Table 3 is indicative of an inherent top-down information hierarchy, more dynamic and two-way information flows mediated by social media (Reuter, Hughes & Kaufhold 2018) plays a significant role, so information flowed both ways.

Table 3 (column 3) indicates community-based organisations (CBOs), NGOs, and informal community groups provide more specific and contextual information. They followed a more organic approach to understanding the complexities of community response and the needs of vulnerable persons.

Framing vulnerability

There were a range of perspectives on vulnerability. Several interviewees highlighted the transient or temporary nature of vulnerability. This might be for a few days following hospitalisation. For some households, this may occur for the part of the day when the only car (and transport) for the family was unavailable because it had been driven to the primary income earner's work. Similarly, fast moving grass fires in peri-urban areas after school may mean that unsupervised school children are vulnerable until a parent or caregiver arrives home. Although the interviewees were conscious of the Department of Health and Human Services (DHHS) lead policy role for this issue, each set of interviewees offered slightly different perspectives. The framing of vulnerability by the interviewees was consistent with the recent Inspector General of Emergency Management's (IGEM) project on Victorian high risk communities. IGEM highlighted four main factors that limit an individual's or a household's ability to respond to an emergency, namely looking after children or pets, medical conditions, disability, and lack of mobility (Hoy 2018). One further point made by two interviewees was the observation that some community members were unable or unwilling to self-identify as vulnerable. An ERO identified the concern that

Table 2: Demographics of the Victorian residents who participated in the online survey (n = 215).

Demographic factor	Criteria	Percent of participants
Identify as belonging to a vulnerable group (i.e., over 60 years old, geographically or socially isolated, suffering from physical limitations and/or of low socioeconomic means)	Identify as belonging to 1 group	77.7%
	Identify as belonging to 2 groups	15.7%
	Identify as belonging to 3 groups	4.7%
	Identify as belonging to 4 groups	1.9%
National background	Australian	75.4%
	Asian	9.3%
	European	8.4%
	American	2.3%
	African	0.9%
	Other	3.7%
Language	From an English speaking background	74.9%
	From a non-English speaking background	25.1%
Gender	Female	54.0%
	Male	45.6%
	Other	0.4%
Highest level of education	High School	33.5%
	Diploma	20.5%
	Bachelor's Degree	27.4%
	Postgraduate Degree	14.4%
	Other	4.2%
Household types	Lone-person households	19.5%
	Families with children	40.5%
	Families without children	27.0%
	Other	13.0%
Employment status	Full-time	31.6%
	Part-time	15.8%
	Casual	7.4%
	Self-employed	5.1%
	Pensioner	5.1%
	Retired	10.2%
	Homemaker	7.4%
	Unemployed	14.0%
	Other	3.4%
Age	18-20	6.0%
	21-29	21.9%
	30-39	30.7%
	40-49	15.8%
	50-59	7.4%
	60-69	11.2%
	70+	7.0%

particularly Baby Boomers will not align themselves with messaging that appears to be directed towards people with any level of frailty or vulnerability.

Connecting to vulnerable persons

The above difficulties around identifying and defining vulnerable persons illuminate the challenges organisations have in engaging them through social media and other means. We now turn to examining how social media is used to engage with vulnerable persons and how information flows throughout the landscape of organisations.

Government agencies, EROs and local government were acutely aware of the risk to vulnerable persons and had formulated strategies for engaging them using actors close to the communities. For this reason, there are strong links between government agencies and NGOs that work directly with vulnerable persons and undertake community engagement. Hence the main strategy remains to interact with more vulnerable people through intermediaries, which we refer to as "information brokers" (Hughes & Palen 2012). One government agency provided the example of targeting middle-aged women because they are more likely to look after young children and older parents, both vulnerable during a heat event. These brokers then may engage more directly via social media. This was supported by analysis of how social media information was spread. Therefore these organisations, used social media to "tie into local trusted networks", understanding where vulnerable persons are connected to the community. It may also involve social media campaigns that target persons who act as information brokers.

By doing so, government agencies, EROs and local governments provide a clear and consistent message, while delegating to citizens the roles translating, providing local knowledge and context, and sharing with vulnerable persons. This is critical because, in addition to the consistent message, it also helps address difficulties in framing multiple messages to different groups and getting individuals to act on them.

There is capability within these organisations to monitor social media and analyse big data in real time to understand community sentiment and better target specific parts of the community. However, these capabilities are not evenly spread across all organisations. There are still challenges around resources to analyse social media streams and that adequate numbers of staff are dedicated to social media communication and initiatives.

Some local government, CBOs, and community groups interviewed expressed concerns around the limited social media capability that they had access to.

The NGOs, CBOs and informal community groups relied on top-down information, but adopted different strategies in using social media to reach out to their constituents, either directly or by making this information more relevant. They relied on information from government agencies, EROs and local government as well as from their constituents so information is updated more regularly, incorporates local knowledge, and tailored for different community group's needs.

Phase 2: social media analysis

One of the questions the project sought to address was how social media is currently being used by relevant organisations and vulnerable community members. Given that around one in five Victorians believe they have limitations which may affect their ability to respond to an emergency (Hoy 2018), how is social media being used to communicate with this significant section of the community? The social media analysis was undertaken to assess the degree to which specific messaging and information was targeting the more vulnerable sections of the community.

Analysis was undertaken for the posts on the Facebook pages (1,864 posts from the CFA, VicEmergency and SES; and 3,246 posts from 10 community groups) using keywords potentially related to vulnerable populations. This filtering retrieved a total of 35 posts from formal organisations, and 10 posts from community groups. Figure 1 illustrates one of the most frequent types of messages issued as a Facebook post by formal emergency organisations.

Similar messages were collected from the CFA, SES, and VicEmergency.

Table 3: The role of different organisations in addressing vulnerable persons' informational needs.

Organisation	Focus on vulnerable communities	Information specificity and information flow
Government agencies	Provide information to wider community; some provision to engage the vulnerable specifically.	Broad scope, incident specific information. Emphasis of flow from agency to community. Some flow from community to agencies.
EROs	Provide information to wider community; some provision to engage the vulnerable specifically.	Broad scope, incident specific information. Emphasis of flow from government to ERO to community. Some flow from community to EROs.
Local governments	Identify the vulnerable and develop suitable communication and support activities.	District- or community-centric. Information flow largely from local government to community. Some flow from community to local government.
NGOs, CBOs, informal groups	Utilise local networks and connections to identify and support community member needs, including vulnerable persons.	Local community; combine information from official sources with localised content; sharing local knowledge/information; greater multi-directional information flow. Some members of CBO/NGOs may interact with local councils and attend municipal/ERO forums. Group members share knowledge and provide assistance to one another. These groups tend to operate closed (restricted) social media groups and telephone trees.
Non-traditional actors (platform-based)	Provide information to wider community; connect persons who need help.	Customer-centric; use largely government and ERO content to assist customers; or not providing guidance or information at all.

Figure 1: Example of a Facebook post by an emergency organisation.

These organisations provided standard messages that highlight the need to check on immediate neighbours and vulnerable groups within families and communities. The 10 posts from community groups follow the same pattern ('look after, 'keep an eye', etc.). With the exception of people with heart/lung/asthma conditions (addressed using the first person) messages were targeted to the general population rather than to specific groups. This may be consistent with the expectation that social media content will be shared across networks and, perhaps more importantly, will be relayed offline to the relevant individuals. The task of filtering, adding context, and translating these messages was explicitly left to social media users as information brokers with a duty of care. In this regard, the fact that the posts tend to use similar and repetitive formulas across organisations and platforms ('look out', 'look after', etc.) may help to reinforce the message about the expected duty of care towards vulnerable groups (Poblet-Balcell, Karanasios & Cooper 2018).

Phase 3: individual perspectives

Focus groups and interviews were conducted with different vulnerable groups across Victoria, in total capturing the views of 47 persons—both users and non-users of social media. The four main themes identified from these interviews related to: social media use patterns, awareness of emergency services' use of social media and apps, trust and attitudes towards social media, and the important role of informal community networks and relationships. Discussion of each of these themes follows.

Consistent patterns of social media use were found for some demographic groups. Women tended to be greater users of social media and used it to improve and share their understanding potential threats. Many non-users of social media explained that they rely on users of social media for information and passing on up-to-date information. Some older individuals were very clear in their comments that they had no interest or desire to become users of social media.

Table 4: Key themes and findings from online survey of 215 Victorian social media users who identified as either being over 60 years old, geographically or socially isolated, suffering from physical limitations and/or of low socioeconomic means.

Key themes	Findings
Use of social media and technology	• The most used devices were smartphones (78%), laptops and desktops (66%), and tablets (31%). Regular mobile phones were used often by just under 1 in 5 respondents (19%). Other technologies used included gaming consoles (2%) and smart televisions (4%). • Facebook was the most commonly used platform (70% using this platform 'often'). • social media usage was on average higher for younger users and women. • Women tended to show a more positive attitude towards the use of social media during an emergency.
Use of social media during an emergency or severe weather event	• During an extreme weather event, 7% of respondents said they would spend the same amount of time on social media as they would during normal conditions, 38% would spend less time on social media, and 55% would spend more time on social media. • The information searched for on social media was weather conditions or warnings (85% of respondents), damage caused by the event (66%), road or traffic conditions (65%), location of family or friends (55%), information about how others are coping (49%), what to do to keep safe (49%), and eyewitness photos or videos (47%). • Almost two-thirds of respondents reported that they had received information about extreme weather events via social media indirectly.
Trust and attitudes towards social media as a reliable and helpful source of information	• 61% of respondents said that they would not trust messages on social media, except for messages posted by official sources. • Over 70% of respondents rated EROs and government agencies' social media as very or extremely helpful, and the third highest rated social media provider for these two categories (i.e., very or extremely helpful) was local groups (49%). • 68% of respondents agreed that the information provided on social media by EROs meets their needs. • 61% of respondents believed that their information needs during extreme weather events are very specific, with 50% preferring to use community groups on social media to obtain information because it is tailored to their needs.
Use of social media by EROs	• 87% of respondents thought that it was important that EROs use social media. • There was a mixture of responses to the question asking whether EROs should regularly monitor social media—75% said they should, 53% said they should expect a response within one hour, and 62% said emergency services were too busy to monitor social media during an emergency.

Over the last eight years there has been significant investment by government organisations and EROs in the development of social media platforms and emergency apps. Interestingly, a common theme from interviews and focus groups was the low levels of knowledge of how emergency services use social media and tools such as the VicEmergency app.

Several of the interview questions probed on the topics of trust and attitudes towards social media as a reliable and helpful source of information. Interviewees expressed varying levels of trust in the veracity of the information on social media.

The final theme highlighted the important role of informal community networks and relationships. Interviewees emphasized the central role these networks and relationships played in helping people to make sense of potential emergencies. These relationships allowed people to develop more specific understanding of what was going on locally. Moreover, the knowledge base of these community networks was strengthened by connections into the local EROs, Victoria Police, and local and state government agencies.

The focus groups and individual interviews informed the design of an online survey. The online survey was completed by 215 Victorian social media users who identified as being either over 60 years old, geographically or socially isolated, suffering from physical limitations and/or of low socioeconomic means. The key findings from this survey clustered under four themes: use of social media and technology, use of social media during an emergency or severe weather event, trust and attitudes towards social media as a reliable and helpful source of information, and use of social media by EROs. Discussion of each theme follows and a summary of these findings is provided in Table 4.

Use of social media and technology

The survey found that the most used devices were smartphones (78%), laptops and desktops (66%), and tablets (31%). Regular mobile phones are used somewhat less with 19% respondents reporting that they used these devices 'often'. A small number respondents noted using other technologies such as gaming consoles (2%) and smart televisions (4%). Facebook was the most commonly used social media platform, with 70% of respondents using this platform 'often'. social media use was on average higher for younger respondents and women indicated a more positive attitude towards the use of social media during an emergency.

Use of social media during an emergency or severe weather event

Respondents varied in their reporting of whether they would use of social media during an emergency. A small number reported the same level of social media usage (7%), slightly more than one-third (38%) reported they would use social media less, and just over half reported increased social media usage (55%). On balance this suggests that a greater proportion of respondents would tend to increase their use of social media during an emergency, although clearly some respondents would spend less time on social media. The most sought information on social media during an emergency was weather conditions or warnings (85%), damage caused by the event (66%), road or traffic conditions (65%), location of family or friends (55%), information about how others are coping (49%), what to do to keep safe (49%), and eyewitness photos or videos (47%). This pattern of results suggests that social media is used to obtain information for multiple purposes including sensemaking, informing decision making, and checking on family and friends. One of the more interesting findings concerned the reach of social media. Almost two-thirds of respondents reported that they had received information about extreme weather events via social media indirectly.

Trust and attitudes towards social media as a reliable and helpful source of information

The survey suggested that the level of trust and attitudes towards social media was a more complex story and in some respects appeared slightly contradictory. Respondents were quite specific about their trust of social media sources, with 61% of respondents noting they would not trust messages on social media, except for those posted by official sources. Helpfulness ratings of ERO and government provided social media was high with 70% of respondents rating this as 'very' or 'extremely helpful'. Local community group social media was the third highest rated source for helpfulness with 49% rating it as very of extremely helpful. There was generally a positive view of EROs social media with 68% of respondents agreeing that the information provided by EROs met their needs. The survey highlighted that 61% of respondents believed they had very specific information needs during extreme weather events. Interestingly, 50% of respondents preferred to use community groups social media to obtain this information because it was tailored to their needs.

Use of social media by EROs

There was widely held belief (87% of respondents) that it was important for EROs to use social media. However, there were varying views on how attentive EROs should be in terms of monitoring and replying to queries on social media. Three-quarters (75%) of respondents said that EROs should monitor social media. Just over half of respondents (53%) said EROs should respond to queries on social media within one hour, and 62% said that the emergency services were too busy to respond to monitor social media during an emergency. The survey findings suggests that social media is now seen as a core activity for EROs.

Discussion: implications from this research

The three phases of research undertaken in this project each provide some important insight into how social media is used to inform more vulnerable Victorians. The organisational interviewees offered a quite nuanced description of vulnerability, recognising the importance of temporal and contextual factors. This perspective means that in essence all Victorians could periodically be vulnerable. The observation that circa 1 in 5 (19%) of Victorians believe they have limitations which may affect their ability to respond to an emergency underscores this point (Hoy 2018). However, it was also observed that some community members may not self-identify as vulnerable, and this has implications for the type of approach required to more fully engage the community in this discussion.

The organisational interviews highlighted the central role that government organisations and EROs played in providing core messaging and information through social media and other channels. These organisations worked hard to make sure they provided timely and sound information. However, this information was generally more generic and tended not to be targeted towards specific groups who may be considered more vulnerable.

A further insight was the multiple and complementary approaches used by organisations to interact with more vulnerable sections of the community. social media was used by government organisations and EROs to recruit and engage information brokers to reach people who may be more vulnerable, an approach previously identified by Hughes and Palen (2012). Local government, NGOs, community-based organisations, and informal groups made extensive use of informal networks to maintain contact and generate information most relevant to locals. Digital platforms are increasingly used to match people in need with others who can help (e.g. Ready2Help), mapping applications, and for crowdsourcing (Poblet et al. 2017). In particular community Facebook groups play a central role by blending official information from EROs and government with knowledge from local networks to provide more granular and contextualised information.

A final insight from the interviews were the variation in social media capability across organisations in the sector. The larger government departments interviewed tended to have greater social media capability and in some cases supplementary resources such as digital marketing expertise. At the local government and community-level, social media resources were more limited and in some instances very sparse. The recent development of virtual operation support teams (VOST) provides the potential opportunity for organisations to build greater surge capacity to resource social media monitoring and management during larger scale emergencies (McLennan et al. 2016).

The social media analysis highlighted that social media postings specifically targeting more vulnerable sections of the community were less common. Less than 1% of the Facebook posting reviewed targeted sections of the community who may be more vulnerable. Moreover, these postings tended to target brokers such as middle-aged women rather than the more vulnerable. The limited attention provided to more vulnerable sections of the community is consistent with other research undertaken in the sector (e.g. IFRC 2013).

The interviews, focus groups, and online survey highlighted a number of features of how people interact through technology and social media and some of their attitudes towards using social media platforms. Facebook is currently the most used social media platform in Victoria and this finding is consistent with other research (e.g. Yellow 2018). Smartphones, computers, and tablets were the most common technologies used. social media is used during emergencies to obtain information for various purposes including sensemaking, informing decision making, and checking on family and friends. On balance more community members are likely to use social media during a larger scale emergency although it is also important to note that some community members may spend less time on social media.

The reach of social media appears to be somewhat wider than direct users given that almost two-thirds of respondents reported that they had received information about extreme weather events via social media indirectly. The level of trust and attitude towards social media was a slightly more complex story. Although there was a positive view of EROs' social media, half of respondents preferred to obtain information from their local community group's social media. These findings suggest that respondents value trustworthiness and tailored information and that perhaps local community groups as known actors with local understanding offer both of these. This pattern is similar to that identified by Bird et al. (2012) who noted that government websites and social media ranked higher for trustworthiness but community social media ranked higher for usefulness and timeliness.

The survey highlighted that ERO use of social media tends to be seen as core activity by users. However, there was some inconsistencies around the expectations of social media monitoring and response to social media queries by EROs. This mismatch between the use of social media by EROs and public expectation has previously been identified by Reuter et al. (2018).

The research identified three main sets of issues, which create both opportunities and challenges for the sector.

The nature of the information flows and roles of actors

There is a tension between the top-down model which emphasises clear and consistent information with the demand for information that is contextualised to individuals' needs. Almost 50% of the respondents surveyed noted that they preferred to use community groups' social media because it is tailored to meet their needs.

For vulnerable groups, a challenge is the balance between consistent/clear information and targeted information. The use of 'information brokers' is one strategy used to navigate this tension.

There is a need to better explain how all the actors fit in the emerging information landscape, in particular new actors such as organic community and volunteer groups, and extending organisations such as Facebook and other platform-based actors. There is also a need to understand how to utilise such organisations, groups and platforms during emergencies. Along with the growing convergence of actors, there is a parallel increase in complexity and thus divergent interpretations may take place. These may result in outcomes and behaviour that is difficult to predict.

Understanding that not all information channels are well suited to some sections of the community. These issues include when and how social media is used (and the related aspect of connectivity).

Technology, practices and capabilities

There is a need to build effective internal capability within organisations to use social media, enact communication strategies for vulnerable persons on social media, as well as engage the volunteer base. While acknowledging the role of social media, there is unevenness in capability and resourcing. This is important because our study shows that 88% of individuals expect to use social media more in the future for emergencies. Other studies show that two-thirds of adults rely on social media for their news (Moon 2017). Our study also showed that expectations of emergency services are likely to grow with 75% agreeing that emergency services should regularly monitor their social media sites to respond to requests and 52% expecting a response within an hour.

There have been rapid changes in technology and social media usage over the past 15 years. It is important that organisations are aware of which social media platforms vulnerable people are more likely to turn to, as well as the types of information they tend to seek and share. Our study showed that individuals use social media (73%) for emergency related information, which is only second to TV news (87%) and more than radio (61%).

There is a need to ensure social media complements traditional information and communication channels rather than substitutes them. This is important for segments of the population that do not use social media.

Particularly for NGOs, CBOs, and informal community-groups there is a need to put into place good practices to allow for local information sharing whilst accommodating top-down information.

There is a need to evaluate the effectiveness of current information and communication strategies; i.e., Are users engaging with it? How far does information travel through information brokers? In our study individuals considered the information sought from emergency response organisations and government agencies as either “extremely helpful” or “very helpful” (93% and 88% respectively). While this data shows that information provided directly by EROs is well received, this does not indicate whether the information positively influenced behaviour and does not capture how effective information brokers have been in reaching particular sections of the community. A second issue that arises from the increasing reliance on NGOs and community groups to translate and contextualise information from government and EROs is the need for some best practice guidelines (ideally co-designed) and training to support these groups to do this effectively.

Engaging at risk groups and vulnerability

In recent years there has been an increased focus on vulnerability and emergencies (DHHS 2018; MAV 2018; VCOSS 2018), however the term vulnerability was contested in our study. Consideration and future research are required to better understand when, why and how long people are vulnerable, as this is not part of the mainstream or social media discourse. Likewise, studies on social media use in emergencies tend to treat populations as homogenous rather than consider the use by at-risk groups.

There are three main strategies that can be used with social media to engage vulnerable communities. The first is the simplest and uses social media to broadcast emergency related information, advice and warnings. This approach is mainly used by government agencies and EROs. The second is using social media to crowdsource and thus tap into local knowledge, images and local updates. Local community groups make extensive use this approach although local government, NGOs and some community-facing parts of EROs use this approach too. The third is using social media to find and engage information brokers, trusted intermediaries for vulnerable persons. This approach is mainly used by government agencies and EROs.

There is a need to manage the challenge of effectively identifying vulnerable persons in light of the multifaceted and fluid nature of vulnerability. In our survey 62% individuals with a vulnerability used social media to share emergency information—tapping into groups well connected with their communities of practice could help spread the reach of relevant information.

Conclusion

Since the 2014 National Review of Emergency Warnings and Information (EMV 2014), ongoing changes in technology and the growth in social media use has continued at quite a pace. These developments create ongoing challenges and opportunities for all actors in the sector. Our research found that Victorian organisations were attune to the issue of risk and vulnerability for communities they serve. Moreover, many of these organisations were continuing to invest in and develop good social media capability.

An ongoing tension in the sector is between ensuring the provision of reliable and accurate information (albeit more generic), and information that is more granular and made relevant for a specific community. social media is enabling local communities to utilise reliable official information, but also to enhance this with local knowledge to create a shared information that is more meaningful and useful. These community networks help people to be part of a local network, sharing local knowledge and resources. This has become commonplace across Victoria.

The use of social media to engage information brokers appears to be a very useful strategy to reach more vulnerable community members. It is a simple way to help ensure community member susceptible to the negative effects of large scale emergencies or severe weather events can be supported. This approach could be further broadened to ensure that other sections of the community who may not traditionally be thought as vulnerable are reached through this strategy.

The recent development of VOSTs provides the opportunity for the sector to create surge capacity, enabling the application of additional and valuable social media capability during and post large-scale emergencies. However, the more effective use of VOSTs is likely to require further work by the sector to formalise this potential surge capacity and to ensure that these teams can appropriately coordinate and integrate their activities with other key actors. This may require more formal arrangements between government organisations/EROs and VOST groups and the development of an appropriate collaboration framework.

Individuals interviewed as part of this study highlight a growing expectation of more meaningful social media interaction with EROs and government agencies. These agencies will need carefully consider how they will respond to this growing demand.

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Peer-reviewed article

It's raining news: exploring the impact of mass-SMS on preparedness for a severe weather event

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ABSTRACT

Location-based telephone warning systems are a relatively new tool for emergency managers to distribute warnings and emergency information to targeted populations. Although some research has examined their impact on how they support action and decision making by community, there are gaps in the literature for many use cases. This paper presents research examining the impact of a large-scale use of a location-based telephone warning system on awareness of and preparedness for a severe weather event in the Australian state of Victoria.

Introduction

The distribution of warnings and information to communities likely to be affected by an emergency are highly important. This has been acknowledged at an international level as one of the Seven Global Targets of the Sendai Framework for Disaster Risk Reduction (United Nations 2015), and in the State of Victoria as the second of its State Emergency Management Priorities (State of Victoria 2017). Across Australia there has been a dramatic improvement across most elements of the total warning system over the past decades (Dufty 2014). There is also an increasing recognition that systems to disseminate warning information to communities, and an understanding of how individuals interpret and act on warning information are key to total warning system performance (Anderson-Berry et al. 2018). At the same time there has been an intense focus on warnings in Australian disaster reviews and inquiries with 14.6% of communication-related findings from reviews between 2010 and 2016 relating to warnings (Ryan 2017). New technologies have enabled a range of new distribution channels for warnings (Sorensen & Sorensen 2007; Martin & Rice 2012). A particular focus over the last decade has been the development and use of fixed line and mobile telephone-based warning systems such as Wireless Emergency Alert in the USA (Bean et al. 2015) and NL-Alert in the Netherlands (Gutteling et al. 2018). The international literature has demonstrated that telephone warning systems can prompt protective behaviour.

After the 2009 Victorian Bushfires the Council of Australian Governments agreed to develop a national telephone-based emergency warning system known initially as the National Emergency Warning System and subsequently as Emergency Alert (EA). This system initially sent alerts to community via landline and mobile telephones based on the service address of the subscriber and became operational in December 2009 (Handmer et al. 2011). Despite a number of challenges associated with location-based warnings (Aloudat & Michael 2011; Aloudat et al. 2011) the system was upgraded to be able to deliver location-based warnings to mobile telephones in 2013 (Federal Minister for Justice et al. 2013).

In the first years after the introduction of Emergency Alert a range of grey literature reports on its performance were published (Handmer et al. 2011; Torrens Resilience Institute 2011). These studies have generally found high levels of awareness of and satisfaction with Emergency Alert, that respondents intended to comply with any directives in an EA message, and that in actual emergencies receiving EA messages was associated with greater levels of action and seeking of further information. However, since the introduction of location-based warnings in 2013, there has been limited publication of research and evaluation of Emergency Alert.

The authors are also not aware of any unpublished work that has been conducted immediately after an emergency event in recent years.

In late November 2017, the Bureau of Meteorology forecast that a significant rain event would impact Victoria in the coming days. As a result of this forecast, a Flood Watch was issued for the entire State of Victoria on Wednesday 29 November. In preparation for this event, the State Control Centre, 10 Incident Control Centres and eight Regional Control Centres were activated. The high confidence and extreme nature of the forecast rainfall led to an unprecedented public information effort which included extensive traditional and social media messaging, tactical advertising and the largest Emergency Alert campaign in Victoria to date. This involved the distribution of 7.4 million text messages on the evening of Friday 1 December using location-based technology to a large swathe of Victoria including metropolitan Melbourne, representing approximately 88 per cent of the Victorian population (Figure 1).

Unlike most other uses of Emergency Alert which are coincident with warnings, this message was intended to promote readiness and awareness in advance of the expected flood and rainfall event. Unlike messages connected to warnings, the calls to action in this message were intended to support general awareness and preparedness:

> *SMS from VicSES. Flooding is expected across Victoria this weekend. Heaviest rain on Saturday. Check on family and friends. Stay informed. www.emergency.vic.gov.au*

Emergency Alert message sent by Victoria State Emergency Service (VICSES) on 1 December 2017.

The deployment of Emergency Alert in this mode presented a unique opportunity to understand whether it can increase community awareness and preparedness immediately before a flood or severe weather event. This was also an opportunity to undertake a rare evaluation of location-based mobile telephone warnings in the Australian context. VICSES rapidly commissioned Colmar Brunton, a commercial social research provider, to undertake a community survey to understand the role the emergency alert messages played in the event, whether perceptions or actions changed on receiving them, and whether this was affected by the time of receipt, number received, or message content.

Methods

3,804 Victorians were surveyed between the 18th and 23rd December 2017 using a combination of telephone and online survey tools. Areas that were more impacted by the heavy rain event or received targeted warnings were oversampled, including Euroa, Mansfield, Myrtleford and areas around the Elwood Canal in southeast Melbourne.

A dual Computer Assisted Telephone Interviewing (CATI) and online methodology were used to complete the fieldwork. n=599 CATI interviews were administered and n=3,205 online surveys were completed, totaling n=3,804 completed surveys. The online fieldwork was conducted between the 18th and 22nd of December while CATI took place between the 20th and 23rd of December.

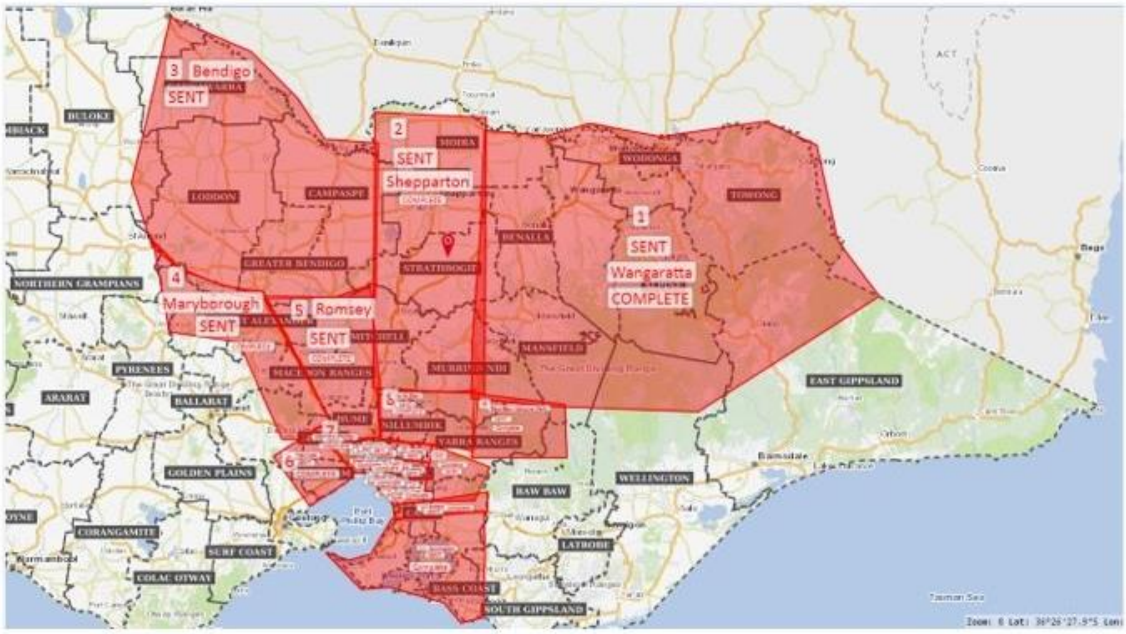

Figure 1: Map showing areas Emergency Alert was distributed.

Table 1: Sample frame.

Area	Phone - n	Phone %	Online - n	Online %
Euroa	42	1.1%	1	<0.1%
Mansfield	36	0.9%	4	0.1%
Myrtleford	32	0.8%	1	<0.1%
Elwood Canal	6	0.2%	200	5.3%
Rest of Vic	483	12.7%	2,999	78.8%
Sub-total	599	15.7%	3,205	84.3%
Total	3,804			

Colmar Brunton and VICSES collaborated on writing the quantitative questionnaire for this project. Respondents were asked up to 28 questions across relevant topics including awareness of the flood event and warnings, sources of additional information about the event, preparation for the event, experiences of the event and personal demographics. Fieldwork collection was scripted, administered and managed via Sawtooth Software.

Analysis of the data file was primarily conducted via Q Research Software and SPSS 15.0 for Windows. Statistical significance testing was conducted via Q Research Software. All tests were performed at 95 per cent confidence ($p = 0.05$). The False Discovery Rate (FDR) assumption was assumed for the purposes of multiple comparison correction, when comparing three or more sub-groups such as the four key locations of interest to the rest of Victoria. Subgroups analysed include respondents who received the Emergency Alert message (n=1805), had previously experienced a flood (n=721), thought the event would be severe (n=2494), considered the Emergency Alert welcome (n=1406) and unwelcome (n=78) and important (n=1228) and unimportant (n=203), and the four oversampled areas (Euroa n=43, Mansfield n=40, Myrtleford n=33, Elwood canal n=206). Not all subgroups were analysed on all questions.

Weighting was applied to the final data file to ensure maximum representativeness. Rim weighting was used based on gender, age and location from the 2016 Census conducted by the Australian Bureau of Statistics, weight factors range between 0.73 and 1.40.

Results

While 18 per cent of survey respondents said that they weren't sure when they became aware of the impending heavy rainfall event, 77 per cent of respondents recalled being aware prior to the Emergency Alert messages being sent on the evening of the Friday December 1. Television (50%) and Radio (25%) were the primary information sources for this initial awareness.

Of the entire sample, 48 per cent recalled receiving the Emergency Alert message. Due to the use of multiple Emergency Alert campaigns, some individuals received multiple messages (see Figure 2) with 6 per cent receiving 4 or more messages and 1 per cent receiving 10 or more.

Of Victorians who recall receiving an Emergency Alert message, comprehension of the message and its contents was high with 98 per cent believing they understood the message and 94 per cent understanding who it was from. Recall of elements of the Emergency Alert message was also high, as shown in Figure 3, with 93 per cent recalling at least one element.

Figure 2: Number of alerts received.

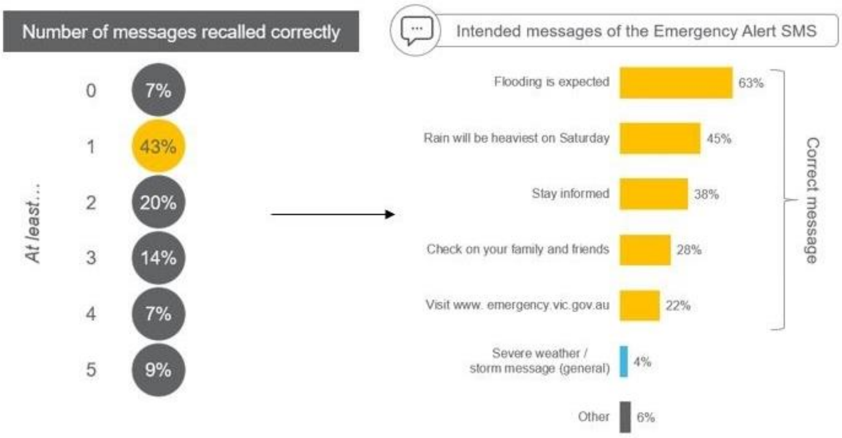

Figure 3: Recall of elements of the Emergency Alert message.

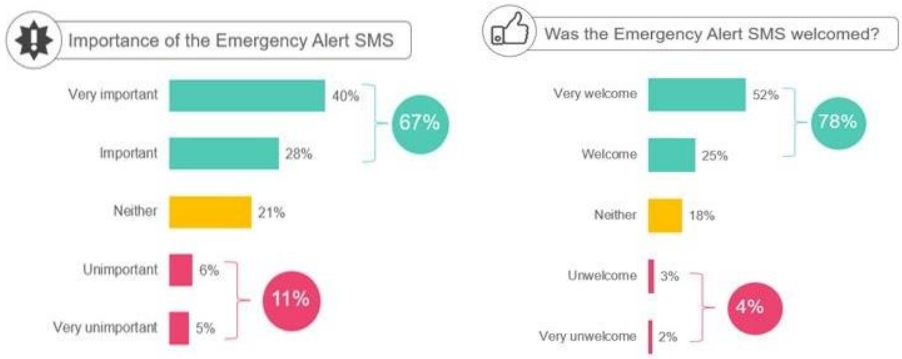

Figure 4: Perceived importance of Emergency Alert SMS and perceptions of welcomeness.

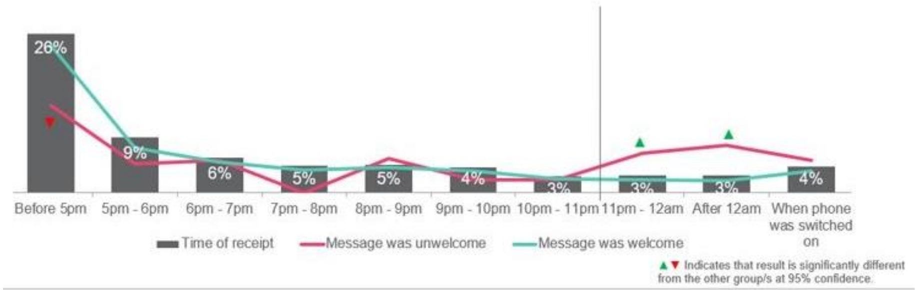

Figure 5: Time of Alert receipt and perceptions of welcomeness.

A majority of those who received the Emergency Alert believed it was important (67%) and welcomed it (78%) with only a small proportion of respondents reacting negatively as shown in Figure 4.

The recalled time of receipt of the Emergency Alert message didn't affect its perceived importance. However, those who recalled receiving the message after 10pm were more likely to consider it unwelcome as shown in Figure 5. The subgroups of individuals who considered the Emergency Alert unwelcome, and who received it in the hours after 10pm was proportionally small compared to the overall sample.

The majority of the recipients of the Emergency Alert followed its advice with 22 per cent responding that they checked on their family and friends and 56 per cent that they listened to the radio for warnings and advice. 60 per cent of respondents who received an Emergency Alert took some other action after receiving the message with 43 per cent seeking or sharing information, 29 per cent changing plans to avoid the event and 19 per cent taking action to prepare their property.

The proportion of respondents who took any sort of preparedness action was higher among those who recalled receiving an Emergency Alert message (74%), than it was for those who recall not receiving an Emergency Alert message (61%).

Similarly, higher rates among those who took preparedness actions was also observed in the groups of respondents that had previously experienced a flood (77%) and those who believed the event would be severe (73%). This was consistent across all actions that were surveyed. Table 2 shows the proportion of respondents who took a range of preparedness actions in these three groups; those who received an Emergency Alert message, those who had prior flood experience and those who thought the event would be severe. This tables shows that the rates of action-taking were similar for a vast range of preparedness actions across these three groups. Differences in the rates of action-taking between these three groups were not statistically significant. Note that these groups are not mutually exclusive.

There is evidence to suggest that the respondents may have interpreted the survey questions on flood warnings to include the Emergency Alert message. Although no Flood Warning or Prepare to Evacuate Warning was issued through Emergency Alert, 73 per cent of people who recalled receiving a warning believed they'd received it via SMS. Furthermore, 59 per cent of those who had received an Emergency Alert message also recalled receiving a Flood Warning or Prepare to Evacuate Warning versus 18 per cent of those who didn't receive an Emergency Alert message.

Table 2: Rates of preparedness actions for those who received the Emergency Alert, had previously experienced a flood and expected the event to be severe

Preparedness action	Received Emergency Alert	Prior flood experience	Thought the event would be severe
Listened to radio for warnings and advice	28%	28%	28%
Cancelled my plans to avoid travelling and leaving home	24%	28%	24%
Ensured family and neighbours were aware of the situation	20%	22%	19%
Cleared gutters	16%	20%	17%
Checked Vic Emergency Website (emergency.vic.gov.au) or App for flood warnings	14%	16%	12%
Changed my plans to avoid flood affected areas or adverse conditions	12%	14%	12%
Secured objects that were likely to float and cause damage	11%	13%	12%
Left work early to avoid travelling in adverse conditions	9%	9%	8%
Cleared drains in the street outside my home to ensure water would flow away	8%	11%	8%
Safely placed valuables and important documents up as high as possible	7%	10%	6%
Ensured adequate supply of water and food	7%	10%	6%
Got prepared to evacuate if advised by authorities	6%	8%	5%
Went over my emergency plan and located my emergency kit	5%	7%	4%
Checked local council or Catchment Management Authority (CMA) website to find out if I was in a flood prone area	3%	4%	2%
Laid sand bags to protect the property	3%	4%	2%
Turned off water, gas, electricity at the mains	2%	3%	2%
Raised chemicals and oils well above ground level	2%	3%	1%
Other (specify)	7%	10%	8%
NET: Took some sort of preparatory action	74%	77%	73%
None of the above	26%	23%	27%
Column n	1805	721	2494

Discussion

Emergency Alert provided a valuable and appreciated method of providing information to the community who both welcomed the message and thought it was important. Understanding of the message content, in this instance, was high. Prior research has shown a high level of satisfaction with the Emergency Alert system and strong support for mobile phones as a delivery mode (Handmer et al. 2011). This has been reflected in this study with a very high proportion of respondents indicating they welcomed the Emergency Alert message and thought it was important. There was a small increase in the proportion of respondents who did not welcome the Emergency Alert, when it arrived after 10pm, however this did not affect assessments of its importance. While 'warning fatigue' and 'warning dependence' have not been identified in this study, continued monitoring across jurisdictions is recommended.

Depending on how Emergency Alert is used, it is possible for recipients to receive multiple messages. Though the proportion of people who received many messages in this event was small, the absolute number would have been significant due to the total number of messages distributed. This may have implications for future use of Emergency Alert in the location-based mode for a large population.

The results show that two thirds of respondents took some form of action to prepare for the heavy rainfall and flooding event. Previous research commissioned by VICSES has found that only 48 per cent of Victorians had any interest in preparing for emergencies (New Focus 2015). Significantly, 60% of respondents to this survey reported taking some form of preparedness action upon receipt of the Emergency Alert message. This validates findings from previous studies of Emergency Alert which found that a majority of respondents would follow the intended call-to-action in an Emergency Alert message (Handmer et al. 2011). This is consistent with other research indicating that preparedness action increases when an emergency is forecast. Just-in-time preparedness behaviour has been observed in other emergencies, most notably in website visits and disaster app downloads immediately before and during Hurricane Sandy (Kirsch et al. 2016).

The results also indicate that receipt of a simple text message may increase preparedness behaviour in a population already aware of a forecast emergency. The preparedness rate of those who recalled receiving an Emergency Alert message was higher than those who did not and similar to those who had previously experienced a flood. Prior disaster experience as a correlate of preparedness behaviour has been well demonstrated in the literature (Kohn et al. 2012). The robustness of this relationship has led emergency services to explore the use of simulation and virtual reality in efforts to increase preparedness (Oaten 2018; University of South Australia 2018). The results of this study suggest that a simple text message prior to a forecast emergency may be just as effective.

The high rates of recall demonstrated throughout the survey showed the utility of conducting the fieldwork within three weeks of the conclusion of the event. Recall rates can vary substantially based on the length of time research is conducted after an event of interest (Kjellsson et al. 2014; Jenkins et al. 2002). This survey only sampled at a single point in time so it is not possible to estimate the recall decay that would have occurred. However, it's likely that the rapidity with which the fieldwork was conducted improved data quality and reliability.

This research has also demonstrated the value of large sample survey. The proportion of respondents who did not welcome the Emergency Alert message and the proportion of respondents who received it late in the evening were both small. The findings regarding the welcomeness and importance of the message versus the time of receipt would likely not have been detected in a smaller sample, due to inadequate statistical power.

One further implication for both research and practice are the results suggesting the respondents may have interpreted the survey questions on flood warnings to include the Emergency Alert message. In the emergency management sector the term warnings can have very specific meaning (Emergency Management Victoria 2017), however the general public may ascribe different meanings to the term. This has implications for both practice, for example designing communications that aim to improve public understanding of warning systems, and research where responses are already highly dependent on question and answer wording. Further research into public perceptions of warnings and public information including the importance of different information in driving decision making would help understand this better.

Conclusion

A large sample survey of Victoria was conducted after the December 2017 heavy rainfall event to examine how people responded to an Emergency Alert message and other media and warnings surrounding the event, and how people prepared.

This study has demonstrated the benefits of conducting post-event research with large sample sizes and as soon as possible after an emergency has concluded. The high rates of recall and ability to analyse small sub-groups has improved the quality of the research and the level of findings that is has produced. To support the implementation of rapid post-event research agencies that may commission it should prepare pre-written research briefs and establish or utilise panels of research providers where possible. Research also needs to account for the emergency management sector interpreting terms, such as warnings, differently to the general public. This issue of interpretation could be accounted through further research into community perceptions of warnings and other public information.

This research supports guidance for practitioners on the use of Emergency Alert to support preparedness. Key points supported by this research include using brief messages that contain clear calls to action. Where avoidable, non-time critical messages that are intended to support general event preparedness shouldn't be sent after 10pm to minimise the chance that recipients may not welcome the message.

The Emergency Alert messages prompted people to act and prepare for the heavy rainfall event and may have been effective at promoting action in people who would otherwise not have taken it. Further work is required to explore how emergency services may facilitate this just-in-time preparedness in communities and whether it's associated with improved outcomes after an emergency.

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