Effective Communication of Household Wildfire Risk through WebGIS: Considerations in Content, Representation and Design

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Abstract

Wildfires have a considerable negative impact in many regions around the world, through both the human fatalities they cause and the economic losses that result from them. Public warnings have a critical role to play in reducing the negative impact of wildfires by informing at-risk populations of wildfire threats at an early stage and stimulating protective behaviours. However, how to build 'effective' public warnings to achieve the performance of such protective behaviours has been a perennial issue, as the general public often do not always comply with the actions suggested by warnings. Currently, public warnings for wildfires, similar to many other hazards, are predominantly disseminated in text-based or verbal formats, conveying an assortment of information regarding the hazard, risk, and responses. In recent years, map-based communication approaches have experienced increased attention in the public warning arena due to their use in many other sectors. Yet, no systematic guidance exists on how to design effective map-based warning instruments, resulting in varied subjectively determined designs and unsatisfactory behavioural outcomes.

This thesis proposes that map-based warning approaches have the potential to substantially improve warning results, and presents an empirically tested design for effective map-based wildfire warning tools in the Australian context. Specifically, the thesis addresses three research questions: i) what information elements are important and should be integrated into the map-based warning tool to improve individuals' understanding and perception of risk and decision-making during a wildfire incident? ii) what is the most effective method (i.e. text, cartographic or a hybrid approach) for presenting these information elements to enhance the accuracy of residents' risk perception and spur proper responses to the danger? and iii) how should the interactive elements of a map-based warning tool be designed to enable easy, efficient access and exploration of spatially enabled hazard and risk information?

A holistic, user-centred design approach was employed to answer the three questions, comprising four major research stages, including i) a conceptual design, ii) domain experts'

consultation, iii) a users' needs assessment, and iv) a tool prototyping and usability and effectiveness evaluation. Each research component will be presented in this thesis as an independent paper.

Specifically, the first paper provides a theoretical review of the literature on effective public warnings, and presents a conceptual framework to guide the development of map-based, *personalised* warnings that may revolutionise the way in which people perceive and respond to warnings. This is followed by a case study to illustrate how the conceptual framework can be applied to develop a map-based *personalised* warning tool for Australian wildfires. The second paper presents the development of a concrete definition and operationalisation of the required level of household preparedness for staying and defending a property in case of a wildfire threat. Such a definition and operationalisation was lacking in the extant literature, yet it serves as a crucial component for implementing the *personalised* wildfire warning model.

Through a comparison of the effectiveness of map- and text- based communication approaches for wildfire warnings in an experimental setting, the third paper shows that the appropriately designed map representations outperformed textual description for communicating most wildfire warning information by improving comprehension, elevating risk perception and increasing appeal to the public. Finally, the fourth paper presents the evaluation of a *personalised*, web-based wildfire mapping application prototyped for public warnings in Australia based on the results from the previous research components. The results demonstrated variations in participants' decision-making approaches, suggesting varied information needs. A map-based warning tool therefore needs to highlight the identified imperative information, such as map of specific wildfire locations, to accommodate a wide audience. Furthermore, a number of heuristics were identified for the design of an effective interactive interface to facilitate the control of, and access to the various maps and information presented on the visual warning interface.

The research steps presented in this thesis collectively contribute to the identification of appropriate content, representations, and interactive design elements to provide effective, map-based wildfire warnings. Whilst mainly focused on the Australian context, this design can be extended for application in other countries by accounting for local political, cultural and demographic contexts. Moreover, the holistic user-centred approach adopted in this research can also provide systematic methodological guidance for designing effective map-based warning instruments for other hazards.

Acknowledgements

My PhD study, like that of many others, has turned out to be an arduous but rewarding journey. I owe thanks to many people who supported me throughout this process in diverse ways.

Statement of Candidate Contribution

The main body of this thesis is comprised of four chapters (Chapter 3-6), each of which is an independent manuscript presenting work that has been published or being prepared for publication in peer-reviewed journals. All of the manuscripts are co-authored with my supervisors (i.e. Dr. Bryan Boruff and Dr. Ilona McNeill), where I am the first and corresponding author. The bibliographical details of the work and where it appears in the thesis are outlined below.

Chapter 3 is a manuscript in preparation for submission to the *International Journal of Digital Earth* as "Towards Personalised Public Early Warnings: Harnessing Technological Advancements to Promote Better Individual Decision Making" by Y. Cao, B. Boruff and I. McNeill.

Chapter 4 has been published by *Natural Hazards Review*. The citation is: Cao, Y., Boruff, B., & McNeill, I. (2016). "Defining Sufficient Household Preparedness for Active Wildfire Defence: Toward an Australian Baseline." Natural hazards review 17(1). The pilot study preceding this work has also been published (presented in Appendix 1) with a citation of: Cao, Y., Boruff, B., & McNeill, I. (2013). "Should I Stay or Should I Go?" Defining the Preparatory Conditions in Support of Active Defence for Different Fire Danger Ratings. Proceedings of Bushfire CRC & AFAC 2013 Conference Research Forum, Melbourne, Australia, Bushfire CRC.

Chapter 5 has been submitted to the *International Journal of Disaster Risk Reduction* with a title of "Is A Picture Worth A Thousand Words? Evaluating the Effectiveness of Maps for Delivering Wildfire Warning Information". The authorship is Y. Cao, B. Boruff and I. McNeill, and it is currently under revision.

Chapter 6 has been submitted to *Natural Hazards* titled as "The smoke is rising but where is the fire: exploring effective map design for enhanced wildfire warnings" by Y. Cao, B. Boruff and I. McNeill , and is currently under review.

For all the co-authored work in this thesis, I completed a substantial part of the research including literature review, research method design, and data collection, collation and analysis. I also independently drafted all the manuscripts to provide research background, description of methods and results, and discussion and conclusion. The co-authors (i.e. Dr. Bryan Boruff and Dr. Ilona McNeill) offered supervision and advice during the research and assisted in language editing for the drafted manuscripts. Dr. Bryan Boruff also provided financial support for a large part of the research. Permission of both co-authors has been obtained to include all the work in my thesis.

Student Signature

Coordinating Supervisor Signature.

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Chapter 1. Introduction

1.1 Wildfire hazard and disaster management

Wildfire is a recurrent and serious problem in many areas around the world, including North America, Southern Europe, Southern Africa, and Australia (Westerling et al., 2006, Flannigan et al., 2006, Piñol et al., 1998, Hennessy et al., 2005), to name a few. Whilst wildfire usually originates in uninhabited rural landscapes, it may become uncontrollable and spread to threaten nearby populations. Studies have demonstrated an increasing trend in wildfire risk, exacerbated by global warning and aggravated weather conditions (Piñol et al., 1998, Williams et al., 2001, Hennessy et al., 2005, Flannigan et al., 2006, Westerling et al., 2006, Yoon et al., 2015), and expansion of cities along the urban fringe and increased interest in alternative rural lifestyles (Hammer et al., 2009, Buxton et al., 2011). As a result, the last decade has seen a number of wildfire catastrophes involving casualties, injuries and economic losses. Examples include the Greek serial forest fires in 2007 that caused 65 fatalities and over 1.75 billion US$ in losses (Guha-Sapir et al., 2015); the Australian Black Saturday fires that consumed 173 lives and ravaged over 3,000 structures only a short drive from the metropolis of Melbourne (Teague et al., 2010); and the more recent California wildfire in September 2015 that resulted in four civilian fatalities and razed 1,955 structures (CAL FIRE 2015). The growing trend of wildfire impact is likely to continue in the foreseeable future, necessitating improved risk management measures to minimise potential damages.

In a general disaster context, systematic and comprehensive disaster and risk management has long been advocated to comprise four cyclical stages with reference to the outbreak of a particular event (Figure 1, EMA, 2004). These include a *prevention* stage, which is an ongoing process whereby preventative strategies are undertaken to reduce the potential consequences of a hazard when the occurrence of the next event is unknown (Board on Natural Disasters of the National Research Concil, 1999, EMA, 2004); a *preparedness* stage when a likely hazard or threat is identified but impact has not yet occurred, and thus education and information are provided to prepare the community, and arrangements and plans are

established to reduce losses and assure survival; a *response* stage whereby actions are carried out right before and during the impact of a hazardous event, to save lives, assuage sufferings, and alleviate financial losses; and a *recovery* stage in the after-math of the impact to return the disrupted societal and physical environment to a normal status (Alexander, 2002, EMA, 2004, Coppola, 2006, Shaw and Gupta, 2009).
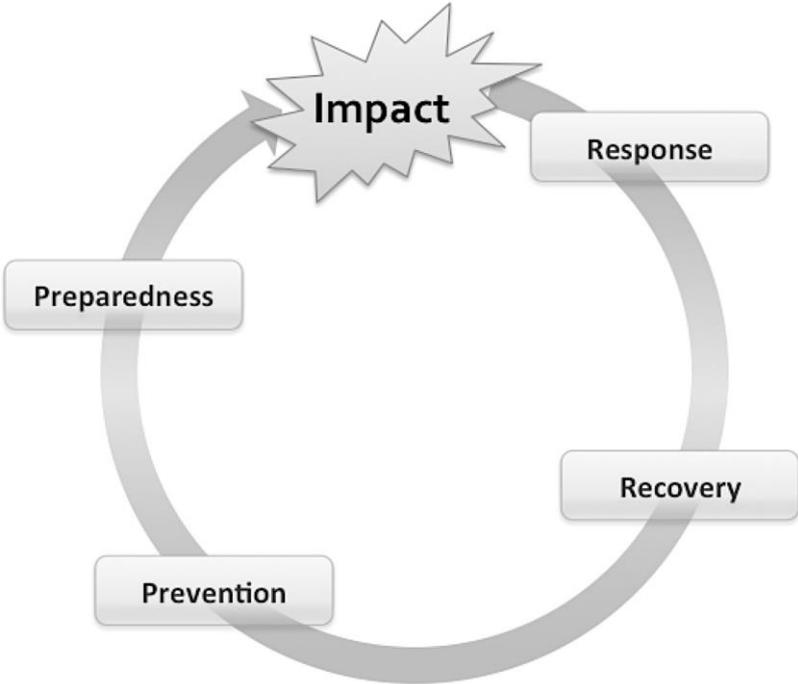
Figure 1.1 The disaster management cycle.

There is a high degree of variation in the specific application of disaster management measures across hazard types, contingent upon the nature of the hazards (e.g. predictability, magnitude, impact on human society, etc.). In the context of wildfire management, the last several decades have seen a transition from a hazards centric approach that emphasised fire suppression to a more holistic strategy addressing wildfire risks across all stages of the disaster management cycle (Shroder and Paton, 2014). Table 1.1 demonstrates the measures typically adopted to manage wildfire risks during *prevention*, *preparedness*, *response*, and *recovery* respectively.

Table 1.1 Typical wildfire management measures for each disaster management phase

Disaster management stages	Typical wildfire management measures
Prevention	Mapping of risk areas Zoning/land-use management Prescribed burning Regulations regarding fuel reduction Legislations for building construction in wildfire prone areas Community safety education campaigns
Preparedness	Preparations for fire suppression, rescue and relief operations Preparations for warning systems Plans for population evacuation
Response	Mobilisation of suppression, rescue and relief operations Warning dissemination Execution of evacuation plans Damage assessment
Recovery	Infrastructure and service rehabilitation Financial support/assistance

The operationalisation of wildfire management measures however, varies across countries depending on the specific wildfire management strategy (Shroder and Paton, 2014). For example, mandatory evacuation is the most prevalent strategy for coping with an impending wildfire threat in many countries (Paveglio et al., 2008, Cova et al., 2009). In contrast, Australian policy encourages residents to take responsibility for their own lives and properties and allows residents to decide by themselves whether to stay and defend one's home or leave early during the onset of a wildfire, unless the Fire Danger Rating (FDR) indicates a 'Catastrophic' fire weather condition (Tibbits et al., 2008). This policy has been built on a large volume of research concluding that both actions can be safe if executed properly under mild to moderate fire conditions (Lazarus and Elley, 1984, Wilson and Ferguson, 1984, Handmer and Tibbits, 2005, Haynes et al., 2010). Yet, a proper execution of defence or evacuation requires prudent considerations and substantial preparations before and during an event, and any failure in this process will result in great risks to one's life and property (AFAC, 2010, Llewellyn, 2012). Australian wildfire management measures across the four stages of disaster management are hence guided by this central policy. For instance, the policy

and relevant construction regulations and preparatory recommendations are widely publicised during the *prevention* phase prior to the beginning of a wildfire season, advocating and assisting adequate household risk reduction in wildfire prone areas (e.g. CFA, 2013a, DFES, 2014); FDRs are issued during wildfire seasons as a pre-indication of fire severity should a fire starts, providing action advice and suggesting the safety of 'staying and defending' and 'leaving early' under different fire conditions to *prepare* residents for a potential event (CFA, 2013a, DFES, 2015c); and in *response* to an event, agencies often suggest the activation of a pre-decided plan to either 'stay and defend' or 'leave early', or request evacuation if a plan is not prepared. However, this wildfire management strategy is not without its problems. Research has in fact revealed a gap between the conceptualisation of the national policy and the public's understanding and execution of it. For example, those who intend to stay and defend are often underprepared (Tibbits and Whittaker, 2007, McLennan et al., 2011b, Teague et al., 2010, Whittaker et al., 2013), and those who plan to leave early are often confused in regard to what is considered 'early' (Teague et al., 2010, Handmer et al., 2010, McLennan et al., 2011a). Whilst the central tenet of the Australian policy is recognised as reasonable (Teague et al., 2010), efforts need to focus on bridging the gap between its intended use by policy makers and its actual implementation by residents.

1.2 Risk communication

Risk communication is generally referred to as a process of transmitting information concerning a hazard/risk by experts to relevant parties, organisations, communities and/or residents, who are primarily non-experts (National Research Council, 1989). Public risk communication occurs throughout the disaster management cycle, with a goal to stimulate preventive, preparatory, or protective actions by citizens, ultimately saving lives and assuaging damages (Blaikie et al., 1994). Effective risk communication garnering appropriate engagement by community members therefore plays a pivotal role in each phase of disaster management. Using wildfire management as an example, an essential component of wildfire risk *prevention*, namely vulnerability reduction, relies on residents' compliance with fuel management suggestions and building construction regulations; when a wildfire is spreading

to threaten human inhabitants, early evacuation is the safest *response* strategy for saving lives, which is always advocated through public warnings. Therefore, the 'effectiveness' of risk communication during the different phases should be measured by its success in motivating public compliance with the various risk prevention, reduction and protection regulations and/or suggestions provided by authorities (Rohrmann, 1992).

However, risk communication is not a simple process ("Preparing for disaster", 2005). After decades of practice, researchers in the 1980's and 1990's began recognising that risk messages formed by technical and scientific experts were all-too-often not understood by the public in the way they were intended (National Research Council, 1989, Covello, 1990, Fischhoff, 1995, Nigg, 1995). A disjuncture was identified between the definition of risk used by the risk managers and that understood by the general public; the former is concerned with risk to the whole population (e.g. death toll), whilst the latter is concerned with individual risk (Sandman, 1987). Risk messaging by experts thus often failed to elucidate individual 'risk' in an appropriate way. Therefore, researchers advocated that effective risk communication should be person-centred, and informed by scientific understandings of the factors that explain people's risk acceptance and behavioural decisions (Sandman, 1987, National Research Council, 1989, Covello, 1990, Fischhoff, 1995, Morgan, 2002, UNISDR, 2005, Krimsky, 2007, Rodrǵuez et al., 2007).

Research concerned with individuals' response to the communication of health risks has resulted in two prominent socio-psychological models that can be used to inform effective risk communication: Protection Motivation Theory (PMT) and the Transtheoretical Model (TTM). PMT suggests that the adoption of suggested mitigation or protective behaviours is motivated both by perceived personal risk (involving likelihood of the event occurrence, vulnerability and impact severity) and by recognition of response- and self- efficacy (Floyd et al., 2000b, Neuwirth et al., 2000). Therefore risk messages should supply information that can accommodate the perceptual needs of the public in these two aspects. Furthermore, the TTM contends that people can be categorised into different groups based on six decision-making

stages (i.e. precontemplation, contemplation, preparation, action, maintenance, and termination), and social, experiential and psychological factors may differentially impact the final decisions of people in different subgroups (c.f. Prochaska et al., 2008). This indicates that a variety of risk messages may be required to motivate all segments of the population in an effective manner.

When it comes to risk communication for environmental hazards, there are two types of risk, namely long-term probabilistic risk of a hazard and risk associated with an active hazard event. The appropriateness of the specific communication approach that is chosen will depend on which of these two types of risk is being addressed. The first type, long-term probabilistic risk of a hazard, is communicated when the occurrence of the next event is not yet known (i.e. risk communication in the *prevention* stage, referred to as *long-term risk communication* in this thesis). Such long-term risk communication resembles those approaches used to communicate health related risks in two aspects. First, both long-term environmental risk communication and health risk communication tend to be ongoing processes spanning over a long time period (e.g. months or years), providing the communicators sufficient time for message preparation, customisation, and improvement based on recipients' characteristics and feedback (Lindell and Perry, 2012). Second, both communication approaches convey general risk information concerning the probability and possible consequences of a potential future hazard, implying a large degree of uncertainty in the information (Bean et al., 2015). Therefore, guidance yielded by PMT and TTM for health related risk communication can be applied to direct the communication of long-term environmental risk.

The second type of environmental risk is communicated in the *preparedness* and *response* stage of a disaster management cycle to warn people of a predicted/detected impending hazard event (referred to as *early warnings* in this thesis). Research on people's responses to early warnings has resulted in several conclusions that closely mirror suggestions posited by the socio-psychological models for long-term risk communication. For example, in a similar vein to PMT, Lindell and Perry (2004, 2012) suggested that to motivate appropriate protective

behaviours upon the recipient of an early warning an individual's perceptions should include both a sufficient level of personal threat and a sufficient level of response-efficacy of the suggested protective behaviours. However, findings also suggest the need for several subtle differences between the approaches used to communicate long-term and impending risks due to their temporal and probabilistic discrepancy. Specifically, early warnings often require dissemination and action in a more pressing timeframe when compared to long-term risk communication, such as over minutes or hours (Lindell and Perry, 2012). Customised communication based on people's characteristics and decision-making stages as suggested by PMT and TTM is therefore challenging for early warnings. In fact, early warnings are predominantly communicated in generic forms through mass dissemination. Mileti and Sorensen (1990) hence stressed an understanding-believing-personalising process in people's response to early warnings, highlighting the need of self-reliant comprehension and interpretation of the generic threat and response related information in personal terms by individuals to make appropriate response decisions. Furthermore, imminent risk of an approaching hazard communicated through early warnings is more certain in terms of the probability, location and magnitude of the event's occurrence and impact than the long-term probabilistic risk of a hazard event (Bean et al., 2015). This means that early warnings require relatively more accurate communication of the location and scale of the risk as well as the appropriate protective actions than long-term risk communication to generate correct comprehension and response by the at-risk population. In sum, early warnings need to provide certain and accurate information regarding the prospective threat and appropriate responses in a way that can facilitate prompt comprehension, believing and personalisation. Furthermore, they need to do so in the absence of the ability to customise the message for different respondents.

Despite the abundance of theories conceptualising what constitutes 'effective communication', the operationalisation of effective risk messages for both long-term risk communication and early warnings is not easy. In fact, the science community is still in the process of searching for effective forms of risk communication (Bell and Tobin, 2007, Meyer et al., 2012, Bean et

al., 2014, Sherman-Morris et al., 2015, Wood et al., 2015), and such forms should evolve alongside the continuing technological and social transformations. In addition, given the lack of a definitive framework for effective risk communication across hazard types, and cultural and social groups, those developing risk messages need to account for the characteristics of the particular hazard and audience, and continuously seek improvement by incorporating feedback from the target audience (Mileti and Sorensen, 1990).

1.3 The potential of GIS for effective wildfire warnings

Emergency management agencies have been communicating wildfire early warnings to the public for decades, predominantly through text/verbal- based dissemination via radio, TV, newspaper, and/or personal contact. However, severe wildfire events in Australia have revealed that there is still a gap between the information broadcast by emergency management agencies and how individuals interpret and understand the communication. For instance, the recent fire that stormed the town of Yarloop in Western Australia (WA) in January, 2016 was identified as a surprise to the local residents, and resulted in 2 fatalities and destroyed 128 homes, despite the fact that it had been continuously burning in the vicinity for several days (Wahlquist, 2016). Public warnings had been constantly issued since the onset of the fire, delimiting warning areas by reference to local roads and Shire names and urging for the activation of individuals' fire survival plans (i.e. 'stay and defend' or 'leave early'). However, whilst Yarloop was included in the designated warning areas, the name of the town was not explicitly listed in the warning until 25 mins before the fire razed the town. This was deemed as a key reason why unprepared residents ended up fleeing their homes in the last minute (Foster, 2016, Wahlquist, 2016). Another example illustrating the ineffectiveness of current warnings stems from Esperance, Western Australia where four civilians were killed by a fire in November, 2015. Starting on a day of 42 degree Celsius and being fanned by winds of 70-80 km/h, the fire was beyond defence (Powell, 2015). However, the warnings continued to deliver generic and uniform advice suggesting people to execute their fire plan of either staying and defending or leaving early, failing to communicate the ferocity of the fire. Farmers stated in the aftermath of the fire that they would have evacuated rather than trying to

fight the fire if they had knowledge of the severity of the fire at an early stage (Powell, 2015). The failure of current wildfire warnings to trigger appropriate action that was demonstrated by these two instances highlights the problem of existing text-based messages in conveying the location and magnitude of wildfire risks in a specific, clear and effective way.

An alternative approach to communicating wildfire risk in text form is communicating it through the use of maps, which has the potential to enhance the specificity and clarity of the depiction of geographically related risk and warning information through visualisation. Researchers have stressed a range of perceptual benefits of map-mediated risk communication (Mills and Curtis, 2008, Hagemeier-Klose and Wagner, 2009, Dransch et al., 2010). First, as with the old saying, "a picture is worth a thousand words," visual representation of hazard related information should be more appealing and enlightening than text based approaches (Rohrmann, 2003, Dransch et al., 2010). Second, map representation has been recognised for its ability to facilitate intuitive cognition of spatial-temporal relationships and patterns (MacEachren, 1995, Lloyd, 1997), which is essential in understanding hazard likelihood and impact in relation to one's own location (Dransch et al., 2010). In addition to the inherent advantages of using conventional maps, the use of contemporary interactive maps supported by GIS technologies has been recognised for its potentially heightened effectiveness for risk communication with the public in several important aspects. First, the GIS framework allows for the integration of a multitude of spatial information concerning hazards and risks whilst maintaining a suitable degree of complexity with ease of understanding (Dransch et al., 2010). That is, users can actively control map layers and scales to focus on information of personal interest, and explore the spatial links between multiple risk layers. Furthermore, webGIS technology allows for location-based personalisation of maps, providing for a higher degree of contextualisation to overcome the complex cognitive challenges of personal risk perceptions (Dransch et al., 2010). Finally, web-based GIS benefits from internet technology (Rohrmann, 2003) through convenient and efficient information access, timely updates and information transmission, and personal information storage and retrieval capabilities. Nowadays, webGIS based instruments have become unprecedented in their accessibility due to the advent of smart

phones and advances in wireless data communication technology. This means that map-mediated approaches can be applicable to the communication of early warnings for imminent threats in near real-time manner. In addition, the abundant spatial data offered by the advanced technologies for monitoring, detecting, and predicting various types of hazards including wildfires (Alexander, 1991, Cova, 1999, Mileti, 1999, Thomas et al., 2007, Lin and Lee, 2008) further increases the feasibility of using map-based early warning systems.

Some applications of maps for public early warnings of imminent threats have emerged in recent years; however there is significant room for improvement. In the case of wildfires, current examples of map-based warnings include the two map-based warning applications recently launched within Australia (EMV, 2015, Government of South Australia, 2015), VicEmergency and Alert SA. Similar manifestations in the U.S. include the California Fire Map (CAL FIRE 2016) and Google Crisis Maps (Google Crisis Response, 2015). These wildfire maps often provide a varied selection of map layers to indicate wildfire risks through interactive mapping interfaces. For example, California Fire Map focuses on illustrating the general location of wildfires, and occasionally demonstrates fire perimeters. By contrast, VicEmergency has begun to provide an enriched fusion of map layers involving fire shapes, warning areas and weather conditions since the most recent wildfire season (2015-2016). However, existing wildfire maps are often designed based on the subjective judgment of those creating the warnings (i.e. cartographer, technician or emergency management personnel) without systematic user consultation, leaving their effectiveness in motivating public behaviours unclear. In fact, residents who viewed screenshots from the VicEmergency map on social media have furnished negative feedback. These screenshots of wildfire maps, often delineating both fire perimeters and warning areas, appear to confuse residents in terms of comprehending the depicted wildfire threat in relation to their own location and identifying appropriate responses (see Figure 1.2 for an example). This highlights a clear need of user-centred considerations with respect to map content, representations, and interface design in order to build usable and understandable mapping applications for wildfire early warnings. The design of such mapping tools needs to account for the diversity of spatial information

available (e.g. hazard, warning, and vulnerability data) for use within a map-based early warning system in light of users' perceptual needs for situational understanding.

Figure 1.2 Left: screenshots of the communication of wildfire warnings by the Country Fire Authority (CFA), Victoria, Australia via their official Facebook account. A snapshot of the VicEmergency map for the particular event is demonstrated in the message. Right: comments following the warning message on Facebook, showing difficulties for the public to personalise the mapped area and the meaning of the warning in related to one's own locations.

1.4 Research objectives and questions

The research presented in this thesis seeks to explore an effective, webGIS-based method for communicating imminent wildfire risks to at-risk individuals. As defined earlier, the 'effectiveness' for risk communication is measured by its success in motivating safe and appropriate response behaviours. In the specific context of early warnings, this translates into the performance of appropriate protective actions as a result of warning comprehension, personal risk perception, and recognition of response efficacy (Mileti and Sorensen, 1990,

Lindell and Perry, 2012). This research therefore seeks to develop a mapping instrument for wildfire early warnings that can achieve the cognitive and behavioural objectives for improved warning responses. The design of such a map-mediated warning instrument is concerned with three dimensions, including the content, hazard and risk representations, and system design. Consequently, the project presented in this thesis was directed by the following three major research questions:

RQ1: What information elements are important and should be integrated into a map-based warning tool to improve individuals' understanding and perception of risk and decision-making in case of a wildfire incident?

RQ2: What are the most effective methods (i.e. text, cartographic or a hybrid approach) for presenting the information elements to enhance residents' risk perception and spur proper response to the danger?

RQ3: What is an appropriate design for an easy-to-use and understandable web mapping interface with interactive features that enable efficient access and exploration of spatially enabled hazard, risk and warning information?

The output of the project was an innovative web-based mapping instrument that is intended to accommodate users' needs and enhance individuals' response to wildfire early warnings.

1.5 Thesis outline

This thesis is organised into seven Chapters. Chapter 1 provides an introduction to the research including the overall aim and research questions. Chapter 2 offers an overview of the methodology used to explore an effective map-based warning approach for Australian wildfires. This includes the presentation of a user-centred design process, which outlines the general research workflow for designing a webGIS based wildfire warning instrument. The chapter further introduces four individual research steps that constitute the overall research framework. The purpose and methodology of each step is outlined, and a holistic picture is

created to illustrate how the research steps collectively serve to address the research aim and three research questions. Finally, a discussion is provided to identify how the research framework can be applied and adapted to guide user-centred design of effective mapping tools for the communication of other hazard warnings.

Chapter 3 through Chapter 6 present the four research steps in more detail as individual journal publications, each providing a relevant literature review, the specific methodology used, research results, a discussion and a conclusion. Specifically, Chapter 3 explores the theories of public response to early warnings, highlighting the need for *personalised* public warnings. This is followed by a discussion of how existing GIS technology and spatial products might accommodate such needs. A conceptual framework is then presented to provide hands-on guidance for local agencies to extend the current application of GIS technologies to supply *personalised* public warnings. Finally, a case study is presented to showcase the application of the conceptual framework in developing a Standardised Household Action Advice and Risk Communication (SHAARC) model in the context of Australian wildfire hazards. The SHAARC model seeks to supply *personalised* risk and warning information through two major components: i) location-based visualisation of the hazard and warning context using maps, and ii) provision of tailored guidance for protective actions through household-specific vulnerability and risk assessment.

Chapter 4 presents research focused on the development of a tangible definition for the required level of household preparedness for active defence against wildfires within an Australian context. The chapter outlines the experts-based consultation approach used to obtain a national baseline for the definition. The resulting instrument serves as an essential component of the SHAARC model conceived in Chapter 3 by assisting in the production of household-specific response guidance in the context of an individual's wildfire survival plan (i.e. 'staying and defending' and 'leaving early').

Chapter 5 presents an empirical study conducted in Western Australia, which assessed whether maps accommodate users' needs in a better way than texts when it comes to the

communication of wildfire early warnings. Furthermore, the study compares multiple map representations in an attempt to identify the optimal cartographic methods for delivering multifaceted wildfire warning information. The results of this study highlight the potential benefits of using map-based warning communication for improving warning comprehension and response, and help identify the appropriate mapping methods for visualising hazard and warning information in a webGIS based application.

Chapter 6 presents the final study, which sought to identify the important information content and optimal interface design for a map-based early wildfire warning tool. This is achieved through a user-centred evaluative study of a prototyped map-based wildfire warning tool that builds on the SHAARC model and the effective cartographic representations identified in the study presented in Chapter 5. The results from this study and the study presented in Chapter 5 collectively provide evidence-based guidelines for the design of a refined map-based warning application by defining its most effective content, representations, and design.

Finally, Chapter 7 summarises the findings from the four studies presented in Chapters 3 through 6 and discusses their implications. This chapter also provides recommendations for future research to extend the current effort in moving towards optimised map-based warnings that can substantially improve responses to these warnings.

To conclude, the research project presented in this thesis offers unique insights into the role of web-based mapping technologies in providing effective wildfire warnings. It offers both theoretical foundations and empirical evidence regarding the effectiveness of map-mediated warning communication, and attempts to not only motivate application and investment by local agencies, but also facilitate the implementation of effective map-based warning tools by providing a directly usable and customisable solution. Moreover, the user-centred design process provides general guidance for extending the work of designing effective map-based early warning tools for other types of hazards.

Chapter 2. Research methodology

A user-centred framework was utilised as the methodological foundation for designing an innovative webGIS based tool for wildfire public early warnings. The overall methodology draws upon the rich body of literature that investigates and illustrates user-centred design approaches for developing map-based visualisation tools for general data exploration and communication in other domains (Gabbard et al., 1999, Robinson, 2005). However, the research workflow (Figure 2.1) was adapted to account for the specific communication objectives of public early warnings and the design questions defined for developing a warning application within a web-mapping environment. The remainder of the chapter will explicate each major research step comprising the design process, and summarise a general framework to guide user-centred design of map-mediated early warning instruments that can be used for other types of hazards.
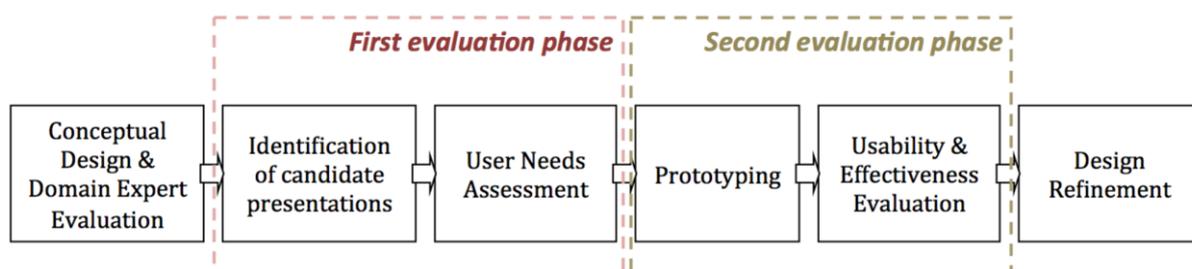
Figure 2.1 The user-centred research workflow for designing a map-mediated wildfire public warning tool.

2.1 Conceptual Design

The purpose of the initial phase was to conceptualise a web-based mapping framework and develop a structure for the user-centred evaluation and design. In line with the overall communication objective (i.e. stimulating protective behaviours) and research questions (i.e. RQ1, 2 and 3 demonstrated in Chapter 1 with respect to the content, representation, and interface design respectively), a Standardised Household Action Advice and Risk

Communication (SHAARC) framework was conceived for delivering spatially enabled wildfire warning information in a comprehensive and effective manner that can support and facilitate individuals' cognition, processing and response (Chapter 3). Specifically, the SHAARC framework specified the fundamental focus points for addressing the three research questions respectively:

Focus point 1 for RQ1. The wildfire map-warning tool should integrate information concerning two major aspects:

a. First, the warning tool had to integrate a wide range of information important for depicting the unfolding wildfire situation and its prospective consequences. Seven specific information elements were identified, including: fire location, fire suppression status, wind conditions, fire spread prediction, alerts and warnings, road closures, and evacuation centre locations. All the information elements were drawn from what has been included in the conventional text warnings. However, the level of accuracy of the same information presented often differs depending on whether it is presented using texts or maps. This is both due to the inherent ambiguity of text in depicting spatial information and due to the fact that certain highly accurate spatial information can only be presented as a map. One salient example is fire-spread prediction, which has been described in conventional text warnings using an estimated time of arrival for a whole warning zone or suburb. But contemporary fire spread simulation models are able to yield much more accurate spatial and temporal prediction of the fire progression. These models are often used by emergency managers for operational planning but are rarely provided to the public. In fact, all the seven information elements identified above have already been made accessible in the forms of maps for use within emergency management teams, therefore the mapped content should be examined for its usability by the public.

b. Second, the tool had to provide a household-specific vulnerability and risk assessment with tailored action advice. The purpose of communicating this information would be

to promote efficient reasoning and decision-making by individuals. To provide personalised action advices, a model was required to explicitly define wildfire vulnerability at the household level and provide individualised action advice given the specific hazard condition. In the Australian context, authorities generally allow for individuals' choice between 'leaving early' and 'staying and defending' a property when the Fire Danger Rating (FDR) level is not Catastrophic on the condition that the household is adequately prepared (AFAC, 2010). However, the policy and advice currently lack an explicit definition of the required 'preparedness' for active defence. Consequently, a definition of 'preparedness' was developed in the current research phase via a series of consultative studies with wildfire community safety experts across Australia (Cao et al., 2013, Chapter 4). This definition was then incorporated in the design of a *Household Action Advice Model* (HAAM, Chapter 3) to enable the provision of personalised response advice based on a household's characteristics. Notable is that neither the input of household characteristics nor the output of action advice from HAAM is spatial in nature. They therefore cannot be mapped, but rather are described in text.

Focus point 2 for RQ2. To integrate all seven spatial information elements identified in *Focus point 1.a* and provide a comprehensive and easy-to-read picture of the wildfire situation for individuals, the following two aspects needed consideration:

a. First, it was necessary to determine the most effective representation method for each spatial information element to ease users' comprehension of the information. It was possible that the most effective representation method would vary for different information elements. Further, whilst the hypothesis was that cartographic design is more effective than textual description (Dransch et al., 2010), users' evaluation could furnish surprising results, or suggest a combination of both approaches.

b. Second, it was important to design the tool in a way that enabled household-centred map viewing (i.e. marking and centring one's location on the integrated wildfire

maps), and support location-based information processing (e.g. calculation of one's distance to the fire) to facilitate the locating of oneself/property within the context of the wildfire (Dransch et al., 2010).

Focus point 3 for RQ3. Given the large spectrum of potential information content and variability of effective representation means, an interactive webGIS platform should be designed with the following two considerations:

   a. Given the large spectrum of potential information content and variability of effective representation means, an interactive webGIS platform should be utilised to enable the integration of multiple map layers, each portraying a different information element (*Focus point 1.a*), and potentially combine the map-based information with textual annotations. In doing so it was important to allow for easy map manipulation and information access by the users;

   b. Furthermore, the interactive webGIS platform should be utilised to integrate HAAM and the presentation of tailored action advice (*Focus point 1.b*) in text due to the aspatial nature of such information.

To summarise, this research phase provided a conceptual formula for an effective wildfire map-warning tool by specifying the potentially useful design considerations for addressing RQ1, 2 and 3 respectively. Directed by these considerations, further empirical evaluation could be conducted with the public to assess the importance of identified information elements, determine the most effective representation method, and design an usable interactive mapping interface.

2.2 Two-phase user-centred assessment

Due to the multiple dimensions of the evaluation tasks, two interdependent evaluation phases, namely *user needs assessment* (Chapter 5) and *usability and effectiveness test* (Chapter 6), were conducted to identify the appropriate content, representations and design collectively on

the account of the defined 'effectiveness' goals (Figure 2.2). Specifically, as discussed in Chapter 1, the ultimate goal of public warnings is to elicit protective behaviours by individuals as intended by emergency management agencies. To achieve this goal, people need to first understand the communicated information, and then interpret risks in personal terms before deciding whether/which protective actions are viable and feasible (Mileti and Sorensen, 1990, Lindell and Perry, 2012). The measure of 'effectiveness' of a map-warning tool therefore should examine the extent to which the following three anticipated outcomes are achieved:

1. The (mapped) information is comprehended;

2. Personal related risk perception is facilitated; and

3. Adaptive behaviours is stimulated (Handmer, 1985).
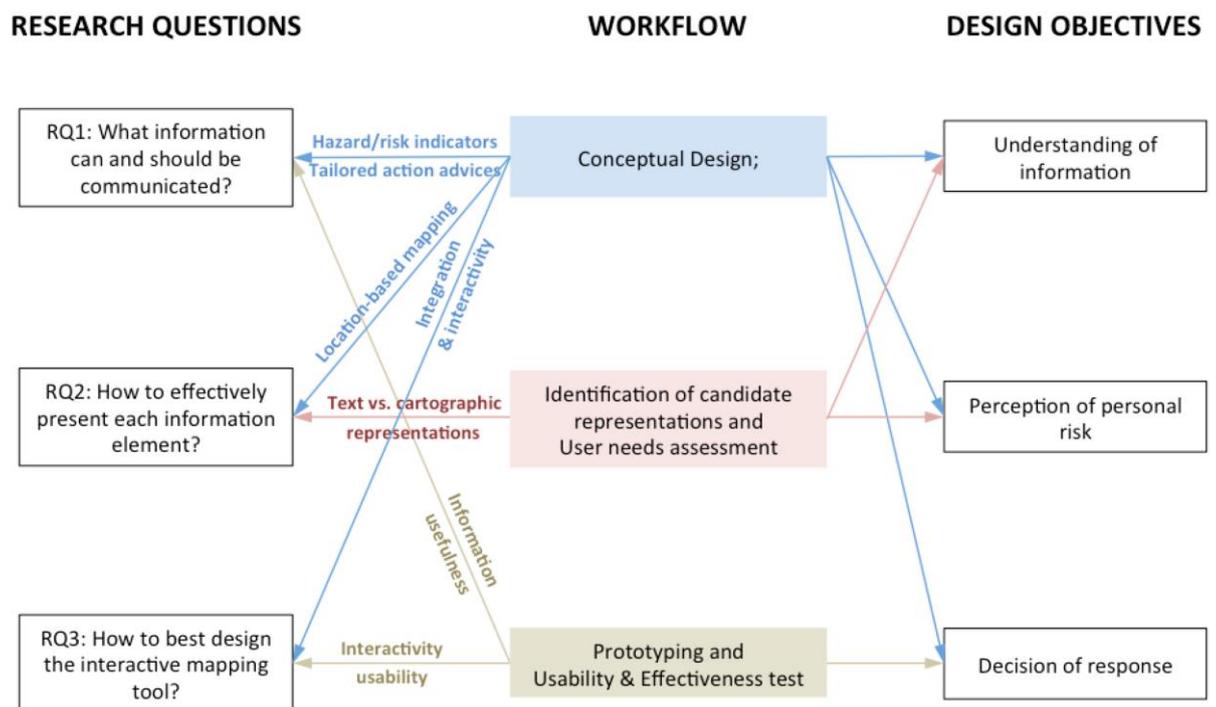
Figure 2.2 A general design and evaluation framework for this research. The steps shown in Figure 2.1 are mapped onto the research questions each attempts to answer and the design objectives each is meant to achieve. How a specific research question was answered by each research step is summarised in text next to the arrows.

2.2.1 User needs assessment

The first evaluation phase focused on addressing RQ2, especially *Focus point 2.a*, i.e. identifying the most effective representation method(s) for each spatial information element.

This phase started with the identification of candidate text-based messaging and map-based representations for each information element by drawing from existing text-based wildfire warnings, and visualisation and mapping standards adopted by Australian emergency services. Additional visualisation techniques that may better accommodate the needs of laypeople were also identified based on relevant cartographic literatures.

Next, designs were created using the candidate representations for all seven spatial information elements (Table 2.1). A *user needs assessment* was then conducted via an online survey with residents from three wildfire prone suburbs in Western Australia to compare the effectiveness of the designs for each information element. Table 2.1 further lists the specific research questions tested through this experimental setting. Of note is that 'effectiveness' (i.e. *effectiveness tasks* in Table 2.1) was measured through the dimensions of *accuracy of understanding* (including specific questions on locating, orienting and risk comprehension), *risk perception*, *individual preference* and *response efficiency*.

Generally, the survey findings showed a corroborated effectiveness of maps (in contrast with texts) for communicating a majority of the wildfire information elements in relation to the physical environment. The most effective cartographic representation for each information element was identified, as well as several critical text descriptors that may be combined with maps to provide optimal communication.

Table 2.1 Research design for the two user-centred evaluation phases

	Users' needs assessment	Usability and effectiveness evaluation
Evaluation and design aims	*Focus point 2.a.* More specifically: a) Are maps more effective than text? b) Which cartographic representation is the most effective?	*Focus point 1.a & b* *Focus point 2.b* *Focus point 3.a & b*
Tested materials	Seven information elements: a) Fire location, b) Fire suppression status, c) Wind forecast, d) Fire spread prediction, e) Fire alert levels and areas, f) Road closure, g) Evacuation centre in the community. Designs created to depict each information using: a) Text, b) Multiple cartographic representations.	Prototyped web-mapping application that integrate a) All seven information elements using the identified most effective representation means for each element (text, cartographic representation, or a combination of both); b) HAAM to provide tailored action advisories
Effectiveness tasks (Dependent Variables)	a) Accuracy of understanding b) Perception of risk in personal terms c) Subjective preference of representation means d) Response time spend for interpretation	a) Intended response to the wildfire and the decision-making process b) Interaction with the tool interface
Factors (Independent Variables)	Designs	a) Fire plans ('stay', 'go', and 'wait and see') b) Fire emergency scenarios (signified by three alert categories indicating fire emergency levels: 'advice', 'watch and act', and 'emergency')
Experimental design	A constant fire emergency scenario simulated for three suburbs respectively	3*3 factorial design by 'fire plans' and fire emergency scenarios
Tested questions	1) Does the accuracy of understanding vary across designs? 2) Does people' risk perceptions vary across designs? 3) Does response efficiency vary across designs? 4) What design do people like the most?	1) What information content is important to facilitate risk perceptions and decision-making? 2) How to present the information using an interactive mapping interface whilst ensuring usability and ease of information access?

2.2.2 Usability and effectiveness evaluation

Based on the findings from *users' needs assessment*, a prototype of a web-based wildfire mapping tool was developed to integrate and deliver the seven spatial information elements using the most effective representations through a location-based mapping approach. Furthermore, the HAAM was incorporated and presented through the web interface to deliver tailored action advice in text. Trivial warning information, such as firefighting operations and emergency contact information, was also added to the tool to provide an integrated warning system. As such, the interactivity and integration designs adhere to all the preliminary design aspects identified in the *Conceptual Design* phase.

To test the usability of the prototyped web-based mapping tool, verbal protocol analysis (VPA, Ericsson and Simon 1993) was employed in the form of semi-structured interviews. Participants were first asked to explore the mapping tool on their own whilst 'thinking aloud'. They were then directed to describe and explain their intended response to a simulated situation (Table 2.1). Finally, participants were asked to rate the importance of each information element and provide general feedback on the design of the mapping tool.

For the analysis of results, the participants' recorded interactions with the mapping tool and responses in the interviews were used to: 1) investigate how each information element was used by residents in their cognitive process of perceiving risk and making decisions; and 2) identify users' access to each information element to pinpoint potential deficiencies of the interface design. This resulted in the identification of which critical information elements would need to be communicated through the tool. Additionally, a list of user-favoured design features was constructed to enable improved tool usability, including suggestions on the layout and designs of legends and text annotations, and map manipulation preferences, among others.

2.3 Discussion and conclusion: a general framework

The presented user-centred design process for devising an effective wildfire mapping tool provides a general approach to designing effective map-based early warnings. More specifically, this framework provides a general structure of the overarching design questions and design objectives, as well as design and evaluation phases necessary for giving the user a central role in the design. Whilst answers to specific research questions may vary for different types of hazards, the general methodology can serve to clarify the goals and provide transferrable evaluation techniques for the design of map-based public warning tools with respect to other hazards.

Figure 2.2 encapsulates the research phases, their contribution to the investigation of the research questions, and their connection to the different warning objectives. First, the conceptual design phase provides a fundamental structure for the overall tool design concerning each research question. Whilst the specific features, such as specific risk indicators and personalised action advice model should differ by hazard type, the general concept of each *Focus point* is transferrable. Second, the holistic experimental design of the two evaluation phases, i.e. the research questions to be tested and design objectives to be attained by each phase, can be employed to guide the multi-dimensional evaluation process for other hazard contexts. However, the specific materials and questions tested in each evaluation phase need to be adjusted in correspondence with the modified *Focus points* identified in the conceptual design phase.

Chapter 3. Towards Personalised Public Early Warnings: Harnessing Technological Advancements to Promote Better Individual Decision Making

Abstract

Official alerts and warnings are essential for informing the public of potential hazards and promoting timely response before a disaster occurs. However, research has identified that traditional early warnings released by emergency management officials, such as generic text messages based on large geographic regions, often fail to promote appropriate protective actions by residents in danger. Recently, map-based communication approaches have experienced increased attention for risk communication, however no systematic framework exists to guide the design of effective mapping instruments for public early warning purposes. This study sought to offer scientific guidance for developing effective, map-mediated public warnings by bringing together the scholarly understanding of public's needs for effective warnings with spatial technologies for providing map-based, individualised decision support tools. This resulted in a conceptual framework that can be used to direct the design and implementation of map-mediated, *personalised* warning instruments. An example is then provided illustrating how such a model could be conceptualised for personalised bushfire early warnings in an Australian context. Underpinned by advanced webGIS technology, the proposed framework shows a ground-breaking approach to supporting risk assessment and warning communication for impending threats at household levels, potentially fostering more efficient and effective risk personalisation and decision making by individuals. Such a personalised warning communication means can be coupled with existing location-based alert dissemination services (e.g. using GPS locations embedded in smartphones) to offer a complete solution for improved official warnings.

3.1 Introduction and Motivation

Official alerts and warnings play a vital role in emergency management. They are developed and disseminated with an intent to protect the health and safety of citizens by informing them of potential risks to motivate their engagement in protective behaviours in a timely manner (Quarantelli, 1984, Mileti and Sorensen, 1990, UNISDR 2005). Historically, the dissemination of official warnings to the public has been limited to basic approaches such as warning sirens, or passive communication through mass media including radio, TV and newspapers. The past decade has seen increased applications of internet-based communication as well as more targeted information communication technologies, such as location-based services (Bean et al., 2015, EMV 2014a), to improve the dissemination of detailed public warnings and increase accessibility for at-risk populations. However, even when official warnings are fully accessible, they do not necessarily stimulate the execution of protective actions. For instance, studies on evacuation behaviours have repeatedly documented the tendency of warning recipients to delay or avoid evacuation, if not ignoring the warnings altogether (e.g. Perry et al., 1982, Sorensen, 1991, Lindell et al., 2005, Sharma et al., 2009, Smith and Kain, 2010, McLennan et al., 2012, Lindell et al., 2015b). In fact, it has been well acknowledged that human response to warning messages is a complex and variable process, often resulting in noncompliance (Moore et al., 1963, Anderson, 1969, Leik et al., 1981, Perry et al., 1982, Quarantelli, 1984, Mileti and O'Brien, 1992, Mileti and Peek, 2000). It is hence imperative for emergency managers to not only assure timely issuance of and accessibility to warnings, but also contemplate their 'effectiveness' in an attempt to achieve the desired behavioural outcomes (Mileti and Sorensen, 1990, UNISDR 2005, Gladwin et al., 2007).

To inform the development of effective warnings, a substantial body of literature has focused on understanding individual psychological processing of warnings and examining the effect of warning attributes on public responses (e.g. Baker, 1991, Mileti and Fitzpatrick, 1992, Dow and Cutter, 1998, Drabek, 1999, Hammer and Schmidlin, 2002, Lindell et al., 2005, Parker et al., 2009, Lindell et al., 2015b, Huang et al., 2015). Studies have demonstrated in the first instance that public responses to warnings are not based on a 'stimulus-response model' of

behaviour (Perry et al., 1981, Nigg, 1995, Sorensen, 2000). Rather, individuals who receive a warning message need to experience a sequence of cognitive stages prior to making decisions and taking actions. Based on a review of relevant empirical studies, Mileti and colleagues (Mileti and Sorensen, 1990, Mileti and Peek, 2000) proposed a conceptual model to characterise people's processing of warnings, which has hitherto been acknowledged and employed as one of the classic models guiding warning-response research (Sharma et al., 2009, Paton, 2006, Bean et al., 2014). Specifically, the model suggests that people who receive a warning need to heed the warning, comprehend the literal meaning of the warning, determine whether or not to believe the message, personalise the warning, and finally, respond to the warning by taking a protective action (Mileti and Sorensen, 1990, Mileti and Peek, 2000). Of particular interest to this study is the personalisation stage, which serves as a direct and critical psychological facilitator for the final decision and execution of an appropriate response. Lindell and Perry (2012) have further specified that warning *personalisation* is comprised of two perceptual substages. The first is the perception of hazard impact as being certain and severe to oneself (i.e. *personalisation* of hazard threat), which, in the case of successful progression, will arouse one's intention to respond (Perry et al., 1980, Mileti and Sorensen, 1990, Perry and Lindell, 1991, Sorensen, 1991, Mileti and O'Brien, 1992, Nigg, 1995, Lindell and Perry, 2012). This is followed by the second substage in which an individual needs to assess the efficacy and feasibility of the suggested protective measure(s) under their particular circumstances (i.e. *personalisation* of response guidance), to make the decision of compliance with or refusal of the suggested response, or seek an alternative response (Perry and Lindell, 1991, Nigg, 1995, Floyd et al., 2000a, Lindell and Perry, 2012). The personal assessment of response guidance is especially imperative when more than one protective response is suggested as viable (e.g. both evacuate early and shelter in place are suggested to be viable for many hazards such as floods and bushfires), as often only one course of actions is safe under the particular conditions (Lindell and Perry, 2012). Consequently, effective warnings should deliver information expounding both the impending risk and appropriate protective behaviours (Lindell and Perry, 2012) in an accurate, specific and adequate manner (Mileti and Peek, 2000) to facilitate not only comprehension of and

belief in a warning, but also personalised perception of i) the threat that warrants a response and ii) response-efficacy and feasibility for oneself.

Current text-based 'official' warnings often seek to comply with the general principles of effective warnings defined by researchers and describe both the hazard and its likely consequences and guidance for protective actions (see Figure 3.1 for an example). However, text-based warning communication exhibits several inherent limitations in eliciting the intended perceptual and behavioural outcomes. First, as a hazard often covers large areas that do not align with political boundaries, text-based messages are innately ambiguous and unspecific in delineating the spatial information concerning hazards and risks (Dransch et al., 2010, EMV 2014b). Unclear description of hazards and risks will yield inaccurate understanding by the public, jeopardising the foundation of an appropriate warning process. Another problem of text-based warnings is that they are all-too-often generically constructed for a whole region, providing uniform depiction of the risk and appropriate response(s) for a large geographic context. Such generic text messages, even if going to a great length to explicate the hazard threat and suggested response(s), still require individuals' interpretation and assessment in relation to their personal circumstances (i.e. the *personalisation* stage). For many types of hazards, such as tornados, wildfires and floods, people at different locations in the same community may be faced with different hazard likelihood, severity, and lead times. Furthermore, individuals/households may exhibit distinct levels or types of vulnerability, requiring different protective measures. Therefore, the personal assessment of hazard threats and response guidance should be location- and household- specific. It is overtly arduous, if not impossible, to process and describe the hazard and response guidance for each individual location and household using text-based warnings. However, the generic text-based warnings that leave the personal interpretation of hazard threats and response viability to individuals are likely to result in erroneous decisions or a need for more information, delaying the response process (Mileti and Sorensen, 1990, Nigg, 1995, Lindell, 2000, Parker et al., 2009, Lindell and Perry, 2012).

In addition to the challenges of comprehending and personalising text-based generic warnings, unclear and inaccurate text-based warning messages may increase the chance of 'normalcy bias'. 'Normalcy bias' is a common human reaction to warnings whereby people tend to intuitively assume the incredibility and/or irrelevance of a new warning as a first reaction without endeavouring to understand and process a warning (Nigg, 1995, Gutteling and Wiegman, 1996, Lindell and Perry, 2004). Unclear, inaccurate and/or lengthy text-based warnings that fail to elicit prompt understanding and easy risk personalisation are therefore also likely to fail to grasp individuals' attention and help circumvent 'normalcy bias', resulting in ignorance of the warning altogether.

Figure 3.1 An example of current textual warnings issued for bushfires within Western Australia. Source: Department of Fire and Emergency Services (DFES).

Due to the issues associated with text-based warnings, it is peculiar that the conventional text- or verbal-based approaches are still predominantly used for communicating public warnings nowadays. An alternative approach to text-based warnings is map-based communication facilitated by Geographic Information Systems (GIS), which has been increasingly advocated over the recent years by researchers for its potential effectiveness in improving public responses to risk communication (Mills and Curtis, 2008, Hagemeier-Klose and Wagner, 2009, Dransch et al., 2010, Lieske et al., 2014). The advantages of map- and GIS- based warning methods exist in several facets. First, maps can enhance warning vividness and engage heeding through effective visual representation. Second, the visual integration of multi-faceted hazard and warning information may also ease understanding complexity in comparison to lengthy text-based description (Dransch et al., 2010). Third, maps enable explicit delineation of location and space irrespective of their alignment with political boundaries, increasing the accuracy in depicting the spatial information. Fourth, web- and mobile- based GIS can be employed to enable *personalised* visual communication of hazard threats based on one's location. This can be achieved by supplying location-based visualisation of the hazard and risk conditions (i.e. marking one's location and using it as the centre and aligning all maps around it) (Dransch et al., 2010). Through allowance for interactive map exploration, the location-based hazard and risk visualisation may amplify risk personalisation and contextualisation (Hagemeier-Klose and Wagner, 2009, Dransch et al., 2010). Finally, we propose that sophisticated webGIS based warning systems can be built to enable the communication of *personalised* response guidance with the intent to facilitate individuals' perception of response- and self- efficacy. Such warning systems can be attained by integrating webGIS and decision models at individual/household levels that can support interactive and personalised assessment of response feasibility and safety by accounting for location-specific hazard conditions and household-specific vulnerability. Such advanced GIS to support localised geographic inquiries and spatial decision making is generally defined as spatial decision support systems (SDSS). Theoretically, personal-level SDSS could be readily realised in a webGIS environment and accessed via the Internet or mobile device; however, a paucity of literature has provided pragmatic guidance for the implementation of such personalised, map-

mediated GIS or SDSS in the public early warning context. In fact, advanced GIS and other geospatial technologies have increasingly prevailed in the emergency management sectors, offering abundant, accurate and timely spatial information regarding risks. However, there has been limited research contemplating the appropriate structure for employing maps and GIS for communicating warnings to the public.

To close this gap, the aim of the current paper was to create guidelines for the development of effective map-based early warning systems for natural hazards. This was achieved by examining contemporary technological advances in the emergency management sectors and deliberating how existing GIS technology and cartographic products can be harnessed to construct substantially improved public warning systems under the guidance of the socio-psychological scholarship. In the following sections, we first discuss the current application of geospatial technologies for emergency management and public warnings. Next, we propose a conceptual framework for the development of map-mediated *personalised* warning systems for natural hazards by exploiting and extending existing technological powers and information capabilities of emergency management services. This is followed by an example of an application of the framework for communicating *personalised* warnings of bushfires in Australia. The development of the framework and its application in the context of Australian bushfires form an important step forward in identifying how GIS technology can be utilised for delivering comprehensive, location-based, personalised public warnings in a way that facilitates the perception of self-related risk and decision-making at the individual/household level.

3.2 The geospatial revolution: what can it offer and what has been harnessed for public warnings?

Over the past several decades, geospatial technologies such as GIS, remote sensing and GPS have been increasingly adopted by the emergency management community (Cova, 1999, Cutter, 2003, Thomas et al., 2007). This is fuelled by the spatial nature of the information underpinning hazards and risks (Cova, 1999), and the capability offered by geospatial

technologies to efficiently acquire, process, manage, and visualise large volumes of spatial data. For instance, emergency management activities are often initiated based on the identification or forecasting of a hazard using technologies such as weather surveillance radar networks, earth observation satellites, and reconnaissance aircrafts mounted with airborne measurements (Mileti, 1999, Geoscience Australia, 2005, Lin and Lee, 2008, Krajewski et al., 2011, Lindell and Brooks, 2013, NOAA, 2014). The resulting geo-referenced information concerning a particular hazard event is often analysed using advanced GIS and/or SDSS to understand the existing hazard conditions, project dispersion, predict impacts and make intelligent and structured response decisions (Cova, 1999, Mileti, 1999, Thomas et al., 2007, Steinmetz et al., 2010, Pollino et al., 2011).

The extensive utilisation of geospatial technologies for hazard identification and emergency management yields ample, timely and accurate spatial information concerning a hazard event and its potential impact. Such spatial information is often visualised in the form of maps in near real-time, enabling emergency managers to share knowledge within and between organisations and make informed and timely decisions. However, when it comes to warning the public, the use of maps becomes limited and the accurate spatial information is rarely released. Figure 3.2 illustrates the general flow of hazard-risk *spatial* information from hazard detection to management, leading to warning construction and dissemination of a typical text- and verbal- based (*current*) public warning. Despite the assorted maps produced during the hazard detection and management process (Figure 3.2.*a*, *b*, and *c*), the accurate spatial information is often translated into words to describe the hazard location, risks and warnings to the public (Figure 3.2.*d*), losing the original accuracy and specificity.
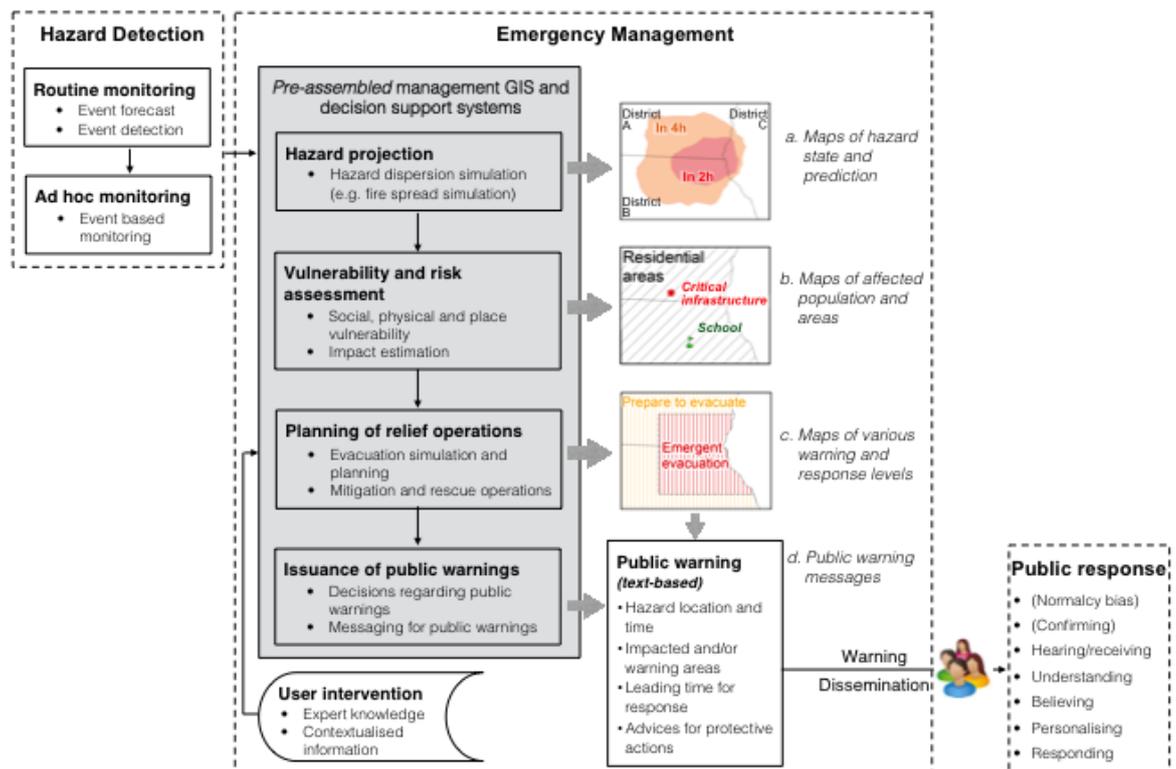
Figure 3.2 The schematic structure and general information flow (with a focus on spatial information) for the generation of a text-based public warning. Mileti and Sorensen's (1990) definition of a complete and typical public warning system, which comprises a detection subsystem, a management subsystem and a public response subsystem, was used to characterise the typical mechanisms for warning generation and dissemination originating from hazard detection. However, with a focus of the timeline for constructing public warnings during the onset of an emergency, this figure does not demonstrate iterative linkage between subsystems described by Mileti and Sorensen (1990), which are generally maintained prior to and following the event.

Admittedly, over recent years, there have been increased attempts by emergency agencies to use maps to convey information to the public during crises. Specifically, public warning maps to date can be categorised based on the amount of visual content conveyed; *simplistic warning maps* demonstrate only cursory locations of hazard events (e.g. CAL FIRE 2016, DFES 2015a) or designated warning areas (e.g. NWS 2008) serving as supplementary information to comprehensive text-based warnings, whereas *enriched warning maps* provide more specific risk explanatory information in visual forms. An example for the latter is the 'cone of uncertainty' (COU) map used to depict not only designated warning areas, but also current

and predicted tropical cyclone tracks and the associated uncertainties (NHC 2015). Recent years have also seen an increase in the application of webGIS technology to provide online interactive map-based warnings, and such instruments are often promoted as primary interfaces for accessing warning information. Examples include the USGS (2012) Flood Inundation Mapping application, the VicEmergency (EMV 2015) and AlertSA (Government of South Australia, 2015) mapping systems launched in Australia for bushfire warning communication, and Google's Crisis Maps (Google Crisis Response, 2015), to name a few.

However, these mapping tools have often been designed based on the subjective judgement of cartographers, technicians or emergency service personnel, remaining largely inconsistent in terms of map content, information representation and functionality. In fact, several studies have revealed the deficiency of certain enriched warning maps in eliciting appropriate comprehension and responses. For instance, tornado warning maps have been found to lead to erroneous risk assumptions and interpretations (Ash et al., 2014, Lindell et al., 2015a), implying the need of further visual information explicating the hazard situation. Furthermore, it has been posited that the COU map challenges the general public to understand its intended meaning (Broad et al., 2007), warranting more effective hazard representation or interactivity to assist in the exploration of multi-faceted information. The implication is that public warning maps developed with a focus on data and technologies may not effectively achieve the goal of motivating response.

As highlighted in the previous discussion of public warning literature, effective warning messages should deliver accurate, specific and sufficient information with an aim to facilitate personal perception of risk and reasoning of response guidance. In addition, current GIS technology can provide for *personalised* information communication and decision support and thus potentially aid in the elicitation of appropriate responses by individuals. Therefore, the development of map-based warning systems should be guided by the theoretical understanding of effective warnings to offer truly improved, *personalised* warnings; however,

to date research regarding how such *personalised* public warning systems can be constructed has been scant.

3.3 Conceptualisation of an effective personalised public warning system

To provide systematic guidance for the communication of effective, *personalised* warnings through a webGIS platform, a conceptual framework was developed (Figure 3.3). Off-the-shelf geospatial technologies and products from the current emergency management system (illustrated in Figure 3.2) are identified to assure the feasibility of the proposed warning framework. Corresponding with the psychological needs of warning recipients, the framework was developed with the intent to fundamentally improve the way public warnings are perceived by: i) facilitating prompt and adequate risk personalisation at an early stage; and ii) aiding the reasoning of response-efficacy under one's particular circumstances. To this end, a personalised warning system should comprise two primary components (Figure 3.3):

a. A semi-/automated personalised webGIS (Figure 3.3.*a*) that integrates and presents a comprehensive and appropriate array of hazard-risk information pertinent to one's location through an individualised map view; and

b. A 'personal vulnerability/risk assessment' module (Figure 3.3.*b*) that assesses individual/household-specific vulnerability and risk information and offers tailored advisories concerning appropriate responses.
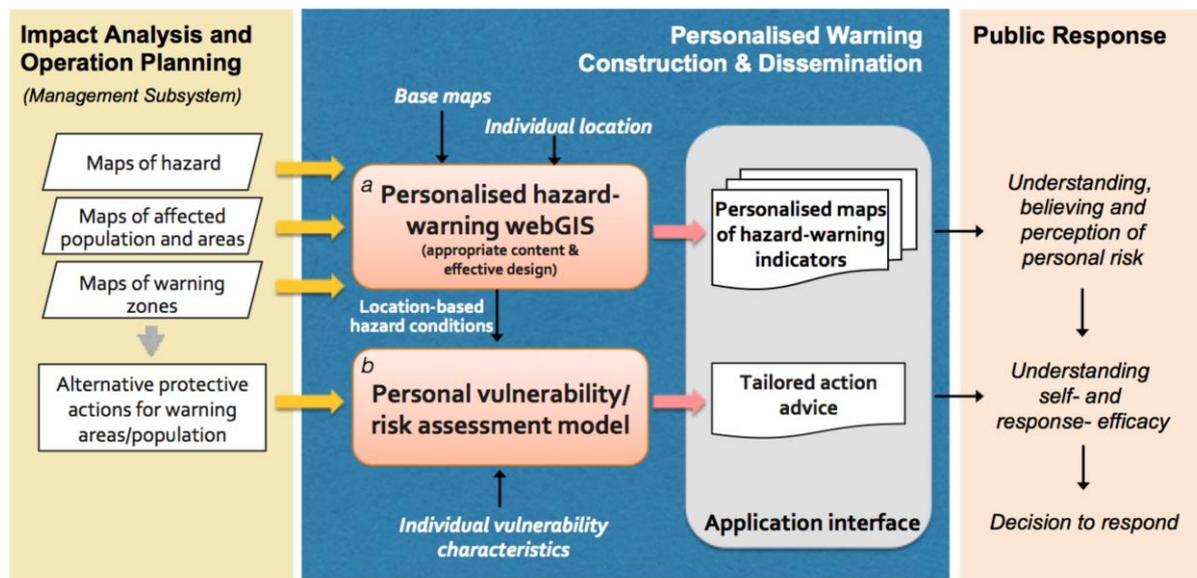
Figure 3.3. The conceptual framework for a personalised, map-mediated warning dissemination model. The maps generated within the management subsystem are shown on the left, corresponding with the map products shown in Figure 3.2.*a*, *b*, and *c*.

The personalised hazard-warning webGIS

For the first component, the personalised hazard-warning webGIS, it is of significant importance that the webGIS provides personalised visualisation of hazard threats pertinent to one's location in order to facilitate risk personalisation. Such personalised visualisation can be achieved by coupling hazard-warning related maps with prominent marking and centring of individuals' location. Individuals' location can be obtained via an interactive interface or using GPS locators embedded in smartphones if accessed as a mobile application. The design of specific map outputs should differ across hazards and geographical/cultural/political contexts, and should be selected based on user-centred investigation of two critical questions: i) what spatial hazard-risk information needs to be communicated (Hagemeier-Klose and Wagner, 2009, Dransch et al., 2010, Meyer et al., 2012), and ii) how can maps (web-map interfaces) be designed to effectively present this information for public consumption (Dransch et al., 2010, Lieske, 2012, Meyer et al., 2012).

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With an aim to facilitate risk personalisation, the investigation of the first design question should be built on an understanding of the information required to conceptualise individual 'risk'. One's *risk* to a given hazard is collectively determined by the individual's *exposure* to the threat, the intensity of the *hazard*, and the person's *vulnerability* or capacity to cope with the potential impact (Crichton, 1999). As alluded to earlier, one's *exposure* to a hazard threat and the associated *hazard* intensity are subject to the person's location. These two components of individual risk are therefore geographic in nature, lending themselves to a map-based delivery. A range of specific spatial indicators for reasoning *exposure* and *hazard* can be initially drawn from the heterogeneous spatial information housed within the management GIS/SDSS (Figure 3.2.*a*, *b*, and *c*). For example, maps of current and predicted hazard extent and magnitude (Figure 3.2.*a*) can be communicated to support individuals' understanding of the hazard location, severity of potential impact and remaining time before impact at their specific location. Furthermore, maps of affected areas and warning zones (Figure 3.2.*b* and *c*) can aid in individuals' identification and/or reassurance of their exposure to the hazard threat. These existing hazard and risk maps therefore can be easily integrated into the 'personalised hazard-warning webGIS' to elucidate *hazard* and *exposure*. However, as stressed by many researchers (Mills and Curtis, 2008, Hagemeier-Klose and Wagner, 2009, Dransch et al., 2010, Meyer et al., 2012), the spatial content used by emergency managers and professionals are not always helpful or appropriate for communication to the public. It is therefore crucial that end-users' (i.e. community members') are consulted to identify and confirm the necessity and effectiveness of heterogeneous spatial hazard-risk information delivered as maps.

Furthermore, the effectiveness of information elements also hinges on the format in which they are presented. Especially, as maps produced for experts may not be readable by nonprofessionals (Mills and Curtis, 2008, Hagemeier-Klose and Wagner, 2009, Meyer et al., 2012), it is important to identify an appropriate representation method for public consumption (i.e. the second design question). Such an investigation may start with a comparative assessment of multiple cartographic methods for representing warning information, followed by an iterative design process to identify the optimal representation means (Lieske, 2012). In

addition, for certain information elements, textual descriptions may be found to be more effective than maps, and thus a combination of maps with textual annotations may be necessary.

Finally, it needs to be acknowledged that some critical warning elements, such as *response guidance*, and information *source* (Mileti and Sorensen, 1990), are aspatial and thus cannot be directly mapped. For the sake of providing an integrated information bundle, necessary textual information should be incorporated through intelligent and balanced design of an interactive web-mapping interface.

The personal vulnerability/risk assessment model

The second major component of a personalised public warning structure concerns the provision of personalised response advice based on computer-aided risk assessment for an individual/household taking into account the hazard threat for one's particular location and the underlying vulnerability. This component becomes increasingly important as response options become more plentiful and their relative appropriateness is more dependent upon variations in hazard intensity and vulnerability.

Generally, the 'personal vulnerability/risk assessment model' should follow a four-step mechanism (as illustrated in Figure 3.3): i) identify pertinent knowledge of hazard threats and warnings for a particular location from the location-based hazard and warning webGIS; ii) distil generic alternative responses suggested for the associated warning area or population group(s); iii) incorporate user-provided vulnerability information; and iv) integrate the information attained from the first three steps to assess an individual's eligibility for certain actions using predefined thresholds, and provide tailored action advice along with relevant *hazard*, *exposure* and *vulnerability* indicators to help individuals comprehend and make appropriate decisions. Notably, the first two steps depend on up-to-date hazard and warning data fed into the hazard and warning webGIS during events, whilst the third step is concerned with individual vulnerability characteristics, which can be collected prior to an event. Such

data collection in advance is especially necessary when the vulnerability assessment for deciding appropriate actions requires evaluation of a wide spectrum of personal/household information, needing time for data entry. In such cases, residents from hazard prone areas should be encouraged to answer questions regarding their vulnerability characteristics as registered users in the beginning of a hazardous season, and the information can be saved, retrieved and feed into the personal vulnerability/risk assessment model for generating personalised action advice during an event.

To give a more specific example of how a 'personal vulnerability/risk assessment model' may work, a model for flood emergencies was conceptualised. When a flood threat is forecasted, the model would first identify *hazard* indicators based on one's location via the webGIS structure, such as expected water levels, time of arrival, and duration of inundation (step i). If emergency managers have designated warning areas, the system could also discern whether an individual or household is located within the warning zone and therefore *exposed* to the threat, and identify what protective actions (e.g. evacuation and/or shelter-in-place) could be suggested (step ii). Next, if more than one action could be suggested, personal vulnerability information could be retrieved for a registered user (step iii) to examine personal/household *vulnerability* in relation to physical hazard characteristics and suggest appropriate action(s) based on pre-defined criteria (e.g. predicted water level, duration of inundation, and flood-resistance of the building, etc. as suggested by Haynes et al. (2009)) (step iv). If for instance, sheltering in place is feasible based on the decision model and is also desirable by the resident, the system would provide specific advice on how to make preparations, such as the amount of food supply needed given the estimated duration of impact (Haynes et al., 2009).

To summarise, the conceptual framework presented in Figure 3.3 demonstrates a general structure for producing and communicating personalised hazard warnings through a web-based mapping interface. Resonating with the psychological needs of the public for effective warnings, this conceptual framework attempts to provide *comprehensive* as well as *personalised* visual warnings. The *personalisation* in this approach draws upon two specific

facets: i) location-based mapping of hazard and warning information, and ii) the modelling and communication of individualised response guidance. Operationally, a personalised risk and warning webGIS should be designed based on a systematic understanding of the 'what and how' to present spatial indicators of *hazard* and *exposure*, followed by the establishment of a personal vulnerability/risk assessment model to streamline the provision of individually tailored action advice. In the following section we showcase the conceptual development of a personalised bushfire warning tool in an Australian context based on the general framework.

3.4 Case study: conceptual development of a personalised bushfire warning system

3.4.1 The Australian context

In Australia, bushfire remains one of the most deadly natural hazards due to the nation's peri-urban development and unique meteorological and biophysical environments (Whitaker, 2010). The devastating Victorian bushfires of February 2009, also known as the Black Saturday Bushfires, caused 173 fatalities, destroyed more than 2000 homes, and resulted in severe economic, social and environmental costs (Teague et al., 2010). The national policy concerning community safety appeals for shared responsibility in which individuals are given the option to choose between leaving early or actively defending an adequately prepared property (AFAC 2010). This policy is based on findings from previous bushfire investigations (Wilson and Ferguson, 1984, Handmer and Tibbits, 2005, Teague et al., 2010), which identified that the chance of human survival is comparably high if either action is appropriately enacted. Whilst it is stressed within the policy that early evacuation is always the safest strategy, it becomes increasingly dangerous when delayed (Haynes et al., 2010) and actively defending a property can provide for safe shelter, under conditions of sufficient preparation (Handmer and Tibbits, 2005, Whittaker et al., 2013). Therefore, the policy implies that people must be self-sufficient in assessing the timeliness of evacuation and/or preparedness for active defence, and plan for response accordingly (Tibbits and Whittaker, 2007, Paveglio et al., 2007). Post-fire studies however, have revealed a significant adoption of

the 'wait and see' strategy, leaving the decision to the day and commonly resulting in late evacuation (Rhodes, 2007a, Tibbits and Whittaker, 2007, Handmer et al., 2010, Whittaker and Handmer, 2010, Dunlop et al., 2011, McLennan and Elliott, 2012). Furthermore, people who plan to 'stay and defend' often fail to prepare their household to a desirable level, and overestimate their capacity to protect their property (Rhodes, 2007b, Tibbits and Whittaker, 2007, McLennan et al., 2011b, Trigg et al., 2015a). Researchers have identified that such individuals' misjudgement in the feasibility of their chosen response to a fire threat is in part due to the absence of explicit communication of viable protective approaches as well as accurate, timely, comprehensive and location-specific hazard information (Teague et al., 2010, McLennan and Elliott, 2012).

3.4.2 Development of a personalised bushfire warning framework

Figure 3.4 presents a Standardised Household Action Advice and Risk Communication (SHAARC) framework conceptualised for delivering personalised, spatially enabled bushfire warning information. Based on the general framework illustrated in the previous section, the conceptual development of SHAARC involved two major components: designing a webGIS for generating and delivering personalised hazard and warning maps, coupled with a vulnerability/risk assessment model (named 'Household Action Advice Submodel') to evaluate household situation and provide tailored action advice.
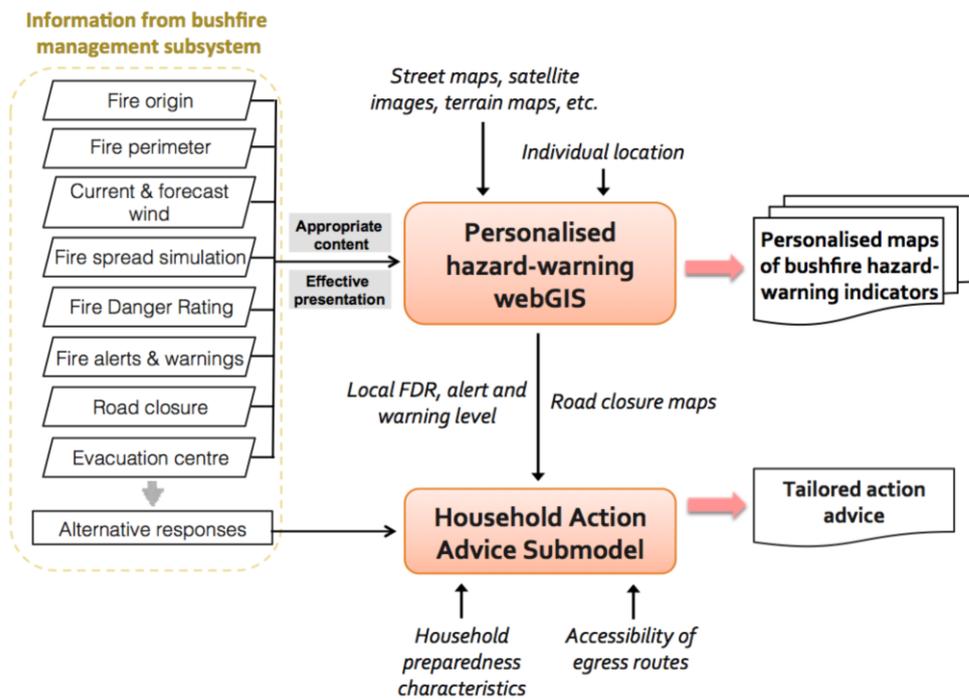
Figure 3.4. Conceptualisation of the Standardised Household Action Advice and Risk Communication (SHAARC) framework, derived from the general framework demonstrated in Figure 3.3.

Designing the personalised hazard and warning webGIS

As discussed in the previous section, the design of a personalised hazard and warning webGIS mainly concerns the identification of potential spatial information regarding individual *exposure* and associated *hazard*, followed by user-centred investigations in appropriate content and representation. In a bushfire context, a range of *exposure* and *intensity* indicators (Figure 3.4) can be drawn from the spatial information available within the current emergency management and warning system. The following paragraphs will discuss these indicators in more detail.

Factors related to exposure. The most straightforward indicator of one's exposure to a bushfire threat is inclusion within a warning zone. In Australia, two types of bushfire warnings are used: severe fire weather warnings based on *Fire Danger Ratings* (FDR), and

bushfire alerts. The FDR is a national system indicating the intensity of current and forecast fire weather for a region (National Bushfire Warnings Taskforce, 2009). It is derived from the forest fire danger index (FFDI), which indicates the degree of danger of a fire spread (both vertically and horizontally) in common fuel types (Luke and McArthur, 1978). A 'severe weather warning' issued on a 'Catastrophic' or 'Extreme' FDR day indicates that fires are likely to occur and, if started, are likely to be uncontrollable and unpredictable, and spread rapidly. Residents are consequently advised to leave risky areas early on such days irrespective of a fire event and one's prior fire plan. The second warning type is *bushfire alerts* triggered by an actual bushfire threat to humans. They are issued at three levels as a function of fire weather severity (as indicated by the FDR), and estimated time to impact (Figure 5, National Bushfire Warnings Taskforce, 2009). Specifically, the 'Emergency' level indicates immediate danger and people are recommended to stay and defend or evacuate instantly if the way is clear, or take shelter at home if it is not too late; 'Watch and Act' indicates a possible threat and people should leave immediately or get ready to defend; the 'Advice' level denotes no immediate threat and residents should stay informed (DFES 2015b). Both FDR based severe weather warnings and bushfire alerts are issued for regions or communities, and therefore can be delivered to the public in the form of maps.

Figure 3.5. Trigger matrix for the three alert levels (emergency warning, watch and act, and advice) and related FDR (National Bushfire Warnings Taskforce, 2009).

Factors related to bushfire hazard. An array of bushfire h*azard* indicators can be adopted to delineate current and predicted hazard locations, time, magnitude and intensity. First, the general fire locations are often vaguely described in current text-based warnings, but accurate maps of *fire origin* and near real-time *fire perimeter* are available in bushfire management systems. Second, text-based warnings often depict the general rate of fire spread requiring an individual to estimate the likely time it will take the fire to reach one's location. However, sophisticated and visualised *fire spread simulations* (e.g. Tolhurst et al., 2008, Johnston et al., 2008, Steber et al., 2012) have been increasingly used by emergency managers, and can be incorporated in visual public warnings to demonstrate modelled estimations of lead-time for a specific location. Although the computer-modelled estimations include a degree of uncertainty, they are likely to attenuate the chance of misinterpretation by the public when compared to self-estimation using text-based warnings. Third, bushfire intensity is largely dependent on wind conditions, which are one of the most important information elements in current warnings. Accurate wind maps from the Bureau of Meteorology (BOM 2015) can be integrated into the hazard-warning webGIS to show existing and forecast winds at different locations. Fourth, the general intensity of a bushfire can also be indicated by the *FDR* categories of the day. Finally, *satellite images* and *terrain maps* may be useful as base maps to shed light on local vegetation distribution and topography, both influencing fire behaviour (i.e. rate of fire spread, flame height and magnitude of ember attack).

Developing the Household Action Advice Model

The second module that underlies the SHAARC framework is the Household Action Advice Model (HAAM). The purpose of this model is to assess the safety of alternative protective actions (i.e. in the case of bushfires: staying and defending versus leaving early) and to provide 'tailored action advice' (Figure 3.4). The HAAM builds upon current literature and bushfire community safety policies in Australia, but extends to standardise and automate the analytical process for determining the appropriate responses for an individual household. In addition to the *hazard* and *exposure* indicators identifiable for one's location from the maps

(Figure 3.4), the model also needs to take into account one's *vulnerability*; it then can combine all relevant indicators to comprehend the safety of each given response. Hence, household-level factors that can be used to determine one's *vulnerability*, or capacity, to undertake the two potential responses are identified and discussed respectively.

Vulnerability factors related to 'staying and defending'. The safety of staying and defending a property is primarily subject to the household's *preparedness* (AFAC 2010). Sufficient preparedness should concern multiple aspects, including the modification of vegetation in the surrounds; the design, construction and maintaining of a fire-safe structure; and the preparation of firefighting equipment, resources and power (Penman et al., 2013, Cao et al., 2016). Specific guidance has been provided by fire authorities for long-term household preparation (e.g. Standards Australia, 2009, CFA 2009). However, there is no clear and thorough definition of the legitimate preparatory conditions for householders to safely consider staying and defending (Penman et al., 2013, Cao et al., 2016). The evaluation of 'preparedness' for staying and defending is further complicated by the suggested relationship with fire intensity indicated by FDRs; that is, varied degrees of preparedness are desired for safely staying and defending a property at different FDR levels (Cao et al., 2013). Consequently, an FDR-dependent preparedness assessment model should be established to support more informed individual decision making regarding 'staying and defending'. To this end, the recent study by Cao et al. (2016) has provided a comprehensive and systematic starting point that can be extended to develop local- or household- specific preparedness standards for 'staying and defending'.

Vulnerability factors related to 'leaving early'. One's capability to safely evacuate depends on the accessibility to at least one safe egress route. A straightforward indicator of road safety is *road closure* information released by emergency services or local police. Furthermore, information on the potential fire spread direction and speed, indicated by the *fire spread simulation*, is necessary for evacuees to identify a destination that is away from risks and can

be safely travelled to. *Evacuation centre* information attached to particular events is also critical, and can be incorporated as maps in association with text description (Figure 3.4).

Figure 3.6 shows the operational design of a decision model based on all the identified factors and relationships. During a bushfire event, a user entering the system for bushfire information would be first prompted to enter the address of the property of interest. Drawing upon the spatial information on bushfire Alerts or Severe Weather Warnings streamed via the hazard and warning webGIS (Figure 3.4), the HAAM would determine whether the person is exposed to a potential threat, followed by the identification of generic alternative response(s) suggested by agencies for the corresponding area. Under most scenarios, the alert and warning system would generically suggest two response options, i.e. 'stay and defend' or 'leave early/immediately' (Figure 3.6). One's capacity to stay and defend should be evaluated by a 'Household Preparedness Assessment Model' defining the required preparatory conditions in support of active defence for each FDR by providing a checklist of critical preparatory actions. Cao et al. (2016) have demonstrated the first attempt for building such a model, and further adjustment can be made based on local or household contexts. Residents who plan to stay and defend would be obliged to follow the preparatory requirements from the beginning of a bushfire season, and register and regularly update their preparedness in the web-based bushfire warning system. During the onset of a bushfire, users would be asked to confirm the authenticity of the pre-entered preparatory information, update/provide changes, and provide consent to determine whether they are entitled to stay and defend their property. Furthermore, assessment of the safety of 'evacuation' should focus on whether it is 'too late to leave' as indicated by the availability of at least one safe egress route. Given the up-to-date road closure maps (Figure 3.4), it would be straightforward for the system to identify the accessibility of egress routes, and for users to further pinpoint safe destination(s) and evacuation routes on the map.
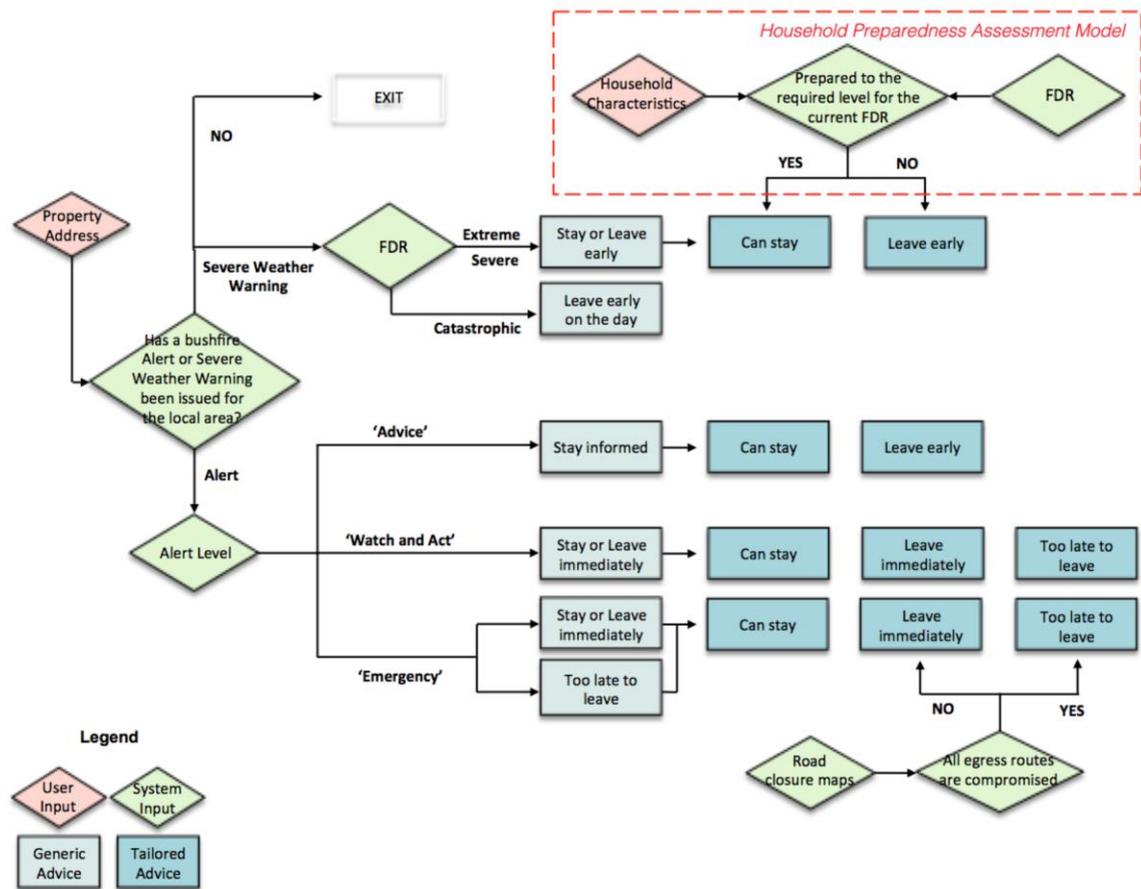
Figure 3.6. Design of the operational decision-tree for the *Household Action Advice Model (HAAM).* In this operational decision-tree, 'stay' signifies staying and defending a property, 'leave' signifies evacuation in general, 'too late to leave' signifies it is too late to safely evacuate. But the advice regarding evacuation can be subdivided to leave immediately and leave early. The latter is usually suggested for severe weather warning scenarios or 'Advice' alert levels, and coupled with messages like 'leave bushfire risk areas the night before or early in the day' or 'people need to stay informed and prepare to leave when the situation gets worse'.

There could be three warning scenarios when the 'generic advice' does not suggest a choice between staying and defending and leaving early (see Figure 3.6). The first is the issuance of a 'Catastrophic' fire weather warning, when people are not encouraged to stay and defend regardless of their level of preparedness. The second is when an 'Advice' fire alert is issued, which indicates that the public should 'stay informed' as the risk is not yet immediate. At this time, individuals should start to think through their planned survival response, i.e. stay and

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defend or leave early. Finally, agencies issuing an 'Emergency' fire alert could suggest to 'put your bushfire plans into action', and 'leave immediately if it is not too late'. However, there may be times when the generic advice given to the whole warned community is 'it is too late to leave', as many exiting routes have been compromised. Such a suggestion signifies a stressed emergency situation; however, people's accessibility to safe egress routes may still be subject to their specific location. Consequently, the system would demonstrate the generic advice of 'too late to leave' (Figure 3.6), but also provide road closure maps to support individual assessment.

As can be seen from Figure 3.6, the HAAM may provide four possible safe responses: stay and defend a property, leave early when not threatened, leave immediately, and seek last resort as it is too late to leave. Current generic warning messages that are issued by local agencies commonly supply brief guidance for undertaking each viable response. The personalised action advice from the SHAARC framework comprises similar components but could be personalised in two regards: i) it suggests a household-specific safe option, and ii) highlights detailed action guidance associated with the strategy suggested by the emergency agency. For instance, the households that are recognised as insufficiently prepared for active defence will first be supplied with a suggestion of leaving early as the safe option, followed by information explaining the risk associated with staying and defending their properties. Furthermore, the advice will highlight specific guidance regarding leaving early (e.g. what things to take and how to evacuate). However, the advice should contain guidance for the other option (i.e. active defence in this example), which is meant for those who are willing to take the risk and enact such a strategy regardless of a negative advice to do so.

In the case of discrepancies between generic and household-modelled safe action(s), the former could be provided but with an emphasis on the fact that it is general advice rather than personalised. For instance, under the 'too late to leave' Emergency scenario (Figure 3.6), a household that is not sufficiently prepared for active defence (indicating the likely danger of sheltering-in-place) but with potential access to safe egress routes should be suggested to

leave immediately in the personalised action advice section. Still, the generic 'too late to leave' advice for the area should also be communicated as subsidiary information, but should not be deemed as the single driver for an individual's evacuation decision. Eventually, messaging protocols can be formulised for all potential output scenarios, restored in the system database, customised (when necessary) by incident managers during the initiation of a warning, and retrieved automatically by the computer system to generate personalised advice based on the results from the individual risk assessments.

3.5 Discussion and conclusion

For decades researchers have endeavoured to determine how public warnings can reduce 'normalcy bias', appeal to the pertinent population, stimulate efficient risk personalisation and elicit appropriate responses. Recent research suggested that map-mediated communication techniques have a potentially significant role to play in increasing warnings' effectiveness by providing a platform for delivering compelling, comprehensive, and location-based visual warning services (Dransch et al., 2010). Additionally, the conceptual framework presented in this paper underscores the need and feasibility for supplying personalised hazard and warning information using maps as well as individualised decision support tools to aid in the interpretation and perception of communicated threat and response guidance at individual/household levels. Such personalised warning communication may minimise the chance of distraction (Terpstra and Vreugdenhil, 2011), misinterpretation, and failure to enact appropriate actions at the appropriate time (Slovic et al., 2004).

In fact, location-based alerting services have been adopted in many countries such as the U.S. and Australia in recent years, providing some personalisation of early warning. Specifically, the location-based alerting service refers to the use of geo-targeting technologies to spatially direct messages to at-risk populations. This is achieved by either targeted communication through registered telephone lines (EMV 2014a), or sending SMS messages to smartphones located within threatened areas using embedded GPS location services (Bennett et al., 2013, Bean et al., 2015). These geo-targeted telephone/SMS messages are predominantly brief and

text-based, as consistent with the comprehensive official warnings delivered through mass media and agency websites. Whilst the receipt of such alerts may facilitate the recognition of personal relevance (EMV 2014a), the brief textual information delivered is likely to lack the power to further promote adequate understanding of hazard threats in relation to oneself and stimulate appropriate responses.

Realistically, the map-mediated warning framework proposed in this paper can be concatenated with the existing location-based alerting to formulate an enhanced personalised warning system that may substantially improve warning outcomes. Firstly, the geo-targeted SMS alert message can be coupled with individually-centred maps that depict critical information concerning the hazard (e.g. accurate hazard locations) and/or warning (e.g. designated warning areas). An easily recognisable background map (e.g. Google street map) should underlie such maps to facilitate geographic contextualisation. Such a personal-centred delineation of hazard/warning relevance, in addition to the geo-targeted dissemination, has been found to further facilitate warning personalisation by the at-risk audience (Bean et al., 2014). Secondly, citizens seeking further information in response to an initial SMS alert can be directed, through an embedded hyperlink within the message, to a comprehensive and personalised map-based warning portal launched as a mobile/online application. Specifically, by typing in one's location or using stored locations for registered users, one can be provided with personalised map views of relevant incidents (i.e. marking and centring an individual's location on the map), along with effectively designed maps depicting the risk situation in the local context (e.g. fire perimeters, wind conditions, FDR, fire spread prediction and closed roads). Additionally, users can be provided with individually assessed response guidance (e.g. whether an individual can stay and defend or leaving immediately as a safe course of action). Through this two-step process the map-based personalised warnings are expected to first elicit attention from the 'right' people, and further facilitate risk confirmation by individuals by promoting the risk understanding-believing-personalising-responding procedure.

The conceptualised framework presented in this paper provides a tangible guidance for the design and implementation of such a revolutionary warning approach. As has been illustrated by the SHAARC model, a comprehensive and personalised warning portal requires the development of two respective components. First, a personalised risk and warning webGIS needs to be designed by addressing the questions: 'what to map' and 'how to map them'? This involves the identification of potential *hazard* and *exposure* indicators based on an understanding of the data capacity of local emergency management agencies for providing accurate spatial information, followed by user-centred investigations to identify the important indicators and appropriate representation methods. Second, a personal risk and vulnerability assessment model needs to be developed by identifying relevant *vulnerability* factors which can be linked with the viable courses of action through consultation with literature and subject-matter experts. In contrast, the proposed map-enabled SMS alerts, which could be used as initial alerts, only require a simplified realisation of the first component, i.e. a mobile-GIS system that can provide an individually-centred map displaying a critical threat and warning indicator (e.g. warning polygons or hazard impact areas) that is to be identified through user-centred evaluation.

The development of the SHAARC model for bushfire warnings in the Australian context further illustrates how to identify potential hazard and exposure indicators for visual integration in a webGIS, and how to model individualised vulnerability conditions to provide tailor action advice. However, both components of the SHAARC (i.e. the hazard and warning webGIS and the household action advice submodel) may largely vary across hazards and local contexts, warranting specific design and development by agencies. For instance, in many countries, evacuation is mandated for wildfire incidents, and the SHAARC model thus needs to be adapted for local policies. For a hazard such as flood, for example, a new model needs to be developed by identifying relevant *hazard* and *exposure* indicators to be incorporated into the webGIS, and recognising household *vulnerability* factors and their relationships with optional protective measures to develop the individual/household decision support module.

It should also be highlighted that the applicability of an advanced warning approach to a hazardous event depends on its forecast potential and predictability (Mileti and Sorensen, 1990, Alexander, 1991). Theoretically, the proposed personalised warning approach is especially valuable for hazards that are evolving, or whose impact is yet to be realised, providing lead time for information dissemination and response taking. For instance, severe earthquakes are known for their large-scale impact with little lead time. Current earthquake detection and warning technologies only allow for limited warning before impact, resulting in finite warning options. On the contrary, the threat of tsunami, although caused by earthquakes, can often be predicted before arrival allowing for the timely dissemination of warning information. Other applicable examples can also be found for tornados and hurricanes, as well as cumulative events like regular floods and droughts. In sum, explicit and effective warning information is especially critical when impact is imminent but the threat cannot be easily conceptualised and sufficient lead time is available for residents to make provisions for early evacuation or alternative measures to prevent a likely catastrophe.

Chapter 4. Defining Sufficient Household Preparedness for Active Wildfire Defence: Toward an Australian Baseline

Abstract

This study begins to offer a tangible definition and operationalisation of the required level of preparedness for safely 'staying and defending' a property by householders in Australian wildfires. A consultative workshop was conducted with a taskforce of national experts from Australia seeking to obtain consensus on the critical nature of a wide-ranging list of preparatory actions. An innovative methodology was employed to account for the potential relationship between the desired levels of preparedness and Fire Danger Ratings (FDRs), the indicator of fire weather intensity, as was long suggested by Australian fire agencies. The resultant model includes a checklist of critical preparatory actions for each FDR that portrays a minimum and essential preparatory condition to guide an individual's decision to stay and defend under the given fire condition. Whilst the definition presented here does not provide a unique solution to ensure the safety of active defence under all household scenarios, it delivers a robust and comprehensive model to be applied to an average Australian residence whilst providing a baseline for further development of local-/household-specific preparedness standards. The model may also serve as a useful starting point for agencies in other countries to undertake a similar exercise.

4.1 Introduction

An increasing number of properties are exposed to wildfire hazard as a result of aggravated fire weather conditions (Piñol et al., 1998, Williams et al., 2001) and expansion along the urban fringe (Hammer et al., 2009). As with most hazards, leaving a threatened area well before a disaster occurs is the safest option for individuals; however, there has been growing international recognition that late evacuation is the most deadly action in wildfires and residents may be able to stay and defend their properties and safely shelter in place in some circumstances (Paveglio et al., 2008, Cova et al., 2009). Within Australia, the national

position endorsed the viability of both actions via a 'prepare, stay and defend or leave early' policy (Tibbits et al., 2008). The key element of this policy was the proactive engagement of householders. It was stressed that the choice to 'stay and defend' was one that required 'adequate' preparation and maintenance throughout the fire season and should be established through a 'Bushfire Survival Plan' (AFAC, 2010). Research following the devastating Black Saturday bushfires in Victoria, 2009 however, identified a potential misinterpretation of the policy as passive sheltering, lacking adequate emphasis on the long-term preparation and planning for active defence as a holistic strategy (Handmer et al., 2010, Teague et al., 2010). The national position was then revised to punctuate that leaving early is always the safest option, whilst the decision to stay and defend requires an evaluation of 'a complex combination of factors' relating to the intensity of the wildfire, the condition of the property being defended, as well as the physical and emotional preparedness of the prospective defenders (Llewellyn, 2012, p.5).

Consequently, it is crucial for homeowners who intend to 'stay and defend' to understand what can be done to prepare their property and themselves, and what a 'sufficient' level of preparedness is (Paveglio et al., 2007), which, based on the national position (Llewellyn, 2012), should be defined as a level of preparedness that ensures the safety and survival of the defenders throughout the active defence process. However, an explicit explanation or operationalisation of 'sufficient preparedness' to achieve the goal of safe active defence has been long missing (Teague et al., 2010, Penman et al., 2013), resulting in considerable misjudgements and perilous decisions by individuals (Tibbits and Whittaker, 2007, Whittaker et al., 2009, McLennan et al., 2015, Trigg et al., 2015b). As Penman et al. (2013) argued, many of the preparatory actions suggested by emergency management organisations and academics alike, are not necessarily critical for the effective reduction of wildfire risk. Furthermore, there are discrepancies in the preparatory actions suggested by each state emergency management agency. Without clarification concerning which preparatory actions are vital for safely 'staying and defending' a property, homeowners are more likely to

undertake preparedness measures that are the easiest to complete but not necessarily the most beneficial for defence (Tibbits and Whittaker, 2007).

The current study seeks to address this void by offering a tangible definition, or in other words an operationalisation, of the level of 'preparedness' required for safely staying and defending a property. More importantly, the operationalisation considers the varied degrees of protection demanded under different fire conditions by linking required levels of 'preparedness' with Fire Danger Rating (FDR) categories, a system adopted in Australia to indicate fire weather intensity and potential fire danger (National Bushfire Warnings Taskforce, 2009). Drawing from a conceptual framework of preparedness for active defence and an analysis of current operational and academic definitions and measurements (in Australia and abroad), a Household Preparedness Workshop was conducted with experts from various Australian agencies to explore the critical nature of a range of wildfire preparatory actions under different FDRs, in an attempt to obtain an expert consensus. The results and discussions from the workshop were collated to form a national baseline for identifying a checklist of *critical* preparatory actions as a *minimum* but *essential* standard to be completed for a given FDR to ensure the safety of defenders and structures to an acceptable level when active defence is enacted. Such an instrument can be used by residents to aid appropriate self-assessment and decision-making during the drafting of 'Bushfire Survival Plans' (i.e. stay and defend or leave early) and/or in the face of an imminent wildfire threat. Moreover, it can serve as an explicit and effective long-term preparation guide for homeowners, especially for those who intend to 'stay and defend' their property.

4.2 Conceptualising household preparedness for active defence

To define and operationalise sufficient preparedness for safely staying and defending a property, it is important to first understand what risks are associated with active defence and how to ensure safety. One factor that is of great importance here is that defenders are directed to seek haven within a safe structure when the main fire front passes (Wilson and Ferguson, 1984, Handmer and Tibbits, 2005, AFAC, 2010) as the impact can be fatal for humans (Butler

and Cohen, 1998). During a passing fire front, a structure can be attacked by both direct flame contact and by radiant heat transfer, potentially causing combustion of exterior materials, or breaking windows and posing dangers to the interior (Blanchi and Leonard, 2005). Therefore, sufficient preparedness means that a building needs to withstand the direct flame contact and radiant heat transfer stemming from the passing fire front without human interventions to ensure safe sheltering. In addition, prior to and following the passage of the main fire front, a fire attack can also take the form of an ember attack, which in fact accounts for a majority of structural losses (Ramsay et al., 1987, Blanchi and Leonard, 2005). Embers created by a wildfire can emanate from a distance up to 700m away (Tolhurst, 2009) and induce small ignitions by piling up against combustible materials adjacent to or on a structure, or entering a building through gaps (Blanchi et al., 2006). If not extinguished, small combustions can grow into to structural fires, providing a secondary source of radiant heat and flames that lead to the ignition of neighbouring structures (Blanchi and Leonard, 2005). Active suppression activities are therefore essential to eliminate the effect of embers (Wilson and Ferguson, 1984, Cohen, 1995) and any failure to provide adequate suppression can result in unsuccessful defence of the structure and threaten a defenders' life. In sum, the safety of a defender in wildfires is largely dependent on whether the defence can be successful, i.e. the structure can survive the fire.

The survival of a structure is a synergistic effect of *pressure* from the various fire attack mechanisms mentioned above and *resistance* (the capability of a building to withstand the given level of pressure) (Blanchi and Leonard, 2005, Tolhurst, 2009). As shown in Figure 4.1, fire *pressure* is dependent upon the fire weather severity on the day of a fire, and the ambient vegetative and topographic conditions surrounding a structure (Cohen, 2000, Tolhurst, 2009). *Resistance* concerns both *structural resistance* and *active resistance*; that is, *resistance* is the ability of a building to withstand radiant heat, flame contact and consecutive ember attack (Blanchi and Leonard, 2005), with human assistance to prevent or suppress potential impacts (Tolhurst, 2009). The wildfire building survival model (Figure 4.1) provides a conceptual framework for understanding the factors that contribute to the survival of a structure whilst

being actively defended. What is important to highlight, is that a number of these factors can be modified, or prepared, prior to a wildfire to maximise the overall chance of survival (denoted by * in Figure 4.1). These factors fall into three broad categories, which correspond with three preparatory goals: attenuating fire pressure, improving structural resistance, and assuring the requirements for active defence.
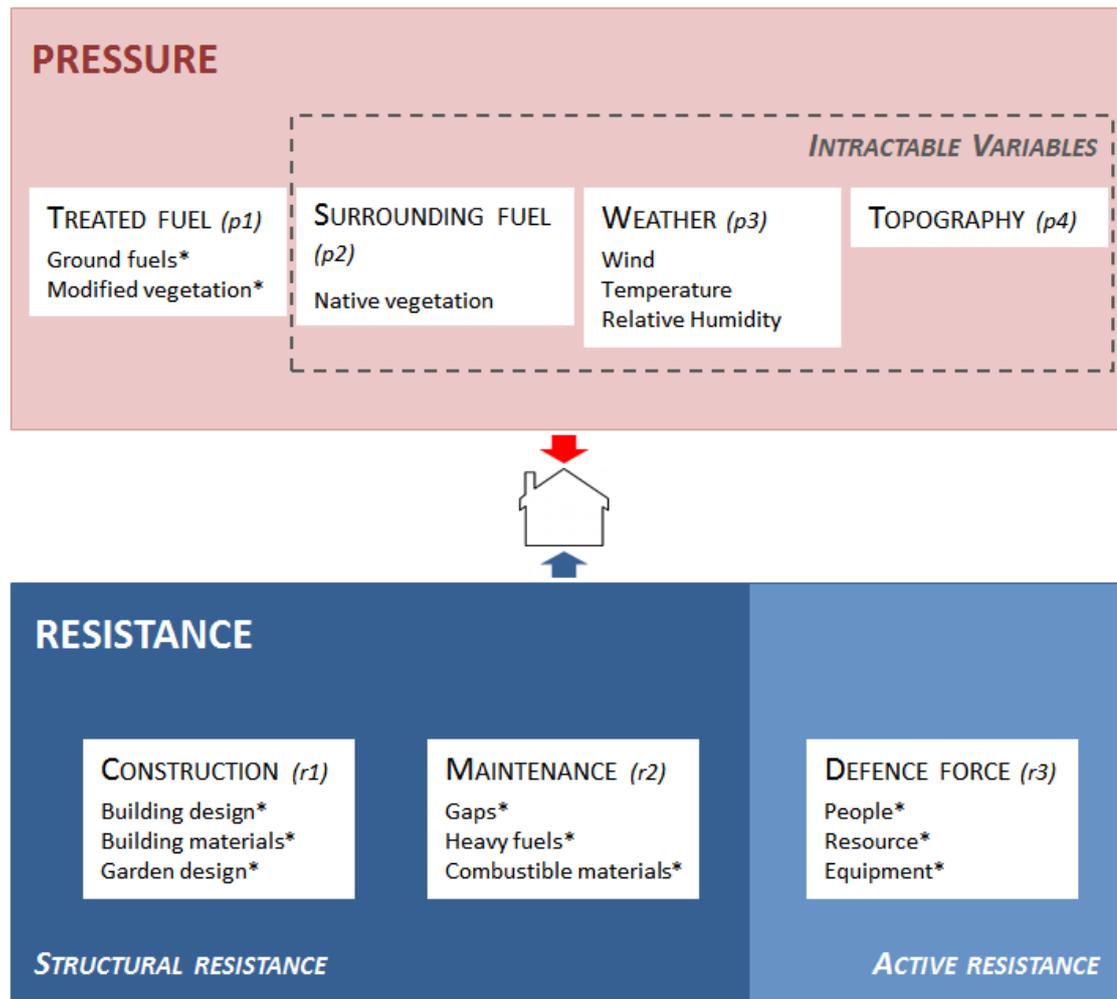
Figure 4.1 Wildfire building survival model, adapted from Tolhurst 2009. * Signifies the aspects that can be modified, prepared and maintained to increase the chance of building survival.

4.2.1 Attenuating fire pressure

One of the most critical strategies for moderating external fire *pressure* is the management

and modification of *fuel* (Figure 4.1 *p1*), a terminology used in the context of wildfires

referring to dry vegetation contributing to the spread and intensity of a wildfire (Webster,

2000). The propagation of flames is contingent upon the contiguity of fuels both horizontally

and vertically, and the intensity of radiation and ferocity of ember attack are a function of the

available fuel load (Hines et al., 2010). Empirical studies have identified that the clearing of

vegetation and fine fuels within the immediate surrounds of a structure (e.g. 10m to 20m from

the structure) significantly improves the chance of house survival (Howard et al., 1973, Foote,

1994). Cohen (1995, 2000, 2004) has experimentally demonstrated that a 40m separation

space between a forest flame and a structure can adequately undermine the ability of radiant

heat to ignite the structure under worse-case scenarios. Tolhurst and Howlett (2003) further

argued an extended and strategically planned fuel treatment space up to 700m, with zones

possessing distinct fuel-reduction levels, to sufficiently moderate ember impact. Overtly, the

distance and specific strategies for vegetation management is still debated, but there exists a

wide agreement that the requirements should be site-specific, hinging on a range of factors

including fire weather intensity, topographic conditions and type and distribution of (native)

vegetation adjacent to the modified zone (Cohen, 2000, Tolhurst, 2009, Syphard et al., 2014).

Rooted in these concepts, the term 'defendable space' (or 'defensible space') has been widely

publicised by emergency management agencies within Australia and abroad to depict an area

in proximity to a structure where fine fuels are reduced to attenuate fire pressure and provide a

safe buffer zone for active defence whilst improving the probability of a safe egress when the

structure becomes untenable (e.g. FEMA, 2000, AFAC, 2010, CFA, 2013a). However, to

provide general guidance for vegetation management, agencies have employed different

approaches to simplifying the intricacy in identifying an appropriate 'distance' and 'strategy'

(further discussed in the following section).

4.2.2 Increasing structural resistance

In addition to moderating fire pressure to a controllable level, buildings and surrounding gardens need to be appropriately designed, constructed and maintained to resist or minimise the possibility of potential ignition (Figure1 *r1*, *r2*). Studies have revealed that the susceptibility of a structure to a wildfire is contingent on the building design and materials (Leonard, 2009). Ignition probability can be significantly decreased by controlling the flammability of building exteriors such as roof and walls (Davis, 1990, Foote, 1994). Strengthened glazing (Bowditch et al., 2006) and protection by shutters or proper screens (Leonard, 2009) are required for exposed windows to resist breaking. Embers should be prevented from entering a building by blocking, screening and sealing vents, gaps and other pathways in walls, on the roof, or under the floor (Blanchi et al., 2006). Furthermore, proper design and configuration of gardens between the dense forest and the structure, such as the use of non-combustible fences (Leonard et al., 2006) and a perimeter road (Blanchi and Leonard, 2005), can also serve as significant firebreaks to buffer the impact of wildfires. Heavy fuels (e.g. woodpiles, combustible outdoor furniture and doormats) and dry fine fuels (e.g. dry grass, leafs and twigs, etc.) stored against or resting on a structure need to be removed to minimise the chance of local combustion (Ramsay et al., 1987, Blanchi and Leonard, 2005). Evidently, most features contributing to structural resistance can either be deliberately considered during the design and construction of the building, or readily modified when weaknesses are identified at a later stage. More importantly, ongoing maintenance is vital to insure the effective performance of many items (Leonard, 2009), such as ensuring no new gaps have developed, and roof gutters, valleys and underfloor spaces are clear of fuels.

4.2.3 Assuring active resistance

Finally, defending a property from wildfires is technically demanding, physically exhausting and psychologically challenging (McLennan et al., 2013). Defence commonly involves prolonged physical exertion with exposure to extreme temperatures, heavy smoke and loud noise (Davis and Dotson, 1987). Fire is also capricious, requiring defenders to be mentally

prepared to make rational and safe decisions, and cope with unexpected circumstances (McLennan et al., 2011c). Furthermore, firefighting experience is uncommon amongst the general public despite large populations living in high-risk areas. To ensure successful defence (Figure 4.1 *r3*), it is therefore important that people who intend to stay acquire and prepare proper firefighting equipment, ensure adequate and reliable water sources, and assure they are physically competent to conduct active defence for an extended period (Tibbits et al., 2008) which may last for hours or days (Blanchi and Leonard, 2005). Furthermore, psychological preparedness, which can be attained through early decision-making (regarding staying and defending or leaving early), considering and planning for various wildfire scenarios, and rehearsing the fire plan with all relevant family members, is essential for mental stability (McLennan et al., 2011c, Prior and Eriksen, 2012). Studies have also demonstrated that the defenders' commitment to stay and actively defend throughout the fire can be achieved via a well-prepared fire plan and may serve as a key element for successful defence (Tibbits et al., 2008). Further to this, psychological preparedness should also involve careful contemplation regarding the possible failure of the defence and the risk of subsequent trauma, so as to reduce the chance of long-lasting mental distress especially when such situations occur (Tibbits et al., 2008).

4.2.4 Preparedness in relation to the 'intractable' conditions

In summary, preparedness of a household for successful defence against a wildfire should include the three aforementioned categories of actions to attenuate fire pressure, increase structural resistance and assure active resistance. However, it is important to bear in mind that the requirements that fall within each of these three categories are partially dependent on several 'intractable' factors, such as the vegetative environment in the broad surroundings (beyond the managed defendable space, Figure 4.1 *p2*), the fire weather on the day (Figure 4.1 *p3*), and the micro topography of the location (Figure 4.1 *p4*). For instance, preventing building damage under extreme fire weather conditions requires greater fuel management,

more solid building structure and maintenance, and more rigorous defence activities than preventing fire damage on a mild fire weather day (Blanchi et al., 2010).

4.3 Existing models of wildfire preparedness

Current approaches to defining and measuring household wildfire preparedness can be categorised as either predictive or assumptive (Table 4.1). Predictive methods result from models quantifying fire pressure (Tolhurst and Howlett, 2003, Tolhurst, 2009), ignition risk (Cohen, 1995, 2000), or the probability of a structure surviving a wildfire (Wilson, 1988, Blanchi et al., 2011). Although not primarily focusing on the relationship with preparedness, these predictive models can be used to determine the levels of the modification (e.g. fuel treatment, improvement of building materials) necessary to accommodate the intractable factors (e.g. topography, fire weather intensity).

However, it has been challenging to explicitly quantify the synergistic effect of the multidimensional *pressure* and *resistance* factors. Some predictive models, such as Wilson's House Survival Meter (1988), tend to over-simplify the process by taking into account a limited number of critical features using crude measurements (see the footnote of Table 4.1). To this end, Cohen's Structure Ignition Assessment Model (1995, 2000) provided a more sophisticated quantification of structure ignitability (not survival, Table 4.1), highlighting the significance of non-flammable roof and exterior materials, as well as vegetation management within 40m of a strucutre to undermine the chance of flame-to-structure ignition. The Household Ignition Likelihood Index (Tolhurst and Howlett, 2003, Tolhurst 2009) focused on, and provided a more comprehensive model of, fire *pressure* by accounting for potential ember effect, providing guidance for a three-suite fuel treatment space with distinctive fuel-reduction levels: a 10m suite adjacent to a structure, a 20m suite (from the edge of the first suite) where the main garden is located, and a third suite where native vegetation is modified for up to 700m from the structure. With appropriate fuel management within the three suites, fire pressure can be adjusted from extreme to moderate for most properties (Tolhurst, 2009). However, the sophisticated

Table 4.1 A critical review of important preparedness models that provide implications for household preparedness

Variables related to building survival		Predictive Models				Assumptive Models			
		Wilson (1988)	Cohen (1995, 2000)	Tolhurst (2009)	Blanchi et al. (2011)	AS3959-2009	Penman et al. (2013)	Various agency-based checklists	Present study
IV	Weather	✓	✓	✓	✓	**constant**[b]	**constant**[b]		✓
	Topography	✓	✓	✓	✓	✓[b]	✓[b]	✓[e]	✓[e]
	Native vegetation	✓	✓	✓	✓	✓[b]	✓[b]	✓[e]	✓[e]
MV	Treated fuel in defendable space	✓[a]	✓	**up to 700m of the structure**	✓	**intractable**[b, c]	**intractable**[b, c, d]	✓	✓
	Building and garden design and construction	✓[a]	✓		✓	✓	**intractable**[c, d]	✓	✓
	Building and garden maintenance	✓[a]					✓	✓	✓
	Defence force	✓[a]		✓			✓	✓	✓

Note: IV = intractable variables; MV = modifiable variables.

[a] These variables are measured using crude approaches in the model. For instance, the 'presence of trees within 40m of the structure' and 'presence of defence force' are assessed as binary variables.

[b] Weather, topography and vegetation within 100m of the building are accounted for as intractable conditions via the BAL calculation in these models.

[c] These modifiable variables are considered as intractable, meaning their modifiability is neglected in the resulting preparedness measures.

[d] Admittedly, Penman et al.'s (2013) definition of adequate preparedness contains several actions regarding garden design (e.g. fences) and vegetation management, but merely concerns limited features and up to 2m of the building.

[e] In the agency-based checklists, topography and native forest are not considered as *pressure* factors that directly impact the required preparatory behaviours. Rather, their effects on fire pressure are accounted for in the self-assessment tools that calculate desired distance for appropriate defendable spaces to cope with the specific biophysical circumstances. To date, such tools have been supplied in conjunction with further preparatory guidance by four state agencies within Australia (i.e. CFA 2009; TFS 2009; CFS 2014; DFES 2014). In the present study, we advocate the importance of site-specific distance assessment to expound the preparatory actions associated with defendable spaces and assume the inclusion of appropriate tools in the resulting preparedness operationalisation. However, the development of such distance assessment tool is beyond the scope of this study.

fuel measurements and modelling procedure require a certain level of expertise for interpretation for specific fuel management, deterring its application by general homeowners (Tolhurst, 2009). Likewise, a probabilistic structural survival model developed by Blanchi et al. (2011) can theoretically be applied to simulate the effects of varied structural designs and fuel management settings and help identify the most suitable and feasible preparatory strategies, but its application potentially requires supervision by experts (Blanchi et al., 2011).

More commonly used measures to guide preparatory actions for residents are checklist-type instruments, referred to as assumptive preparedness models in this paper. Rather than accurately simulating the synergistic effect of the various characteristics on a structure's survival, the assumptive preparedness models focus on what actions can and ought to be conducted by residents to attenuate fire *pressure* and enhance *structural* and *active resistance*. The effective preparatory actions are often identified based on the understanding of *pressure* and *resistance* related factors derived from experimentations, post-fire investigations, and/or field observations (Leonard, 2009). However, due to the lack of holistic and systematic evaluation, existing assumptive models tend to prioritise a selected number of preparatory aspects whilst intentionally neglecting other survival related factors, or assuming they are not variable.

The Australian Standard for "Construction of Buildings in Fire-prone Areas" (AS 3959-2009) is a salient example of an assumptive model. It focuses on ensuring *structural resistance* by providing detailed regulations for building and garden design, configuration and construction to defend against estimated *pressure* indicated by a site-specific assessment of the "Bushfire Attack Level" (BAL). As shown in Table 4.1, the BAL is calculated based on an evaluation of topography, and vegetation types within 100m of the building whilst assuming a *constant* value of the forest fire danger index (FFDI, Noble et al., 1980) across an entire state or a region as a general indicator of weather intensity (e.g. FFDI of 40, equivalent to a Very High FDR, for the state of North Territory and Queensland, and FFDI of 50 and 100, equivalent to a Very High and Extreme FDR, for Victoria alpine and non-alpine areas respectively). Assumed

FFDI values however, are often inaccurate as the fire severity actually varies across a state (Tolhurst, 2009) and by event. A more prominent drawback of using the BAL is its consideration of surrounding vegetation as an intractable condition, disregarding the viability of modifying and creating a defendable space (Table 4.1). Furthermore, as Leonard (2009) has underscored, the construction regulations are 'ineffective when applied in isolation' (p.53) and must be supplemented by proper and sustained building and garden maintenance. Preparations for appropriate suppression activities should also be highlighted to ensure a high level of building survivability (Leonard, 2009).

More comprehensive examples of assumptive models are the preparatory checklists (or guidelines) supplied by emergency management agencies across Australia and in many other countries including the US and Canada. These checklists have been predominantly developed based on the experiential knowledge of local experts, and often include specific behaviours spanning all three preparatory objectives (i.e. attenuating fire *pressure*, increasing *structural resistance* and assuring *active resistance*). A notable contrast between the AS3959-2009 and the checklist-approach is that fire *pressure* is no longer deemed as entirely intractable by acknowledging the modifiability of vegetation to create a defendable space (Table 4.1). The trade-off however, is that the intractable *pressure* variables (i.e. weather, topography and native vegetation in Table 4.1) are not directly included as factors influencing the preparatory actions required for any purpose. It should be highlighted however, that two of the intractable *pressure* factors, topography and broad vegetative conditions, are often considered to have an indirect influence when identifying the distance for a defendable space. Unfortunately, such an approach has not been universally adopted for use in agency-checklists (see the footnote of Table 4.1 for details).

In fact, there has been a notable inconsistency in the overarching strategies suggested for defendable spaces. Specifically, several Australian and US agencies (e.g. FEMA, 2000, TFS, 2012, CFA, 2013a, CFS, 2014, DFES, 2014) encourage a two-zone measure: an *inner zone* (normally 10m to 20m around a structure) where ground fuels and flammable materials are

minimised to eliminate direct flame contact and reduce radiant heat and ember attack, and an *outer zone* (~15m to 50m from the edge of the *inner zone*) where adjustment to vegetation provides for discontinuous fuel arrangements and decreased fuel loads to moderate fire behaviour (Country Fire Authority (CFA), 2013a). The suggestions for the two-zone strategy are often coupled with self-assessment tools for calculating the required distance of each zone based on site-specific topography and native vegetation (TFS, 2009, CFA, 2013a, CFS, 2014, DFES, 2014). Other agencies however, tend to employ a less conservative method prioritising the maintenance of a building's protective zone with a generically defined distance equivalent to an *inner zone*, whilst providing vague descriptions of treatment for the space beyond (e.g. ESA, 2009, RFSQ, 2012).

In addition to the varied definition of defendable space and its associated distances, there is also a high degree of variability in the specific behaviours recommended by various agencies for other preparatory categories. However, a cross-referencing of Australian-based materials from relevant state (and territory) agencies highlights that a small proportion of preparatory actions are referenced in most resources. This implies that some actions may be more essential than others, and that it may not be necessary to complete all items on any one checklist in order to safely stay and defend a property; in other words, the completion of an appropriate subset of crucial actions should ensure adequate preparedness. A number of researchers have attempted to address the variability of effectiveness across preparatory actions, which has resulted in several quantitative measures of preparedness (Collins, 2005, Martin et al., 2007, McLennan and Elliott, 2011, Dunlop et al., 2014). However, the operational significance of the wide-ranging preparatory actions has not yet been systematically scrutinised and explicitly elucidated to address the question of 'sufficiency' for safely staying and defending a property (Cohen, 2000, Penman et al., 2013), often leading to misinterpretation of preparedness by residents (Tibbits and Whittaker, 2007, Penman et al., 2013).

In possibly the first study of its kind, Penman et al. (2013) sought to explicitly address this gap and define the preparatory conditions under which it is safe to stay and defend a property

by identifying a range of critical actions to be completed before a fire event. Furthermore, their preparedness model attempted to unequivocally consider the influence of fire *pressure* on a structure's survivability in defining 'required preparedness'. However, in developing the model, fire *pressure* enacted on a property was evaluated based on the BAL calculation, which, as previously discussed, overlooks the variability in fire weather intensity (Tolhurst, 2009), and disregards the necessity and viability of creating strategic defendable spaces to reduce vegetation hazards (Table 4.1). Furthermore, by assuming that building construction is in conformity with the Australian Standard AS3959-2009 for associated BAL, the model of Penman et al. (2013) focused on the delineation of required preparedness for property maintenance and active defence (Table 4.1). Implicitly, structures that failed to conform to the building standard during construction and design phase, or those that pre-date the regulation, should not rely on this model alone, but also refer to AS3959-2009 for necessary and viable structure modification, such as improvement of roof materials. However, as a building regulation, AS3959-2009 does not specifically highlight what modification activities are feasible and critical.

As such, still largely lacking is a comprehensive and coherent guideline operationalising what equates to 'sufficient preparedness' for householders to make informed and relatively safe decisions regarding active defence. The difficulties in developing such a 'preparedness' operationalisation reside in the intangible synergistic effects of the various *pressure* and *resistance* factors, and the wide spectrum of human interventions that can modify both facets. Consequently, an innovative approach should be identified in line with the existing models to tackle this perennial problem. Firstly, the householder-oriented nature warrants the use of an assumptive model providing tangible and specific behavioural guidance. Secondly, the discussion of the existing assumptive models has revealed two fundamentally different frameworks for operationalising preparedness: a BAL-based framework (Standards Australia, 2009, Penman et al., 2013) that considers fire *pressure* as intractable biophysical conditions that determine the requirements for building *resistance*, and a more integrated preparation-guiding framework (i.e. agency-based checklists) that accounts for the modifiability of all

features whilst employing a simplified consideration of the impact of topography and the broad vegetative context by suggesting site-specific distance for a defendable space. By comparison, the latter framework prevails for accommodating the intended purpose of providing comprehensive and explicit preparatory guidance. However, it needs to be highlighted that an important intractable *pressure* factor, i.e. fire weather intensity, has been omitted in the agencies' checklists for its impact (Table 4.1), impairing the model's completeness and reliability.

4.4 The current study

The goal of the current study was to provide an explicit and comprehensive definition and operationalisation of household preparedness for individuals planning to stay and defend their property so that they may conduct necessary and effective preparations, and/or make appropriate decisions regarding their response strategy. To this end, Penman et al.'s (2013) method for developing a definition of the required preparatory conditions for active defence was employed; that is, a checklist of *critical* preparatory actions as identified by expert opinion. However, the original checklist used to identify the critical items was derived from a variety of agency-based checklists, to yield a more comprehensive definition of preparedness as opposed to a limited focus on selected categories (Penman et al., 2013). This means that the examined checklist encompasses actions spanning all of the three preparatory goals, namely attenuating fire pressure, enhancing structural resistance, and making provisions for defence. Furthermore, to align with the methodology employed by agencies' checklists, the current study considered an adequate defendable space as involving two zones, and their the distances should be identified through site-specific evaluation of topography and native vegetation serving as intractable but influential pressure factors (see the footnote of Table 4.1).

Based on a holistic consideration of building survival factors (Figure 4.1), *fire weather conditions* should also impact the desired level of preparedness. Consequently, the current study sought to define the required levels of 'preparedness' under varied *fire weather conditions* (Table 4.1) using Australia's current FDR system as an indicator. Such an

approach has in fact long been suggested by Australian agencies (as demonstrated in Figure 4.2), but more detailed explanation has been lacking. Therefore, this study addressed the issue by identifying the *critical* preparatory actions required for achieving sufficient preparedness for each FDR category. Whilst the checklist of *critical* preparatory items provided in this paper is not the only solution for assuring property safety, completion of all listed items would define a *minimum* and *essential* preparatory condition for staying and defending an average Australian property at a given FDR.

FIRE DANGER RATING	STAYING AND DEFENDING CAN ONLY BE CONSIDERED IF YOUR HOME IS…						
	CFA(VIC)	RFS(QLD)	DFES(WA)	ESA(ACT)	RFS(NSW)	CFS(SA)	TFS(TAS)
CATASTROPHIC	Never	Never	Never	Never	Never	Never	Never
EXTREME	*situated and constructed or modified* to withstand a bushfire, *prepared to the highest level* and can be actively defended	Never	*prepared to the highest level* with no doubt, *constructed to bushfire protection levels* and can be actively defended	*well prepared, specifically designed* and *constructed* for bushfire and can be actively defended	*prepared to the highest level* and can be actively defended	*prepared to the highest level, constructed to bushfire protection levels* and can be actively defended	*well-prepared* and *well-constructed* and can be actively defended
SEVERE	*well prepared* and can be actively defended	*well prepared* and *well-constructed*	(continued)	*well prepared* and can be actively defended	*well prepared* and can be actively defended	*well prepared* and can be actively defended	*well-prepared* and can be actively defended
VERY HIGH	not stated		*well-prepared* and actively defended	not stated	not stated	not stated	
HIGH		not stated	not stated				
LOW-MODERATE							not stated

Figure 4.2 The required levels of preparedness related to the FDR levels as described in public instructional materials distributed by Australian state and territory agencies (reviewed materials are listed in Table 4.2).

4.5 A pilot study

The core methodology employed in this study for exploring the *critical* nature of each preparatory action under different FDR conditions was first piloted via an online survey in

May 2012 with relevant wildfire experts (N = 36) across Australian emergency management agencies as well as research institutes (Cao et al., 2013). It resulted in confirmation as well as adjustment of the methodology, and therefore is briefly introduced here to provide background and justification for the method used to conduct the Household Preparedness Workshop.

4.5.1 Survey material

Mainly drawing upon current agency-based checklists utilised within Australia and abroad (Table 4.2), a comprehensive list of preparatory actions was constructed as the study material. Scholarly literatures were also reviewed to identify risk-reduction measures omitted or not articulated in agency materials, such as a majority of the items related to the psychological preparedness for staying and defending a property. During compilation, similar preparatory items were amalgamated, and omnibus items were split into several detailed actions to create a comprehensive list of 100 items.

One note to make is that a two-zone approach was adopted in this study in relation to creating a defendable space. This means the comprehensive list of actions included preparatory measures pertinent to maintaining inner and outer zones respectively. However, due to the complex and debatable nature for defining the appropriate distances for inner and outer zones, preparatory behaviours related to the two zones was only differentiated *conceptually* with no specific distances expounded. That is, an *inner zone* was conceptualised as being in close proximity to a structure where fine fuels are minimised to eliminate direct fire impact and attenuate the chance of secondary ignitions, and an *outer zone* was conceptualised as containing discontinuous fuel arrangements to moderate fire behaviour at a larger scale (CFA, 2013a). As stressed earlier, the current study did advocate the significance of defining the adequate distance associated with each fuel-management zone, but assumed the inclusion of existing or improved site-specific distance assessment instruments (e.g. TFS, 2009, CFA, 2013a, CFS, 2014, DFES, 2014). by local agencies prior to the application of the resulting preparedness operationalisation. In the beginning of the survey, the conceptual definitions of

inner and outer zones were explicitly introduced to participants to assist their evaluation of
relevant preparatory actions.

Table 4.2 Agency-based materials used in the derivation of a comprehensive lists of
household preparatory actions

Organisations	Source Materials	Editions
Country Fire Authority (CFA, VIC, AU)	'Prepare. Act. Survive – fire ready kit' pamphlets	2010/2011
Queensland Rural Fire Service (RFS, QLD, AU)	'Prepare. Act. Survive' pamphlets	Version 2, 2012
Department of Fire and Emergency Services (DFES, WA, AU)	'Prepare. Act. Survive' pamphlets	Version 2, 2010
ACT Emergency Services Agency (ESA, ACT, AU)	'Prepare. Act. Survive' pamphlets	2009
NSW Rural Fire Service (RFS, NSW, AU)	'Bushfire Survival Plan' pamphlets	Unknown
Country Fire Service (CFS, SA, AU)	'Preparing Your Property' fact sheets	2009
Tasmania Fire Service (TFS, TAS, AU)	'Prepare to survive' pamphlets	Edition 1, 2009
American Red Cross (USA)	Wildfire preparedness	Unknown
Federal Emergency Management Agency (USA)	Checklist for Homeowners	Unknown

Note: Attempts were made to acquire the newest versions of the materials at the time of the research.
Admittedly, newer version may have been released to date. But a comparison across different versions
found few revisions were made in the methodology of providing preparatory guides, and they would
not influence the issues identified in this paper and the comprehensiveness of the collected materials
used in this research.

4.5.2 Criticality rating

A *criticality rating* approach was established to ask each participating expert to identify for
which FDR(s) a preparatory item is critical, meaning it should be completed by householders
in order to stay and defend a property. More specifically, 'critical' items were defined in the
beginning of the survey as 'the items that will greatly decrease the chance of survival for both
the property and people who stay and defend it if not completed'. Experts were given the
options to choose the FDR levels appropriate to each preparatory item including 'Extreme',
'Severe and above', 'Very High and above', 'High, Low-Moderate and above', and 'Not

critical at any FDR level'. Logically, a preparatory action that is critical at low FDRs should also be critical at higher FDR levels; however, an action that is not necessary at a low FDR may turn out to be critical for a higher FDR to fortify the protection against severe fire conditions. The Catastrophic FDR was not included as an option because there is agreement that people should never stay and defend on days with a Catastrophic FDR, regardless of their level of preparedness (Figure 4.2).

The five different rating options were interpreted as a scale for measuring the level to which completing a preparatory action for staying and defending is critical (Cao et al., 2013). That means, the items rated as critical for an FDR of 'High, Low-Moderate and above' (i.e. all FDRs) were considered to be the most critical as failure in completing such items would pose significant danger to a household even when the fire condition is not acute. The items rated as 'critical at Extreme FDR only' are relatively less critical and only serve as vital protection for a property under severe fire circumstances. Furthermore, items rated as not critical at any FDR level were not considered as critical, and failing to complete the actions should not pre-empt the consideration of staying and defending, independent of fire conditions.

4.5.3 Survey results

Following the pilot study, the wording of several items was adjusted and four additional actions were added to enrich the preparatory checklist based on the feedback from survey participants. Furthermore, experts' rating responses justified the *criticality rating* approach and confirmed that there were different degrees of importance inherent in the preparatory actions, depending on fire weather conditions (Cao et al., 2013). Additionally, a high degree of inter-rater agreement (IRA) was identified for 73% of the items, suggesting the potential for building expert consensus for developing an explicit checklist of critical preparatory actions under each FDR condition (Cao et al., 2013). However, contentions were observed for the remaining items, warranting a more in-depth investigation to understand and reconcile the diverse opinions amongst Australian wildfire experts (Cao et al., 2013).

Responses in the pilot study also revealed three topics worthy of discussion for the rating and application of certain items, involving potential adjustment of wording, necessary conditions for asserting criticality of an item, and the compensatory nature of related items (Cao et al., 2013). Therefore an adjusted *criticality rating* approach was constructed for the subsequent study with experts in an interactive workshop environment. As shown in Figure 4.3, the approach consists of the question for rating each preparatory action, as well as three specific questions asked to prompt and facilitate potential discussion if applicable.

D1_1 Within the Outer Zone, raked up leaf litter and twigs under trees.

- At the FDR of _____, households neglecting or failing to complete this item should not stay and defend their property during a bushfire. (Please tick ONE option.)
  - ☐ Extreme
  - ☐ Severe and above
  - ☐ Very High and above
  - ☐ High, Low-Moderate and above
  - ☐ Not critical at any FDR level

If this item is critical for staying and defending,

- Is there any amendment needed for the content of this item?
  If YES, please state:

  _____

- Is this item only critical for staying and defending under some certain circumstances, or for certain types of properties?
  If YES, please state the condition:

  _____

- Is this item an alternative to other item(s), which means that households who have completed either of them can stay and defend?
  If YES, the alternative item/s is/are: _____

Figure 4.3 An example of the question sheets used in the workshop to facilitate group rating and discussion.

4.6 Consultative workshop

Based on the enriched checklist of 104 preparatory actions and the adjusted *criticality rating*, a Household Preparedness Workshop was conducted in Melbourne in March, 2013 to examine

the critical nature of each action with a taskforce of ten experts (90% male, mean age = 53.4 years, s.d. = 10.1 years) from a variety of emergency service agencies. The objective was to solicit opinions from the experts, seek consensus amongst the members, and/or identify the underlying reasons for discrepancy. The participating experts were identified with the assistance of Australasian Fire and Emergency Services Authority Council (AFAC) as specialists working with wildfire community safety issues (mean role tenure = 10.0 years, s.d. = 10.9 years; mean tenure in emergency services = 24.9 years, s.d. = 12.0 years), each from different fire management agencies. However, the taskforce may over-represent certain states and underrepresent others as four experts were from Victoria, two were from New South Wales and South Australia respectively, and one from Queensland and Tasmania respectively. The researchers recognised this inevitable constraint and endeavoured to minimise state-bias through the modified consensus decision-making procedure, as detailed in the following.

4.6.1 Modified consensus decision-making approach

Consensus decision-making is an approach used by organisations and communities seeking agreement between all members of an interested group (Bressen, 2007). As an alternative to the conventional adversarial decision-making process commonly practiced as the 'majority vote', consensus decision-making seeks to identify a solution that all members can live with (Bressen, 2007, Hartnett, 2011). However, unanimity is not the priority; a more important output from this decision-making process is the viewpoints solicited and synthesised from all interested members to help gain a better understanding of the underlying rationales for decisions (Seeds for Change, 2013). As Burgman et al. (2011) have suggested, the collective learning process amongst peers may be effective in eliminating biased experts' opinions and approaching the 'correct' answer. Set within a workshop format, a customised consensus decision-making procedure was therefore adopted for obtaining group consensus concerning the criticality rating of each preparatory action, and for understanding the reasons for dissent amongst the experts through provocation of appropriate discussion. Discussion and rating

activities were carried out over two consecutive rounds (Figure 4.4) in an attempt to gain consensus, first in small groups and then across the entire group.
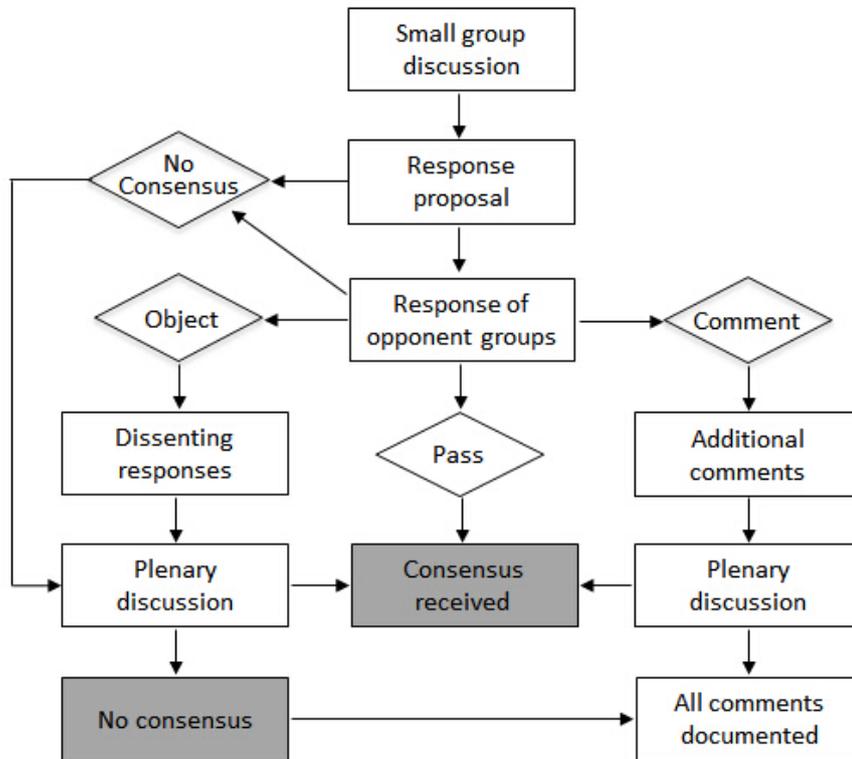
Figure 4.4 Flowchart of the adjusted consensus building method employed in the Household Preparedness Workshop, modified from the procedure depicted by Hartnett 2011.

Small Group Consensus. The ten-member taskforce was divided into three small groups (two groups of three and one group of four) whilst assuring each group contained a mixture of people from distinct states to further offset bias. A booklet containing question sheets for all 104 preparatory actions was given to each group (refer to Figure 4.3 for an example). For each item, group members were requested to: i) attempt consensus concerning the *criticality rating*, and ii) draw potential *comments* when necessary by addressing one or more of the three additional questions as demonstrated in Figure 4.3. When a group could not agree on the criticality rating of an item, the dissent was noted for further discussion in the second round.

Ninety minutes was given to this process, providing approximately one minute to respond to each preparatory item.

Large Group Discussion. The second-round provided an opportunity for plenary discussion to synthesise small group responses, obtain consensus across the entire group and address the reasons for discrepancy between small groups or individual members. One small group was first selected on a random basis as the *proposing group*, and an associated member was asked to read aloud their small group responses (consisting of criticality rating and possible comments) for each item. Their responses were viewed as an initial proposal and a starting point for discussion. Following the identification of each preparatory item, the facilitator (i.e. the first author) called for consensus between the other two *opponent groups*, each of which was given a set of coloured cards signifying various options:

i) Pass (no sign): "Our small group response agrees with the proposed criticality rating and comments."

ii) Comment (yellow sign): "Our small group response agrees with the proposed criticality rating, but we have additional comments."

iii) Object (red sign): "Our small group response does not agree with the proposed criticality rating and/or the suggested comments for this preparatory item."

iv) No Consensus (blue sign): "We did not reach consensus in the small group discussion." This option can be applied by either the proposing group or the opponent groups. Individual opinions were then given, followed by plenary discussion.

The initial statement of the opponent groups was requested to be strictly based on their written responses from the first-round activity. When there was at least one dissenting opinion, plenary discussion was initiated (Figure 4.4), where each party was given the opportunity to provide a response and associated rationales. Any group could opt to support a distinct answer

following the discussion. Full consensus for a preparatory item was reached when a convergent answer was identified and all members declared 'agreement'.

4.7 Collation of results

The workshop's results first suggest adjustment of several preparatory items in the checklist. A number of items (20%, $N_{items} = 104$) were recognised as 'in need of rewording' for a clearer and more accurate description. Furthermore, it was recommended that some items be amalgamated as they were closely related, resulting in a shortened comprehensive list of 97 preparatory items.

For nearly half of the items (44%, $N_{items} = 97$), the workshop resulted in consensual binary criticality ratings (i.e. either critical or not critical) for a given FDR level, amongst which 15 items were agreed upon as critical at all or most FDR levels (see Section 1 of the table in Appendix 1) and 28 items were recognised as not critical under any fire (Section 4 of the table in Appendix 1). However, due to the complexity of the subject, full consensus was not reached for the remaining 54 preparatory items (56%). Specifically, 21 items were considered to be critical at one or more FDRs by all three small groups, but there was no agreement concerning the specific FDR(s) corresponding to each (Section 2 of the table in Appendix 1). The other 33 items were viewed as 'critical' at one or more FDR by some group(s), whereas 'not critical at any FDR' by other(s) (Section 3 of the table in Appendix 1), indicating substantial divergence of opinions in their criticality.

In-depth plenary discussion, especially for the controversial items, revealed the rationales underpinning expert perceptions. It was observed that discrepancy mostly occurred for those seemingly less critical items (i.e. items considered critical only under severe fire conditions by one or more small groups). Notably, one small group (G1) adopted a conservative approach by contending that approximately half of the preparatory items (48%, $N_{items} = 97$) are critical and should be mandated under all FDR conditions. Yet in contrast, the other two groups (G2 and G3) held a distinct position, with one giving the most critical rating to 19% of the 97

items and the other to 18%. Meanwhile, G1 appeared to be the most reluctant to compromise as throughout the consensus seeking procedure, its members only agreed to adjust their original ratings to achieve unanimity for three preparatory items whereas G2 and G3 amended their ratings for eight and twelve items, respectively.

Responses from the small groups were synthesised to offer a national baseline (see Appendix 1) in support of further development of the intended household preparedness operationalisation for defining the conditions for active defence. In the event that a discrepancy existed amongst experts' ratings, the most conservative opinion was selected to reserve safety for all associated FDR conditions. For instance, if an item was rated as critical at all FDR levels by one group and critical at 'Very High' and above by the others, the former response was adopted; if one item was rated as not critical at all, and critical at an FDR of 'Severe' and above by an opposing group, the latter answer was applied. Consequently, items in Section 1, 2 and 3 of the table in Appendix 1 were all categorised as critical at some level on the basis of the conservative approach.

Furthermore, the final ratings from all three small groups were also documented in Appendix 1 in order to stimulate and facilitate future considerations by and decision-making of local emergency management agencies. Comments raised in the plenary discussion for specific (groups of) preparatory items were also collated and recorded in the footnote of Appendix 1, illuminating the potential rationales worth further contemplation for certain contentious as well as agreeable items, or the contingent physical and social conditions of local contexts (e.g. forest environment, climatic conditions, and state regulations, etc.) which require further deliberation in deciding the criticality of an item.

4.8 General discussion

In addition to clarifying the critical nature of each preparatory action under each FDR, the workshop also resulted in the identification of three issues, highlighting the complexity of criticality judgments. These are recapitulated in the following to provide further insights into

the underlying reasoning of the experts' ratings, and facilitate future development and application of the preparedness measure by local agencies.

4.8.1 Assumption for criticality ratings

Whilst specific modifiable criteria regarding building structures were included in the model to extend its application beyond properties that were constructed under the Australian Standard AS3959-2009, one issue that was highlighted through the group discussion was that the overall preparation requirements are heavily dependent on the building construction. Participants therefore adopted a typical Australian residence as a fundamental assumption during the exercise of criticality ratings by assuming the structure contains all the elements evaluated (e.g. windows, roof, under-floor spaces) to produce a generic measurement. This means the critical checklist resulting from the workshop may not be applicable in all aspects to all properties. For instance, if a structure has no open under-floor space, the homeowner can disregard associated actions. Besides, if the checklist is used by people owning older structures (such as those that pre-date current wildfire risk area construction regulations) with unmodifiable or vital design defects, they are likely to find it difficult if not impossible to complete many of the critical preparatory items (e.g. 'block all gaps on the roof', 'seal gaps around window frames'), and it is therefore unlikely that staying and defending would ever become a safe option.

However, if a structure deviates strongly from the notion of a 'typical' residence (e.g. it has no windows and thereby relies on artificial light only), a wider range of critical items may become inapplicable or unnecessary. For the instance of a building with no windows, all the items pertinent to windows can be removed from the critical checklist, and the requirements for moderating fire *pressure* may also be relaxed. The extreme cases will need further reviewing on an individual basis. Currently a number of fire safety inspection programs are in existence across Australia supporting one-on-one examination by trained emergency management personnel. The critical checklist resulting from the present study can also serve as a baseline to be adapted to household-specific safety inspections.

4.8.2 Considerations in creating inner and outer protection zones

The expert opinions concerning the fuel-management zones coincide with those identified in the checklist materials distributed by emergency management agencies. Firstly, maintaining an inner protection zone in the immediate surrounds of a structure was agreed to be the principal focus for creating a defendable space by all participants, whereas there was a variation in the conceptualisation of inner zone distances (generally ranging from10m to 20m). Although minimal in some areas, this difference may result in marked fluctuation in the fire pressure imposed to the structure under adverse topographic, vegetative and FDR conditions. Secondly, a more prominent divergence of viewpoints existed regarding the importance of an 'outer' protection zone, manifested by the discrepancies of ratings for four out of the seven actions in this class (see Section 3 and 4 of the table in Appendix 1). This was mainly due to significant disparities in the conceptualisation of the distance and context associated with the so-called 'outer zone' by the panel members. It was found that one group considered the actions to be applied to a large extent in the neighbouring bushland, while others addressed them in the context of close proximity to a structure, such as 10m to 30m, just beyond the inner zone and not necessarily adjacent to dense native vegetation. Consequently, it is only meaningful to decide whether an inner-/outer-zone item is critical when it is placed in a specific context, especially in terms of distance to the building. In this sense the current approach merely conceptually distinguishing and rating preparatory actions associated with creating inner and outer zones is not adequate. However, due to the current inter-agency variation on this matter, the rating results presented here can provide a suitable starting point for re-assessment by local agencies with more specified overall strategies and defined ranges of distances for considering the actions.

Another concern raised by the experts is that the critical nature of the items pertinent to both the inner and outer zones is profoundly influenced by the ambient biophysical environment, including native vegetation and topography. As discussed previously, the effect of these two intractable *pressure* factors can be accounted for by providing site-specific calculations of the

adequate distances applied to the two fuel management zones, thereby reinforcing our stance on the importance of including such a self-assessment tool in the resulting model (Table 4.1). A related item, for instance, 'within the *Outer Zone*, selectively remove shrubs and small trees to create clumps, and maintain distance between clumps and larger trees' should be completed for the required distance as per the assessment results. Another possible solution for residents is to seek professional help for more detailed appraisal of safe distances. Failure to address the variability in biophysical environments may result in inadequate fuel management plans. Agencies, if not opting for the development of site-specific assessment instruments, should at least attempt to differentiate or categorise the various risk levels across the local districts and define the desired distance of buffer zones accordingly, rather than using a generic definition of defendable space. Moreover, local re-assessment of the criticality of relevant preparatory actions should follow and build upon such explicit conceptualisation or definition of associated distances.

4.8.3 Defining preparedness in relation to FDRs

It was commonly acknowledged by the experts that some preparatory items are not essential in less intensive fires but may become crucial to ensure the protection against more intensive fires, further endorsing our methodology of relating 'preparedness' to FDRs. Admittedly however, it is challenging to tie the criticality of a single item to certain FDRs. More rigorous mechanistic analysis may be necessary to recognise the purpose and rationale of an item for a structure's survival in order to decide at which FDRs it should be mandated. For instance, as stated by one expert in the plenary discussion, the items regarding the creation of an outer zone may be only necessary in fires that are likely to burn out of control, and therefore were counted as critical only during FDRs of Very High and above. Some experts also identified the items for ember-proofing the house (i.e. activities relevant to sealing gaps and enclosing vents around the structure) are only essential when there is an ember issue, which is normally associated with fires at higher FDRs such as 'Severe' and 'Extreme'.

4.9 Recommendations for future development and application

The aim of this study was to develop an assessment tool to aid appropriate decision-making regarding 'staying and defending' by residents. A complete and definitive operationalisation tool should comprise two major components: i) a list of critical preparatory actions that must be assured to attain a *minimum* and *essential* preparedness level for staying and defending; and ii) a list of non-critical but potentially beneficial items to reinforce the protection of the structure. The current study offered a national baseline for considering the criticality of each item, as listed in Appendix 1, by reconciling inconsistencies among various agency-based checklists and eliciting the opinions of experts from diverse state agencies. A national baseline is important as a first step to provide a broad framework and share knowledge for addressing this matter; however, further scrutiny and development by local agencies is required. Admittedly, there is a high degree of diversity in the wildfire hazards across Australia due to the varied weather conditions, vegetative environment and topography, necessitating distinct operationalisations of 'sufficient preparedness' for active defence. The current checklist of critical, contentious and non-critical actions therefore should be re-assessed by state/regional agencies in light of the expert panel responses whilst accounting for local contexts and regulations. Additionally, as discussed above, the actions concerning the creation of inner and outer zones require special attention of agencies to first define site-specific calculations of safe distances for both zones, and subsequently prescribe the criticality of each action. Methodologically, the consensus decision-making approach underlying this national study can be adapted to support the re-assessment procedure.

Furthermore, the suite of critical and non-critical checklists might vary at different FDRs, and such distinctions have been identified for some items as shown in Appendix 1. Based on the methodology of criticality ratings, the critical checklist for a higher FDR is presumed to be inclusive of items critical for a lower FDR. Nevertheless, it is understandable that some agencies may opt to adopt a conservative position, especially for the purpose of providing pre-season preparatory guidance, so that all items are considered critical regardless of FDRs. In this case there will only be one critical checklist developed in the context of 'Severe' or 'Extreme' FDRs, or the regional worse-case scenarios, and applied for all circumstances.

In the Australian context, this household preparedness instrument can be utilised as an assessment tool to aid decision-making during the drafting of 'Bushfire Survival Plans' (i.e. stay and defend or leave early), as well as facilitate re-evaluation of the decision during the onset of a wildfire. In addition, it can be considered as a pre-fire preparation guide for community members to assist their understanding of the importance of each preparatory action and help relate a household's preparedness to their plans. Whilst it is likely that homeowners may find it difficult or unpragmatic to complete all critical items on the checklist and thus opt for an arbitrarily selected list of actions, the presentation of such a concrete definition of critical preparatory conditions should prompt more judicious considerations and decisions regarding staying and defending.

For the communication of this preparedness measure, agencies should provide both the checklist of critical preparatory actions and the list of non-critical but beneficial items. However, agencies have to be cautious about how to deliver the messages in order to encourage proper application of the tool. Households with the full critical checklist completed should be reasonably confident in defending their homes; however, it must be highlighted that safety is never guaranteed, especially during intensive fires. The uncertainty of using this checklist should be tactically communicated using messages such as 'people who are staying and defending should always be prepared for the possibility that their homes may still be destroyed even if actively defended'. Meanwhile, agencies should encourage householders to employ a set of non-critical but beneficial items as supplementary actions beyond the completion of the critical checklist.

4.10 Conclusion

House survival in wildfires is a multi-dimensional subject contingent upon the biophysical environment, house construction and human interventions both prior to and during a fire event. There is no single preparedness model that can accurately account for all households and fire scenarios. The present study provides a robust, explicit and comprehensive baseline for defining and operationalising the required preparedness for safe active defence based on a

common household in an Australian context. Moreover, what distinguishes the results of this study from the other checklist-type measures (e.g. CFA, 2013a) is that the effect of varied fire weather conditions on structural vulnerability (Blanchi et al., 2010) is taken into account by suggesting increased levels of preparedness with an enriched checklist of critical activities at escalated FDR levels. The documented consensus, contention and discussion from the Household Preparedness Workshop exhibit significant advancement in addressing the significance of various actions at different FDR levels. However, due to the constrained time spent for the consensus-seeking process, the resultant criticality rating for each action should only serve as a baseline, requiring more deliberate scrutiny for the development of tangible preparedness standards based on state, local, or even household-specific circumstances. The combination of the critical preparatory actions identified in the resulting model should provide for a *minimum* but *essential* preparatory condition for making the decision of staying and defending. Although sufficient preparedness can never be guaranteed in capricious wildfires, illuminating critical preparations is essential for regulating homeowners' preparatory activities, reducing misinterpretation and underestimation of preparedness (Penman et al., 2013), and improving residents' decision-making with respect to staying and defending a property.

Chapter 5. Is a picture worth a thousand words? Evaluating the effectiveness of maps for delivering wildfire warning information

Abstract

Maps are a sensible approach for communicating wildfire early warnings to the public as they often contain a multitude of spatial information. However, a reluctance of agencies was found in using accurate and timely wildfire maps for public warnings, a sentiment potentially fuelled by beliefs that the public are not fluent map-readers and may be overwhelmed by the large amount of information. To test the validity of these beliefs, this study empirically compared the effectiveness of maps versus traditional text-based approaches for communicating spatial-related wildfire warning information. Through an online survey, 261 residents from wildfire prone areas in Western Australia were asked to view multidimensional spatial information regarding a simulated wildfire scenario presented as either text messages or maps, and were subsequently queried for their comprehension, their risk perceptions, and the attractiveness of the presentation format. Additionally, the survey captured the relative efficiency of the information dissemination approaches. The results showed that appropriately designed maps prevailed over text messages for the communication of most wildfire warning information by improving comprehension, elevating risk perceptions, and increasing appeal to the public. However, an optimal communication approach would be to couple map designs with several imperative textual descriptors. Especially, the textual description of safe shelters in the community (i.e. location names and addresses) yielded indispensible meaning when the locations were well-known landmarks, and hence should not be replaced by map-based depiction. Furthermore, several heuristics were identified to facilitate the design of effective warning maps across hazards in general.

5.1 Introduction

Recent decades have seen an increase in the amount of people and assets exposed to wildfire (or bushfire, in the Australian context) risks due to the decentralisation of cities and amenity-driven population growth along urban fringes (Hammer et al., 2009, Buxton et al., 2011). By definition, wildfires originate in rural landscapes but can spread to threaten nearby human habitations. Fortunately, the lead-time before impact on human habitations often enables the provision of early warnings, which play a critical role in raising threat awareness ahead of impact in the at-risk communities. The ultimate goal of public early warnings is to save lives by stimulating protective behaviours, such as early evacuation. Yet, despite the substantial improvement in warning dissemination over the past decade supported by advanced and diversified information and communications technologies, wildfire catastrophes involving significant numbers of fatalities and injuries continue to occur (Guha-Sapir et al., 2015). Research has demonstrated that the majority of those fatalities are attributable to late evacuation (Haynes et al., 2010, Handmer et al., 2010). Hence, in addition to assuring the timely issuance of warnings, emergency management authorities should scrutinize the 'effectiveness' of these warnings in motivating protective behaviours, especially timely evacuation.

Currently, local emergency management agencies often publish wildfire warnings using their website, coupled with propaganda through multi-media channels. The content of such warnings tends to cover a variety of information elements. Taking the Australian example, inquiries into the 2009 Victorian Black Saturday wildfires (Teague et al., 2010) have driven the adoption of a Common Alerting Protocol Australian Profile (CAP-AU-STD) that stipulates the provision of warning information delineating the exact location of the fire and its likely impact, direction of fire movement, wind conditions, time remaining before impact for a community, and guidance for protective behaviours. The assorted warning information is often conveyed in textual form (see Figure 5.1 for an Australian example). Still, the majority of the information elements are location or direction based, and as wildfires often occur

amidst rural lands and cover a large area that is difficult to be explicitly depicted in words, the text-based warnings tend to contain a high degree of spatial ambiguity (EMV, 2014b).

An alternate communication approach to delivering the spatial-related wildfire warning information is through the use of cartographic representations. Such an option has become technically viable due to advancements in Remote Sensing, Geographic Information Systems (GIS), and wireless communication. Nowadays, a wealth of the wildfire information can be captured, processed, and visualised in a near real-time manner for communication within and between emergency management agencies (Ambrosia et al., 1998, Steber et al., 2012). In line with the increase in cartographic information availability, a topical discussion has started to arise on whether such accurate and timely spatial information portrayal should also be used for public warnings (EMV, 2014b).

Figure 5.1 An example of current textual wildfire warnings issued within Western Australia. Source: Department of Fire and Emergency Services (DFES).

Unfortunately, no research to date has sought to examine the suitability of map-based communication to the public with empirical evidence. With no scientific knowledge available to them, local agencies currently adopt diverse approaches. For example, some take a conservative approach by only presenting cursory point locations of incidents on a map to supplement comprehensive text-based warnings (e.g. DFES 2015a, CAL FIRE 2016). In contrast, others have started to use a more pioneering approach, and use a web-based interactive mapping environment to visually present more specific locational risk-related information, such as fire perimeters, weather monitoring data, and warning polygons. Examples of the latter approach include the VicEmergency developed by the Australian state of Victoria (EMV, 2015), AlertSA launched by South Australia (Government of South Australia, 2015), and the parallel US Wildfires application supported by Google Crisis Map (Google Crisis Response, 2015). VicEmergency and AlertSA have been employed as the default interface for the Victorian and South Australian fire agencies' online warning portals, with conventional textual warnings accessible through hyperlinks for specific incidents. However, these mapping tools are currently more focused on providing a visual facade to increase appeal, and less concerned with the timeliness of the data shared on the platform. For example, the critical geographic information pertinent to advancing incidents (e.g. incident perimeters and warning polygons) appears to only be updated on a daily basis during emergencies. This means that people seeking comprehensive wildfire information still need to refer to the text-based messages, rendering the wildfire maps inappropriate for comprehensive warning purposes. Overall, it appears agencies are still reluctant to communicate warnings through maps, which raises the question 'why?'.

Agencies' reluctance in supplying timely and accurate spatial wildfire information is potentially fuelled by their expectation that people may not be fluent map-readers and can be overwhelmed by too much information (Sorensen, 2000, Kjellgren, 2013). Nevertheless, the recent *National Review of Warnings and Information* in Australia stressed the erroneousness of this allegory and highlighted an increasing community expectation for real-time and specific information delivered through mobile/web-based mapping applications (EMV 2014b).

The report further highlighted that 'assuming' the public is not capable of reading maps 'only delays the inevitable effort required' (EMV 2014, p.50). To provide incentives for the development of 'effective' mapping applications by agencies, we thus need to understand whether and to what extent maps are more effective in communicating warnings to the public than text (EMV 2014b). Moreover, if maps are shown to be more effective, then research needs to provide knowledge with respect to *how* to produce suitable maps for public consumption (EMV 2014b).

In line with this, the current study sought to empirically examine the 'effectiveness' of maps, and compare them with the conventional textual messaging, for the communication of heterogeneous wildfire warning information. As the first study of its kind, the experimental methodology drew upon an understanding of warning 'effectiveness', and a broad literature on the effectiveness of maps for risk communication, which is presented in the remainder of this section.

5.1.1 Defining warning 'effectiveness'

Examination of warning 'effectiveness' should start with a definition of its objectives. As alluded to earlier, public warnings aim to stimulate timely and proper protective behaviours (Quarantelli, 1984). However, general evacuation compliance studies have revealed that such a behavioural goal is not easy to achieve, as citizens who receive an evacuation warning often do not intuitively follow the instruction (Drabek, 1999, Mileti and Peek, 2000, Lindell and Perry, 2004). Rather, a warning message received by at-risk populations may not always attract people's attention for further interpretation (Mileti and Sorensen, 1990, Lindell and Perry, 2012). In addition, once the warning has been noticed, one needs to comprehend and believe the situation, and perceive the threat as inevitable and unbearable for oneself in order to start taking protective actions (Mileti and Sorensen, 1990, Lindell and Perry, 2012). The effectiveness and timeliness of the interpretive and perceptual process are thus critical for triggering prompt actions under the often pressing circumstances. Consequently, the discussion of map effectiveness for public warning or general risk communication purposes

should regard its ability to 1) appeal to the general users for serious information heeding, 2) facilitate warning understanding and risk perception in personal terms, 3) assure efficient information processing and 4) trigger appropriate responses.

5.1.2 Map effectiveness for communicating risk

Research on the use of maps for communicating risk with the public has conventionally focused on communicating which areas are prone to hazards and portraying risk probabilities, such as floodplain maps. Overlaid on local maps, those risk maps aim to facilitate the identification of self-relevance by those who reside in the delineated risk zones. Studies have shown that a majority of citizens can accurately locate oneself on the map and decode the risk level of one's household (Kain and Covi, 2013, Zhang et al., 2004). However, individuals' understanding capability may be compromised when the map delineates a small or narrow risk area on a relatively large map extent (i.e. small scale map; Arlikatti et al., 2006). In addition to facilitating risk comprehension, risk area maps may also elicit a higher level of 'concern' in comparison to textual descriptions of risk probabilities (Bell and Tobin, 2007). Furthermore, in relation to optimising map-design, research has shown that map based risk perceptions can be further enhanced by an appropriate choice of colour schemes (Thompson et al., 2015). However, using maps to only delineate the long-term probability of hazards may not necessarily be positively received by the public (Kain and Covi, 2013) or stimulate risk mitigation behaviours (Zhang et al., 2004, Arlikatti et al., 2006, Bell and Tobin, 2007).

In recent years, there has been an increase in the use of similar maps for the communication of more imminent threats; that is, polygon maps depicting warning areas. Such maps have become imperative following the issuance of storm-based tornado warnings in the U.S (NWS, 2008), which delimit warning areas irrespective of the political boundaries, making the areas impossible to be described in words. In this context, studies have found that identifying one's household as sitting inside a delineated area that is under tornado warning is associated with elevated risk perceptions (Lindell et al., 2015a) and the triggering of protective behaviour (Nagele and Trainor, 2012); however, such effects may assuage as the warning area enlarges

(Nagele and Trainor, 2012). Furthermore, people overtly assume an escalated level of risk near the centroid of a warning polygon and a correspondingly lower level of risk near the edge of a warning polygon (Ash et al., 2014, Lindell et al., 2015a), whereas such an assumption is erroneous and often contradicts the real risk likelihood posed by the tornado course (Ash et al., 2014). One solution to improve understanding and perception accuracy is to provide information regarding the existing location and predicted movement of the hazard to help people's sense making of the risk and warning.

For hazards that tend to migrate and expand geographically, such as tornados, hurricanes, and wildfires, information regarding the existing hazard location is especially critical for the accurate comprehension of the risk situation. To this end, radar images have been used to supplement conventional textual warnings to depict advancing extreme meteorological events. Casteel and Downing (2013) however, found that the attachment of radar images to full-text tornado or flash flood warnings did not show an added effect on the public's risk perception, decision-making and response time. This is potentially due to the complex interpretative and cognitive capabilities required for understanding such realistic earth representation (Lillesand et al., 2015). In contrast to radar images, regular cartographic representations (e.g. a map denoting the current tornado centre) should be relatively easy to understand by laypeople, especially if maps are appropriately simplified and punctuate task-relevant information (MacEachren, 1995). Whilst such maps have not been developed for tornado warnings, they have been used for portraying hurricane courses. That is, the 'cone of uncertainty' (COU) maps convey the current location and the predicted track of tropical cyclone centres, as well as designated warning areas (NHC 2015). However, the COU maps were still found to result in a prominent confusion and misinterpretation of areas to be impacted, and a neglecting of the portrayed warning areas, which has been ascribed to their display of the statistical errors associated with the track prediction (Broad et al., 2007). Consequently, it is important to gain knowledge on how to design maps in an accurate, yet appropriate and user understandable way to ensure they achieve the intended communication goals.

In summary, when communicating warnings for imminent threats, maps may provide for a holistic warning approach to portray not only warning areas but also hazard and risk explanatory information. The majority of the public may have the capacity to accurately understand such risk/warning area maps, and use of such maps may result in improved risk perception and behavioural responses. However, effectiveness of the maps in creating an accurate understanding of the warning by the public and improving their risk perceptions is subject to the nature and complexity of the information they deliver, as well as the appropriateness of the cartographic designs. Furthermore, it is currently unknown whether map-based communication are more effective in attracting attention of the public and in expediting appropriate responses in comparison to text-based approaches.

5.1.3 The current study

To date, no study has explored the effectiveness of maps in comparison to text-based messages for providing wildfire warnings. To address this gap, the current study sought to compare the effectiveness of text versus map forms for presenting all spatial related warning information for wildfires[1] and did so in an Australian context. An examination of typical textual wildfire warnings in Australia[2] helped identify seven information elements (IEs) that can be presented in either text or map forms: 1) fire location/perimeter, 2) fire suppression status (i.e. location of active/contained fire edge), 3) wind condition (current and forecast), 4) fire spread prediction, 5) fire warning levels and areas, 6) road closure information, and 7) evacuation centre locations. Since map effectiveness may depend on its design (Broad et al., 2007, Casteel and Downing, 2013, Ash et al., 2014, Thompson et al., 2015), the current study also aimed to evaluate multiple cartographic designs in order to identify the most effective design for presenting each wildfire IE.

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[1] The communication of aspatial information in textual warning messages, such as response advice, firefighting resources, and contact information of emergency services were not examined.
[2] Although the exact information communicated may differ across states, countries and events, a review of wildfire warnings delivered in Australia and the U.S. did not uncover any additional elements.

In line with the discussion on warning objectives and effectiveness, this study measured 'effectiveness' with respect to four aspects: i) Accuracy of Understanding, ii) Risk Perception, iii) Efficiency, and iv) Preference and Ease of Understanding. Specifically, the study addressed the following questions:

RQ1. Does map-based presentation of wildfire warning information facilitate a more accurate understanding of this information when compared to text-based presentation?

RQ2. Does map-based presentation of wildfire warning information stimulate higher levels of risk perception when compared to text-based presentation?

RQ3. Is map-based presentation of wildfire warning information more efficient (i.e. requiring less time) in promoting situational awareness than text-based presentation?

RQ4. Do participants prefer text or map-based communication of wildfire warning information?

RQ5. What is the optimal approach to communicating each wildfire warning information element?

5.2 Method

An online survey-based study was conducted from February to April in 2014 to quantitatively compare the communication outcomes of text-based messages versus various map designs within an experimental setting. The survey also offered opportunities for participants to provide feedback in order to better understand the differences in effectiveness between texts and maps.

5.2.1 Participants

Survey participants were recruited from three wildfire prone suburbs located in Western Australia: Kelmscott, Roleystone and Mundaring. All three suburbs had been exposed to a

large-scale wildfire in recent years (Government of Western Australia, 2011, SEMC, 2014). The three suburbs were selected purposefully based on their varying residential environment. These include a predominantly urban landscape - Kelmscott (7% rural), a rural-urban interface - Roleystone (22% rural), and a more rural setting - Mundaring (31% rural) (ABS, 2011a).

An invitation postcard was posted to all households in each suburb (approximately 2700, 2000, and 854, respectively) using an unaddressed bulk mail service. Each card included a brief introduction to the study, the URL address of the online survey, and a Quick Response Code (QR Code). In the case of households with multiple adult residents, the researchers used a random sampling method by asking the adult resident with the first 'next-birthday' to participate (Salmon and Nichols, 1983). Two follow-up postcards were mailed in two-week intervals.

In total, 261 individuals accessed the survey, of which 86 were from Kelmscott, 103 from Roleystone, and 72 from Mundaring, resulting in a response rate of 3.2%, 5.2% and 8.4% of the total number of households respectively. Despite the relatively low response rate (Tufte and Graves-Morris, 1983), most participants (242/261) who accessed the survey did fully complete it, and the majority (>200) also supplied comprehensive qualitative comments on the warning designs.

The sample population was generally representative of the gender distribution within the three suburbs. However, there was a disproportionately large number of middle-aged participants (50-69 years old, Sample = 55%) when compared to the community profile of each (Kelmscott = 33%, Roleytone = 41%, Mundaring = 33%; calculated based on the numbers of adults from ABS, 2011b). Moreover, the sample was skewed towards residents with higher education levels (university degrees, Sample = 44%; as compared to Kelmscott = 11%, Roleystone = 20%, Mundaring = 17%, ABS, 2011b). It should also be noted that most participants had resided in their suburb of residence for 10 or more years (64%), and were self-reported daily users of both computers (daily, 94%) and digital maps (daily, 63%). The biases in this sample may be a result of the online nature of the study. However the number of

Australian residents without internet access has been steadily decreasing over time (ABS, 2014). Whilst the results from the survey require interpretation with caution, such a sample does seem to be representative of the potential users of a mapping application for warnings.

5.2.2 Communication of warnings – Independent variables

To test differences between text and map based warning messages, a wildfire emergency scenario was simulated for each suburb respectively. Each scenario involved an 'Emergency' warning (see National Bushfire Warnings Taskforce, 2009) issued for two thirds of the targeted suburb and a 'Watch and Act' warning for the remaining and surrounding suburbs. Other situational factors, such as the distance between the fire and residential area, wind impact, predicted fire course and resultant road closures, were consistent across the different emergency scenarios.

Two design sets were developed to depict each of the seven spatial IEs for each suburb (Figure 5.2). The first set contained a text statement for each IE, which mimicked the national messaging protocols for wildfire warnings (National Bushfire Warnings Taskforce, 2009) as well as the wordings used by the local fire emergency service, i.e. the Department of Fire and Emergency Services (DFES) in Western Australia. The second set comprised map representation(s) for each IE. Due to a lack of established mapping standards for public information in Australia, map representations were developed based on cartographic symbology employed by existing publicly accessible maps (e.g. VicRoads, 2014, BOM 2015, EMV 2015, Government of South Australia, 2015, DFES, 2015a), as well as standards adopted for map production and communication within and between emergency management agencies (EMSINA 2010, RFS 2012, Steber et al., 2012). Several additional element-specific designs were developed based on mapping approaches identified in the literature. Examples include the shaded Isarithmic map (Figure 2 Map4c, Thompson et al., 2015) and animation (Figure 2 Map4d, Campbell and Egbert, 1990) for representing fire spread estimation.

The fire is burning in the area around Canning Mills Rd, west of Canning Rd within Korung National Park.

Approximately 90 hectares have been burnt.

The fire started earlier this morning in the west of Canning Rd and north and Canning Mills Rd.

Update Time: 12/01/2014 10:45AM
Current Time: 12/01/2014 11:00AM

Text 1. Fire location

Map 1a. Fire location

The fire is burning in the area around Canning Mills Rd, west of Canning Rd within Korung National Park.

The fire is currently burning out of control.

Most of the northern boundaries of the fire have been contained.

Update Time: 12/01/2014 10:45AM
Current Time: 12/01/2014 11:00AM

Text 2. Fire suppression status

Map 2a. Fire suppression status

The fire is burning in the area around Canning Mills Rd, west of Canning Rd within Korung National Park.

Winds are forecast to be northerly and north-easterly for the rest of this morning at around 20km/h, and will change to easterly this afternoon around 3pm with higher winds speed at around 30km/h.

Update Time: 12/01/2014 10:45AM
Current Time: 12/01/2014 11:00AM

Text 3. Wind

Map 3a. Arrow wind map

Map 3b. Meteorological wind map

The fire is burning in the area around Canning Mills Rd, west of Canning Rd within Korung National Park.

It is moving in a south-westerly direction at a speed of around 300 meters per hour.

Update Time: 12/01/2014 10:45AM
Current Time: 12/01/2014 11:00AM

Text 4. Fire spread prediction

Map 4a. Point spread map

Map 4b. Isarithmic map: isopleth

Map 4c. Isarithmic map: tinted

Map 4d. Animated spread map

A bushfire Emergency Warning has been issued for people in the eastern part of Martin, northern part of Roleystone, southern part of Canning Mills and western part of Karragullen.

A bushfire Watch and Act has been issued for people in the southern part of Roleystone.

Update Time: 12/01/2014 10:45AM
Current Time: 12/01/2014 11:00AM

Text 5. Fire warning

Map 5a. Point warning map

Map 5b. Polygon warning map

Canning Mills Rd between Mills Rd East and Canning Rd is closed.

Update Time: 12/01/2014 10:45AM
Current Time: 12/01/2014 11:00AM

Text 6. Closed roads

Map 6a. Point road map

Map 6b. Polyline road map

An evacuation centre has been opened at Roleystone Neighbourhood Family Centre at 19 Wygonda Rd, Roleystone.

Update Time: 12/01/2014 10:45AM
Current Time: 12/01/2014 11:00AM

Text 7. Evacuation centre

Map 7a. Evacuation centre

Figure 5.2 Text and map designs for each warning IE tested in this study.

One notion to make is that the communication of predicted fire spread behaviours (IE4) results in non-equivalent information for maps versus text; textual warnings can only provide general fire spread direction and estimated rate of spread, whereas maps can depict estimated time of fire arrival at different locations by using the output from fire spread prediction models. Such models are available to the emergency management services in Australia to produce accurate, real-time predictions albeit within a four-hour uncertainty window (Steber et al., 2012). Map representations of IE4 are thus evaluated in terms of their communication of estimated time of fire arrival for specific locations, whereas text-based representations are evaluated in terms of the communication of general fire spread direction and rate.

5.2.3 Dependent variables

Effectiveness of each warning design was evaluated using four criteria: i) Accuracy of Understanding, ii) Risk Perception, iii) Efficiency, and iv) Preference and Ease of Understanding.

Accuracy of understanding. Questions asked to examine participants' understanding of each IE are shown in Table 5.1. The principle was to simulate the cognitive process of individuals' interpretation of each IE into personal risks, i.e. in relation to one's home location. Haynes et al. (2007) proposed that one's risk comprehension in the spatial domain requires four interpretative skills: locating, orientation, map reading and risk interpretation. Drawing upon this framework, this study interrogated the completion of four types of 'understanding' tasks using maps or texts, each involving the utilisation of one or more of the aforementioned four interpretative skills. These 'understanding' tasks include: i) locating one's home in relation to a delineated risk/warning area, such as a warning zone (*Geo-association*); ii) estimating the distance between the fire location and one's home (*Distance*); iii) orienting the fire location, and interpreting directional information in relation to one's home (*Direction*); and iv) translating *Geo-association*, *Distance*, and/or *Direction* into wildfire risks (*Risk*). The specific 'understanding' questions asked for different IEs differ based on the nature of the information and their intended comprehension objectives. For instance, information depicting a risk area

Table 5.1 Questions displayed following each IE in the survey to evaluate Understanding Accuracy

Types of 'understanding' tasks measured	Specific questions asked
IE1. Fire location	
Direction[a]	What is the direction of the closest fire edge from your property at 10:45?
Distance[a]	Approximately how far is the closest fire edge to your property at 10:45?
IE2. Fire Suppression	
Direction	What does the location of the contained fire edge mean in relation to the location of your property? (The fire edge closest to your property has been: contained, partially contained, or not contained.)
Risk	Do you expect the fire to spread towards your property? (yes or no)
IE3. Wind	
Direction	Is the wind currently pushing the fire towards your property? (yes or no)
Risk	If the fire is not contained, will it be a greater threat to your property in 4hrs than it is currently given the wind forecast? (yes or no)
IE4. Fire Spread	
Direction	Is the fire spreading towards your property? (yes or no)
Risk/ Geo-association[c]	If the fire is not contained, approximately how long will it take for the fire to reach your property? (0-4hrs, 4-8hrs, 8-12hrs, 12-16hrs, or it will not reach my house in 16hrs)
IE5. Fire Warning	
Geo-association	What is the fire warning level for your property at 10:45? (no warning, Advice, Watch and Act, or Emergency)
IE6. Closed Roads	
Direction[a]	What is the general direction of the closed road from your property?
Risk	Would you still be able to travel to the Post Office[b] in (your suburb) from your property by car? (yes or no)
IE7. Evacuation Centre	
Direction[a]	What direction is the evacuation centre from your property?
Distance[a]	Approximately how far is the evacuation centre from your property?

Note. Participants were given the option to answer 'not sure' for each question.

[a] These questions were open-ended.

[b] Used to represent a universally known location within the suburb to test understanding of the impact of road closures on escape routes.

[c] Different operationalisations of 'understanding' were needed for responding to this question using the text and maps. The text required an understanding of *distance*, fire spread rate, and a further calculation of time, whereas the maps, which modelled time of fire arrival, required the *geo-association* of oneself with a delineated zone.

requires *Geo-association*, whereas locational information, such as fire location, is concerned with *Distance* and *Direction*.

Answers to all of the 'understanding' questions were location-specific, based on the participant's home address. Correct answers to the questions were therefore calculated using ArcGIS 10.2 (ESRI, Inc.) using each participant's address. Participants' responses and correct answers were then compared to generate an *Understanding Accuracy* score on a scale from 1-3, where 3 denoted an approximately correct response (e.g. with a difference smaller than 22.5° for *Direction* and less than 0.5km for *Distance*), 2 denoted a response that was close (e.g. with a difference between 22.5° and 45° for *Direction* and 0.5 and 1km for *Distance*), and 1 denoted a response with considerable error (e.g. with a difference greater than 45° for *Direction* and 1km for *Distance*). For close-ended questions with binary options, such as the *Risk* question for IE2 and *Direction* and *Risk* questions for IE3 (Table 5.1), a dichotomous *Understanding Accuracy* coding was adopted (1 = wrong answer and 2 = correct answer), as these questions were relatively simplistic and less location-specific. Since the fire scenarios were simulated to threaten the entire target suburb, correct answers to these binary questions should be constant across all participants from the same suburb.

Risk perception. Risk Perception questions sought to measure the integrative assessment of personal level of risk posed by the wildfire based on the presentation of each IE. More specifically, following the approaches used in relevant risk communication research (Lindell and Whitney, 2000, Martin et al., 2007, Bostrom et al., 2008, McNeill et al., 2013), the measure of *Risk Perception* comprised two indicators: perceived *Likelihood* and perceived *Severity* of the threat of wildfire. Therefore the following two questions were asked in Section 1 in addition to the 'understanding' questions: i) given the known information, how likely do you think it is for this fire to reach your property? ii) if the fire does reach your property, how severe do you think the impact of this fire would be on your property? The *Likelihood* question was asked following the presentation of each IE, whereas the *Severity* question was posted only after the presentation of IE3-5. This is due to the nature of IE1 and 2 in lacking

necessary information for estimating *Severity*. Neither *Risk Perception* question was asked following IE6 and 7, as these two elements of information were not directly related to risk perception. A 7-point Likert scale was applied for both *Risk Perception* questions, anchored by 1 = definitely won't happen/not severe at all to 7 = definitely will happen/extremely severe.

Efficiency. Design *Efficiency* was measured as the time spent by the participants on a page to view each design and complete the corresponding effectiveness questions.

Preference and ease of understanding. These two variables measured participants' subjective preference and opinions. First, participants were requested to choose the design they preferred, or opt for 'no preference'. Furthermore, participants were asked to rate the *Ease of Understanding* of each design on a scale from 1-7, with 1 representing 'extremely difficult' and 7 representing 'extremely easy'.

5.2.4 Survey procedure

The online survey was composed of three sections. In the first section, participants were assigned to either a text-group or a map-group using a randomisation tool ensuring an equal number of participants for each group. Each participant was then provided with all seven IEs one by one, presented using a consistent design style, i.e. either all texts or all maps. For IEs with multiple map designs, each participant from the map-group was presented with a randomly selected cartographic design whilst the number of participants viewing each map design was held approximately equal. Following the viewing of each IE, participants were asked to complete the corresponding questions to measure *Understanding Accuracy,* and *Risk Perception*. Time spent on a page was recorded to measure *Efficiency*. In the second section, participants were presented with each IE again, but with all text and map designs on the same page, and were then asked for the final 'effectiveness' indicator, namely their personal *Preference* and rating of *Ease of Understanding*. They were also asked to provide feedback regarding what they liked and disliked about each design. Finally, in the last section participants were asked for their demographic and personal information.

5.2.5 Data analysis

First, descriptive statistics for *Understanding Accuracy*, *Risk Perception*, *Efficiency*, *Preference* and *Ease of Understanding* were calculated. Then, a comparative analysis was conducted to examine the relative performance of different warning designs. It should be noted that *Accuracy* measures included both dichotomous variables (1=wrong and 2=correct), and ordinal variables on a scale of 1 to 3 (1= wrong, 2= close and 3= correct), as described in the Method section. For the dichotomous variables, a chi-square test was used to compare the different warning designs. For the non-dichotomous variables, as well as for the *Risk Perception* and *Efficiency* measures, a Mann-Whitney U (MWU) test was conducted to compare the medians between warning designs. Furthermore, a Wilcoxon signed-rank test was employed to test the paired-differences in users' ratings of *Ease of Understanding*. The choice of these non-parametric tests was based on the non-normality of the majority of the data and the unequal sample sizes between compared groups. All statistical tests were conducted in SPSS 22.0 using a .05 level of significance. Whilst most of the analysis was quantitative, qualitative data concerning the 'like' and 'dislike' of each warning design acquired in Section 2 of the survey was used as evidence for interpreting the usability of textual and/or map designs, and this data will be discussed along with the quantitative results in the next section.

5.3 Results and discussion

5.3.1 Accuracy of Understanding (in response to RQ1)

Comparative results (Table 5.2) showed that map-based communications were associated with significantly higher levels of *Understanding Accuracy* than the text-based communications for seven out of the 14 'understanding' questions. Significant differences occurred for all IEs except for IE5 (fire warning). Specific patterns of the relative performance of maps versus text-based messages in relation to the four aspects of understanding (i.e. distance, direction, geo-association, and risk) are discussed below.

Table 5.2 Mean values of Accuracy, Risk Perception, and Efficiency measures and comparison between designs

Understanding Accuracy, Risk Perception and Efficiency measures	Text	Map			
		Map a	Map b	Map c	Map d
IE1. Fire location					
Direction (1,2,3)	2.40	2.58			
Distance (1,2,3)	1.52	1.88***†			
Likelihood (1-7)	3.85	4.32*			
Efficiency	168.58	188.09			
IE2. Fire suppression					
Direction (1,2,3)	2.77	2.90*			
Risk (1,2)	1.85	1.89			
Likelihood (1-7)	3.83	4.02*			
Efficiency	75.85	71.72			
IE3. Wind					
Direction (1,2)	1.59	1.74*	1.68		
Risk (1,2)	1.64	1.60	1.56		
Likelihood (1-7)	4.01	4.44*	3.90		
Severity (1-7)	4.75	5.20	4.37		
Efficiency	87.17	92.25*	126.85***		
IE4. Fire spread					
Direction (1,2)	1.73	1.89*	1.97***	1.97***	1.96***
Risk/Geo-association (1,2,3)	1.83	2.71***	1.70	2.52***	2.11
Likelihood (1-7)	4.01	4.25	5.24***	4.79***	5.19***
Severity (1-7)	4.67	4.54	5.76***	5.24	5.00
Efficiency	81.68	88.07	111.91**	78.63	78.54
IE5. Fire warning					
Geo-association (1,2,3)	2.37	2.37	2.62		
Likelihood (1-7)	4.42	4.77	4.89*		
Severity (1-7)	5.07	5.07	5.15		
Efficiency	76.05	74.77	65.93*		
IE6. Closed roads					
Direction (1,2,3)	2.52	2.47	2.76*		
Risk (1,2)	1.99	1.95	2.00		
Efficiency	58.28	52.89	44.88		
IE7. Evacuation centre					
Direction (1,2,3)	2.65	2.58			
Distance (1,2,3)	1.51	1.83***			
Efficiency	42.23	52.27***			

*$p \leqslant .05$; **$p \leqslant .01$; ***$p \leqslant 0.005$

† Based on Chi-Square test for dichotomous measures, and Mann-Whitney U test for the non-dichotomous ones. Asterisks following the mean value of a map design denote a significant difference from the corresponding text design.

Distance. Assessment of distance was considered as a critical aspect for understanding simple

location based information, including fire location (IE1) and evacuation centre location (IE7).

Maps for both IEs yielded significantly higher mean *Understanding Accuracy* scores for

Distance than the respective texts (Map1a, *p* = .003; Map7a, *p* = .002), suggesting the power of maps in facilitating the accurate assessment of distance.

Direction. Significant differences were found for understanding movement related directional information (e.g. "Is the fire spreading towards your property?"), with maps resulting in better comprehension than text for wind direction (Map3a, *p* = .026) and predicted fire movement direction (Map4a, *p* = .035; Map4b, *p* = .002; Map4c, *p* = .005; Map4d, *p* = .005). For the remaining four IEs for which *Direction* was measured (i.e. Fire location, Fire suppression, Closed roads, and Evacuation centre), it was measured as the ability to understand static directional information relative to one's household (e.g. "What is the general direction of the closed road from your property?"). The results demonstrated no difference between the maps and texts for communicating the fire location (IE1) and the evacuation centre location (IE7). However, both the map communicating active/contained fire edge (Map2a, *p* = .035) and the map communicating closed roads (Map6b, *p* = .034) resulted in better directional understanding than the respective text messages.

Geo-association. Geo-association, or one's ability to relate general area-based warning information to the location of one's household, was measured in relation to two IEs. The first regarded how long it would take for the fire to reach one's property (IE4). Results showed that the two maps that used colour in differentiating the time values for various delineated areas, namely the point map (Map4a) and tinted Isarithmic map (Map4c), elicited higher accuracy than text messaging for understanding how long it would take for the fire to reach one's property (Map4a, *p* = .000; Map4c, *p* = .000). Specifically, 80% (N=30) and 67% (N=30) of participants accurately identified the predicted timeframe associated with their home location using the point map (Map4a) and tinted Isarithmic map (Map4c) respectively, whereas only 28% (N=130) accurately estimated the lead-time for their location using the text information (Text4). As discussed in the footnote of Table 5.1 however, response to this question using the text version (Text4) required additional interpretation of the information above and beyond the *Geo-association* needed for the maps. More specifically, as the text only provided

information concerning the direction and rate of fire spread, participants needed to first estimate the distance between the fire and their house (i.e. the *Distance* question measured for IE1), and then calculate likely fire arrival time. The difference in the *Geo-association* measure thus is potentially a result of the distinct nature of the information provided by the text versus maps.

The second IE for which *Geo-association* was measured communicated designated warning areas and associated warning levels (IE5). For understanding the warning level for one's property, results showed a higher level of accuracy elicited by the warning polygon map (Map5b) than by the text-based information. Specifically, 80% (N=64) and 66% (N=126) of participants were able to accurately identify themselves within one of the two warning areas using the warning polygon map (Map5b) and the text message (Text5) respectively. This difference between *Geo-association* using Map5b and Text5 approached statistical significance ($p = .052$).

Risk. No significant differences were observed when using maps versus text based messaging for interpreting *Risk* in terms of a) whether or not the fire was spreading in the respondent's direction based on the current location of the active fire edge (IE2), b) whether the fire, if left uncontained, would form a greater threat in 4 hours' time due to the changed wind impact (IE3), and c) whether the local post office could still be reached based on the impact of the closed roads (IE6). In fact, most participants accurately responded to the *Risk* questions associated with IE2 (Text2: 85%; Map2a: 89%) and IE6 (Text6: 99%; Map6a: 95%; Map6b: 100%), irrespective of communication designs. This was likely due to the simplicity of the dichotomous *Risk* measures, as the fire scenario was simulated to occur at a position that influenced the entire suburbs, resulting in easy interpretation and consistent answers across participants from the same suburb.

In contrast, only a small majority of participants (Text3: 64%; Map3a: 60%; Map3b: 56%) accurately responded to the *Risk* question associated with IE3, despite its simplicity and analogy to *Risk* questions for IE2 and IE6. Theoretically, the interpretation of changed wind

impact (the *Risk* question for IE3) should derive from a correct understanding of current wind direction (i.e. the preceding *Direction* question for IE3). Such an inference was confirmed by a significant correlation found between the *Direction* and *Risk* scores; however, this relationship was stronger in the text condition ($r = .60$, $p = .000$) than in the condition in which people were shown Map3a ($r = .39$, $p = .001$). This indicates that map-viewers who understood current wind direction (i.e. the *Direction* question) represented by arrows were more likely to misinterpret the changed fire impact caused by forecast wind (i.e. the *Risk* question) than text-viewers who understood current wind direction. In fact, 29% of participants (14/49) who comprehended *Direction* correctly after viewing Map3a provided incorrect answers to the *Risk* question, whilst this ratio was 12% (8/68) for people who comprehended *Direction* correctly after viewing Text3. Of the 14 mistaken map-viewers, three suggested a failure in identifying the 'time' of the forecast wind conditions which was indicated in the title of the corresponding legend, providing a potential explanation for their erroneous responses to the changed wind impact. Another possible explanation is that the communication of temporal 'change' may be more prominent and intuitive when communicated in text when compared to communication by maps that differentiate timeframes by using different colours.

Conclusion. In summary, significant differences were found between maps and text-based messages for understanding the wildfire risk situations in relation to one's location. More specifically, for all location and direction related IEs, at least one of the map versions resulted in more accurate assessment of distances and improved understanding of directions than the text-based messages. Furthermore, maps provided more specific information than text in depicting prospective fire movement, facilitating more accurate understanding of potential time of fire arrival for one's location. Finally, the results showed a trend of the warning polygon map resulting in better identification of one's relationship with a designated warning zone than the text-based message, which only provides cursory description of warning areas using suburb names (e.g. northern part of Roleystone). However, maps did not exhibit significantly better interpretation of the impact of fire suppression status and road closure on

one's safety than the text-based messages. In addition, when depicting temporal changes (e.g. current and forecast winds) through the use of different colours, maps did not garner better comprehension than the text-based communication. Nevertheless, texts never elicited a significantly better understanding of information when compared to the maps.

5.3.2 Risk Perception (in response to RQ2)

Based on the survey results, maps generally stimulated a higher degree of perceived threat *Likelihood* than text messages. Table 5.2 shows that at least one map design for each IE, often the one providing a better *Understanding Accuracy*, yielded a *Likelihood* score significantly higher than the corresponding text message.

However, the pattern of results was not as consistent for the *Severity* measure. Whilst all the map designs yielding higher mean *Likelihood* scores than text messages also obtained higher mean *Severity* scores than the corresponding text messages, most of the differences in severity scores between map and text based messages did not reach significance. The exception was the contour fire spread map, which communicated time using labels (Map4b). This is a symbology defined by the Australian emergency operational mapping standards (EMSINA 2010). This map resulted in higher severity scores than the text message ($p = .000$). However, a closer examination revealed that such higher *Likelihood* and *Severity* scores exhibited by Map4b were potentially related to the salient misinterpretation of the predicted fire spread timeframes, as indicated by the poor accuracy of the responses to the preceding *Geo-association* question based on Map4b (Table 5.2). Specifically, we found that 15 out of 35 participants (42.8%) presented with Map4b misinterpreted the lead-time as 0-4 hours, which is significantly shorter than the actual projected time shown on the map. Those participants all reported high ratings of perceived *Likelihood* and *Severity* (≥ 5 on the 1-7 Likert scale). In contrast, the ratio of people reporting a 0-4 hours lead-time and providing high *Likelihood* and *Severity* scores based on Text4 was 10.9% (11/101). Based on these results, it appears that Map4b is not effective in generating accurate understanding of the predicted time zone associated with oneself; however, the higher scores of *Likelihood* and *Severity* tied to Map4b

suggest the map design could potentially increase the chances of a desired response (i.e. early evacuation). Still, further research is needed to test the relative importance of accuracy of understanding versus risk perceptions in determining the overall effectiveness of map-based versus text-based communication for this information element.

5.3.3 Efficiency (in response to RQ3)

A preliminary analysis of the *Efficiency* in terms of the recorded time (in seconds) spent on responding to the questions in relation to each IE revealed a number of extremely long response time spent by participants on particular IEs but not all, suggesting they were random errors. These long amounts of time on particular IEs were thus identified as outliers, and excluded for the analysis of *Efficiency*. As a result, a maximum of two responses were excluded for any one design. The outliers excluded for IE1 were individuals who spent more than 1000 seconds on responding to the questions for this IE (as compared to a mean response time of 178.33 seconds with a standard deviation of 135.92 seconds after exclusion of the two outliers), and those excluded for other IEs all took more than 600 seconds (after exclusion of outliers, mean responses for IE2 to 7: Min = 47.19 seconds, Max = 96.99 seconds; standard deviation for IE2 to 7: Min = 34.22 seconds, Max = 72.31 seconds).

The subsequent comparative analysis on the *Efficiency* of maps versus text revealed mixed results (Table 5.2). The polygon warning map (Map5b) was the only map design where participants spent significantly less time on answering the questions as compared to the text based version ($p = .045$). It is unsurprising that some map designs that were not accurately understood, resulted in longer response time when compared to text messaging. These include the meteorological wind map (Map3b, $p = .000$), and the misinterpreted contour map of fire spread prediction (Map4b, $p = .008$). Interestingly however, several map designs that fostered higher *Understanding Accuracy* scores than the text messages also resulted in prominently longer response time. This occurred for the coloured arrow wind map (Map3a, $p = .047$), and the evacuation centre map (Map7a, $p = .004$). In addition, many other map designs demonstrated appreciably lower (e.g. Map2a and Map6b) or higher (e.g. Map1a) response

time when compared with the corresponding text messages; however, the differences were not significant.

5.3.4 Preference and perceived Ease of Understanding (in response to RQ4)

Preference. In addition to the recording of participants' single choices of *Preference* of communication designs for each IE, their comments regarding what they liked and disliked about each design from Section 2 of the survey were also examined to further the understanding of their *Preference* choices. This revealed that many participants who opted for 'no preference' expressed a preference for more than one design in their comments, advocating for a combined communication approach. Consequently, the preferences of these participants were coded as combined preferences (Table 5.3).

The subsequent analysis of *Preference* results revealed a pattern that contrasted those resulting from the previous objective measures. That is, although maps did not always result in greater *Understanding Accuracy*, *Risk Perception*, and *Efficiency* for communicating wildfire warning IEs when compared to text-based warnings, there was a highly pronounced preference for maps over text messages. As shown in Table 5.3, for all IEs except IE7 (evacuation centre), the majority of participants (Min = 74.4% - IE2; Max = 92.9% - IE4) preferred map designs to text messaging. In contrast, less than 10% of participants preferred the text messages over maps for IE1 to 6. Moreover, the *Preference* choice predominantly focused on one map design for most IEs (i.e. Map1a, Map2a, Map3a, Map5b and Map6b). The Isarithmic (Map4c: 52%) and animated fire spread maps (Map4d: 30.6%) were the only two map designs that were preferred by comparable amounts of participants for the same IE. Furthermore, a small amount of participants (Min = 3.6% - IE4; Max = 13% - IE2) suggested the use of hybrid messaging where maps may be augmented by text. However, the percentage of participants supporting the coupled communication approaches may not be reliable as a coupled approach was only revealed through voluntary suggestions. It is thus possible that more participants who alleged an indistinguishable preference for either a text or map design (i.e. those coded as having 'no preference' in Table 5.3) would have preferred a combined

approach if this had been given as an explicit option. Finally, as stated, IE7 (evacuation centre) was the only element where a greater proportion of the respondents identified that text messaging was preferred (37.1% as opposed to 29.4%), whilst 16.1% advocated a hybrid communication approach and 17.3% had no preference. This indicates the importance of text for conveying the locations of evacuation centres.

Table 5.3 Number of respondents preferring each design, with the percentage of respondents noted in brackets.

IE	Text	Map a	Map b	Map c	Map d	Combine two or more methods[†]	No preference	Total
1	18[a] (7.1)[b]	202 (79.2)				19 (7.5)	16 (6.3)	255
2	20 (7.9)	189 (74.4)				33 (13.0)	12 (4.7)	254
3	25 (9.9)	202 (80.2)	3 (1.2)			**T+a** 16 (6.3) **T+b** 1 (0.4)	5 (2.0)	252
4	3 (1.2)	17 (6.7)	9 (3.6)	131 (52.0)	77 (30.6)	**T+a** 2 (0.8) **T+c** 5 (2.0) **T+d** 2 (0.8)	6 (2.4)	252
5	13 (5.2)	18 (7.2)	202 (81.1)			**T+b** 12 (4.5)	4 (1.6)	249
6	16 (6.5)	33 (13.3)	157 (63.3)			**T+a** 3 (1.1) **T+b** 7 (2.8) **a+b** 10 (4.0) **T+a+b** 2 (0.8)	20 (8.1)	248
7	92 (37.1)	73 (29.4)				40 (16.1)	43 (17.3)	248

[†] **T** = Text, **a** = Map a, **b** = Map b, **c** = Map c, **d** = Map d.
[a] Number of respondents preferring this design.
[b] Percentage of row total.

Ease of understanding The respective rating of *Ease of Understanding* for each warning design is shown in Table 5.4. It follows a pattern similar to that of *Preference*, thereby reinforcing participants' positive attitudes towards the use of maps over text for warning communication. Almost all map designs were regarded as significantly easier to understand than text messaging. The only two maps that did not outperform the text designs in reported

ease of understanding were the meteorological wind map (Map3b) and evacuation centre map (Map7a), which were also the only two map designs that elicited lower numbers of *Preference* responses when compared to the number of people stating a preference for the corresponding text messages (Table 5.3).

Table 5.4 Mean ratings of *Ease of Understanding* (on a Likert-scale of 1-7) and comparison between designs

IE	Text	Map			
		Map a	Map b	Map c	Map d
1	3.64	6.29***[†]			
2	3.85	6.12***			
3	3.91	6.12***	3.71		
4	3.47	4.58***	4.33***	6.06***	5.43***
5	3.83	4.32***	6.37***		
6	4.42	5.52***	6.40***		
7	5.81	5.54			

***p≤0.005

[†] Based on Wilcoxon signed-rank test between each map design and the corresponding text statement.

5.3.5 Optimal warning communications (in response to RQ5)

Based on a synthesis of the quantitative results and participants' qualitative feedback, the most effective approach for communicating each IE was identified out of the representation methods evaluated in this study (Table 5.5). For the first six IEs, one map design was identified to provide the best results across most 'effectiveness' aspects. Specifically, the selected map designs for IE1, 2, 3, 4, and 6 all resulted in higher levels of *Understanding Accuracy,* perceived threat *Likelihood*, and appeal indicated by *Preference* when compared with the respective text messages. For IE5, the warning polygon map (Map5b) for IE5 did not show significant benefits than the text in terms of understanding ($p = .052$), but it did garner higher levels of perceived threat *Likelihood* and *Preference*, and was the only map design that exhibited significantly higher *Efficiency* than texts.

In addition to the most effective map designs for IE1 to 6, participants' comments highlighted a list of critical textual descriptors (Table 5.5) that may offer substantial information that cannot be supplied by maps, and thereby should be coupled with maps to provide optimal communication. Most of the textual descriptors raised by participants as being helpful were well-known landmark names, which were deemed as providing important and specific references that strengthened participants' understanding of the visually depicted locations or areas when possible. For instance, 22 respondents (9.1%, $N_{comments} = 242$) mentioned a preference for the indication of fire location (IE1) using names of roads and national parks (Text1) that are known to them. However, wildfires often occur in vast rural landscapes not close to known landmarks or roads, and thus textual description may not always be recognisable or even achievable. For fire suppression information (IE2), the generalised fire status 'out of control' was identified as imperative for risk interpretation, and thus should be used to augment the map. Moreover, survey responses and participants' feedback provided several potential improvements for the cartographic designs. These improvements are documented in Table 5.5 to assist further exploration.

For IE7, whilst the evaluated map (map7a) facilitated a more accurate assessment of *Distance* of the nearest evacuation centre than the text-based message (Text7), the latter resulted in a lower response time and was preferred by more participants. Participants' comments revealed that knowing the name of the evacuation centre, as it is known to them, would make it easier to travel to the location, and ten participants (5%, $N_{comments} = 202$) identified that having the address to enter into their own GPS for navigation would be optimal. Still, 20 participants (9.9%) identified that the map provided for an immediate understanding of location of the evacuation centre and 20 (9.9%) others liked that the map could be used as a reference for planning an egress route. Consequently, a combined design should be used to suit the varied needs of users.

Further to the effective designs identified for specific IEs, an analysis of participants' responses revealed several heuristics that may facilitate the design of useful maps for effective

communication of imminent hazards and warnings in general. These heuristics are discussed below.

Designing good map symbols. Participants' comments revealed a variety of map reading habits such as being intrigued by the visualisations and tending to disregard the legend and other text information beyond the map extent. This phenomenon was also observed by (Hagemeier-Klose and Wagner, 2009), who concluded that public risk maps need to be understandable 'at first glance' (p. 570). Self-explanatory symbol colours and shapes should be employed to minimise the need for referring to the map legend. For example, the results from the current study and those obtained by Thompson et al.'s (2015) identified that the red and red-yellow colour scheme was appropriate for rendering risk related factors. The use of visual features with shapes that are analogous to the intrinsic nature of the depicted subject may also provide for more intuitive understanding. For instance, line based maps portraying closed roads (Map6b) were more accurately and easily understood when compared to the point based road maps (Map6a). Another example is the arrow based wind maps (Map3a) that demonstrated a significant advantage in ease of understanding over the alternative meteorological wind map (Map3b). However, the intuitiveness of different map symbols is not always universal, and the public's interpretations may be influenced by personal/cultural experiences.

Designing good map legends. With self-explanatory symbology, legends should only provide concise and critical information. For example, some participants (14/221) were unable to comprehend the exemplar legends used in the wind maps (Map3a and 3b). Some respondents mistook the legend as the current/forecast wind situation and not as a guide for understanding the symbols on the map. Therefore exemplar legends should be avoided, and in the case of wind maps, arrow wind maps may be the only viable option to support intuitive understanding. Still, explicit legends are indispensible to aid in accurate comprehension of most symbols, especially when colour and size are used to represent different categories of information. Conventionally, legends are static and include all communicated categories. However, when

mapping discrete risk categories, such as warning levels, a map may only consists of a selection of the categories. For instance, the evaluated warning maps (Map5a and 5b) only showed Emergency and Watch and Act warning levels, but an additional Advice level was also shown in the legend to encompass all three warning levels that compose the Australian wildfire warning system (National Bushfire Warnings Taskforce, 2009). Such a generic legend confused 13 participants ($N_{comments} = 205$) who attempted to look for an 'Advice' polygon such as that displayed on Map5b, whilst two participants actually mistook similarly coloured areas on the basemap with an 'Advice' warning area. This infers the need to dynamically update a legend according to the information presented within the mapped extent when communicating public warnings.

Combining important text elements. As mentioned earlier, an effective warning map should properly incorporate critical text descriptors to facilitate comprehension. This can be achieved by either presenting the textual information in the legend, or adding the information as annotations placed next to the associated map features. Both solutions require concise and prominent design of critical text information, especially for the first option. For instance, a number of participants identified the need for providing the 'update time' for the information on the map as offered by the text messages; ironically this information was consistently provided beneath the scale bar in the bottom right corner of the map designs (Figure 5.2) but remained unnoticed. Therefore text information in the legend, if critical, should use prominent fonts and/or colours. Still, although text information presented as annotations on the map may be relatively easier to identify than text shown in the legend, cautious design is needed to create balanced map presentation and avoid cluttering. In an interactive web-based mapping environment, textual explanations can also be linked to relevant visual features and retrieved through interactions such as rollovers.

Table 5.5 Optimal designs, critical text descriptors and potential cartographic improvement identified from the survey study for each wildfire warning IE

IEs	The most effective design (out of the tested candidates)	Potentially critical text descriptors	Potential improvement for the identified map design
1. Fire location		Road/park names	
2. Fire suppression status		'Out of control'	
3. Wind (current and forecast)			Explore an alternative to 'colour' to better differentiate the changed timeframes.
4. Fire spread prediction			The colour scheme used to represent the four-scale classification may be further examined to ensure easier recognition by a wider audience, including colour-blinded populations.
5. Fire warning		Suburbs names	
6. Road closure		Road names	Current four-point width, 40% transparency and colour may be improved for higher prominence.
7. Evacuation centre	+ An evacuation centre has been opened at Roleystone Neighbourhood Family Centre at 19 Wygonda Rd, Roleystone.		Use more prominent colour for the map symbol, and adjust the abbreviation (i.e. EC) used in the symbol to yield more telling meanings, such as 'Evac'.

5.4 Summary and Conclusions

Despite the growing availability of accurate and timely maps for wildfire monitoring and prediction, their effectiveness for public warnings has not yet been systematically evaluated, deterring agencies from using such maps in their warning communications. The current study was the first to provide a sound empirical examination of the potential effectiveness of maps in improving public responses to wildfire warnings. Importantly, results showed that map-based communication of wildfire information, if appropriately designed, are more effective

than conventional textual messaging in multiple aspects. First, the profound predilection of maps over text-based information by the public indicated their appeal. This could potentially lead to an increased level of information heeding, which is an important aspect of warning effectiveness. Second, results showed that properly designed maps may facilitate a more accurate and/or efficient understanding of the specific location of active fire edges, wind impact on the fire course, lead time for taking actions, designated warning zones, and the location of closed roads when compared to text-based communication. Such an improved understanding provides the mainstay for more successful risk assessment and decision-making in response to the warning. Finally, results showed that maps can result in an elevated perception of threat likelihood, potentially fostering an augmented desire and promptness to take protective actions. By contrast, text-based messages only exhibited increased effectiveness over maps in reducing the response time for understanding information concerning current and forecast wind conditions, fire spread direction and speed, and evacuation centre locations, and did not demonstrate any benefit in terms of appeal, the facilitation of accurate comprehension or the promotion of increased risk perception. Consequently, it is time for emergency management agencies to start catering to the public's desire for spatial information delivered in a specific, clear, accurate and visual form.

The study results further underscored that the significance of using maps is subject to the nature of the IE they are delivering and the type of interpretation required. A salient example of this is the communication of evacuation centre locations, where a hybrid approach that integrates a visual indication of the location on a map with a textual description to explicitly depict the location name and address was punctuated. In a similar vein, several critical textual descriptors, including the road, park and suburb names used to indicate wildfire locations and warning areas, as well as the description of fire suppression status, were identified to offer potentially indispensible meanings. Where appropriate and applicable, these should be incorporated in the maps to provide for enhanced understanding and interpretation.

Implications for practitioners and directions for future work. Although the research presented here has been able to provide several important insights, the current study only examined maps of individual spatial IEs, and future research should examine the design of an effective visualisation combining multiple map layers. The suitable cartographic designs identified for each spatial IE in this study, along with a set of generalised design heuristics, can serve as the first step towards the identification of suitable approaches for comprehensive map-based warning communication. The multidimensional visual and textual information needed for effective wildfire warnings could potentially be delivered using a web-based wildfire mapping application that supports interactive information exploration. Existing map-based warning applications that have been developed by authorities within the US and Australia (EMV 2015, Government of South Australia, 2015, CAL FIRE, 2016) can and need to be re-contemplated and re-designed to suit such needs. As discussed earlier, the existing mapping approaches often only visualise cursory fire locations and provide conventional warning content as associated text-based information. Based upon this research we advocate for supplying more adequate and accurate spatial information via effectively designed maps. As a first step, agencies may start to provide maps that deliver fundamental information underpinning individuals' risk comprehension and perception, including maps of fire locations and active fire edges, wind conditions, warning areas, and road closure information. Meanwhile, more research is needed in determining whether more sophisticated spatial information, such as fire spread prediction, should be delivered, as the amplified spatial specificity provided by the visual form may add to the complexity of people's decision-making. In addition, when delivering multilayered information through interactive mapping applications, further study is needed to assure the effectiveness of information presentation approaches and usability by the public. Importantly, the contradictory results from the objective measure of map effectiveness (for understanding, risk perception and efficiency) versus the subjective evaluation of map designs (i.e. preference and rating of ease of understanding) in the current study highlight that examination of such additional aspects of warning effectiveness should be multifaceted, concatenating both the objective or subjective perspectives.

Another point to be highlighted is that the employment of map-based warning approaches infers a heightened responsibility of the agencies to provide accurate and timely wildfire information. As maps potentially yield a more significant impact on one's response decision than text-based communication through their influence on ease of understanding and risk perceptions, an incorrect delineation of the spatial wildfire information using maps may result in greater adverse affect on people's action taking. For instance, research has suggested that whilst visual delineation of warning polygons may effectively promote responses by those who are within the warning boundaries, it may cause significantly plunged risk perception and response motivation when a person resides outside of the warning polygons (Ash et al., 2014, Lindell et al., 2015a). This means that if the delimitation of a warning zone using maps erroneously excludes certain areas under risk, people located within those areas are likely to misinterpret the prospective hazard impact on themselves as none or extremely low, which may create warning disasters. Therefore, to provide effective map-based warnings, agencies should start by investing in advanced data capacity to provide warning information with enhanced timeliness and accuracy. Furthermore, community education campaigns may be offered to direct appropriate understanding and use of the specific spatial information offered by maps, especially when uncertainty and time lag for providing the warning data cannot be completely avoided.

Finally, it must be acknowledged that maps, like any risk communication or warning approach, do not provide a one-size-fits-all solution (Mills and Curtis, 2008). Consequently, comprehensive and effective map-based warning instruments should only serve as an alternative to textual messaging to promote improved warning outcomes for graphic-favouring populations rather than replacing them altogether.

Chapter 6. The smoke is rising but where is the fire: exploring effective map design for enhanced wildfire warnings

Abstract

In recent years, interactive mapping applications have emerged as an alternative means to text-based messaging for communicating public early warnings concerning wildfires. However, with a paucity of research on how to provide effective map-based wildfire warnings, a high degree of diversity exists in the mapping strategies employed by local agencies. The current study sought to offer guidance for developing effective web-based mapping tools for wildfire warnings by identifying 1) the important content for facilitating individuals' decision-making, and 2) the optimal interface design for ensuring usability and ease of information access. A map-based warning tool was prototyped in the Australian context, followed by a usability and effectiveness evaluation through individual interviews and Verbal Protocol Analysis (VPA) to assess participants' interaction with the mapping interface and information in response to the simulated warning scenario. The results demonstrated variations in participants' approaches to wildfire warning response, revealing varied information needs. Specifically, most participants relied on their own assessment of the prospective threat, requiring specific wildfire-related information before eliciting a response. In contrast, the decision of a minority of the participants was motivated by response guidance from agencies, and accurate wildfire information was less important for their response. Imperative information for both types of residents therefore needs to be highlighted in a map-based warning tool to cater to a wide audience. Furthermore, a number of heuristics were generalised for designing effective interactive functions to facilitate the control of, and access to, the various maps and textual information presented on the map-based warning interface.

6.1 Introduction

Wildfire threat to communities is a significant problem in many countries around the world (Guha-Sapir et al., 2015). Public early warning plays a critical role in protecting lives and reducing injuries by raising risk awareness and promoting protective actions (Quarantelli, 1984, Mileti and Sorensen, 1990). Currently, local officials issue and publish wildfire warnings on their websites in a timely manner, and further propagate the warning messages using short alerts disseminated through multiple channels ranging from conventional mass media to advanced location based phone and SMS services (Bean et al., 2015, Emergency Management Victoria, 2014a). These warnings offer a comprehensive range of textual information concerning fire setting and movement, influence of prevailing winds, location of communities under threat, and suggested protective actions.

Due to the salient spatial nature of wildfire warning information, discussions surrounding an alternative, map based approach have emerged in recent years with the intent to add spatial clarity to the text based messages. However, the strategies employed by emergency management agencies for providing wildfire warnings using maps are diverse. The predominant approach is to furnish simple maps illustrating cursory fire locations using point based markers as a supplement to comprehensive textual messages (Figure 6.1.*a*). More recently, a growing number of local emergency agencies have begun to supply the public with maps depicting enriched wildfire warning information including fire perimeters, wind conditions, and warning polygons via interactive web-based mapping applications (Figure 6.1.b and c, EMV 2015, Government of South Australia, 2015, Google Crisis Response, 2015). Also, some of these agencies have adopted the interactive mapping applications as the default information portal for public warnings, providing conventional textual warnings as secondary information (e.g. Figure 6.1.*c*, EMV 2015, Government of South Australia, 2015). Yet, a high degree of diversity still exists in the content provided in the maps, in the cartographic representation used to depict warning information, and in the interactive functionalities allowed by the mapping interfaces.
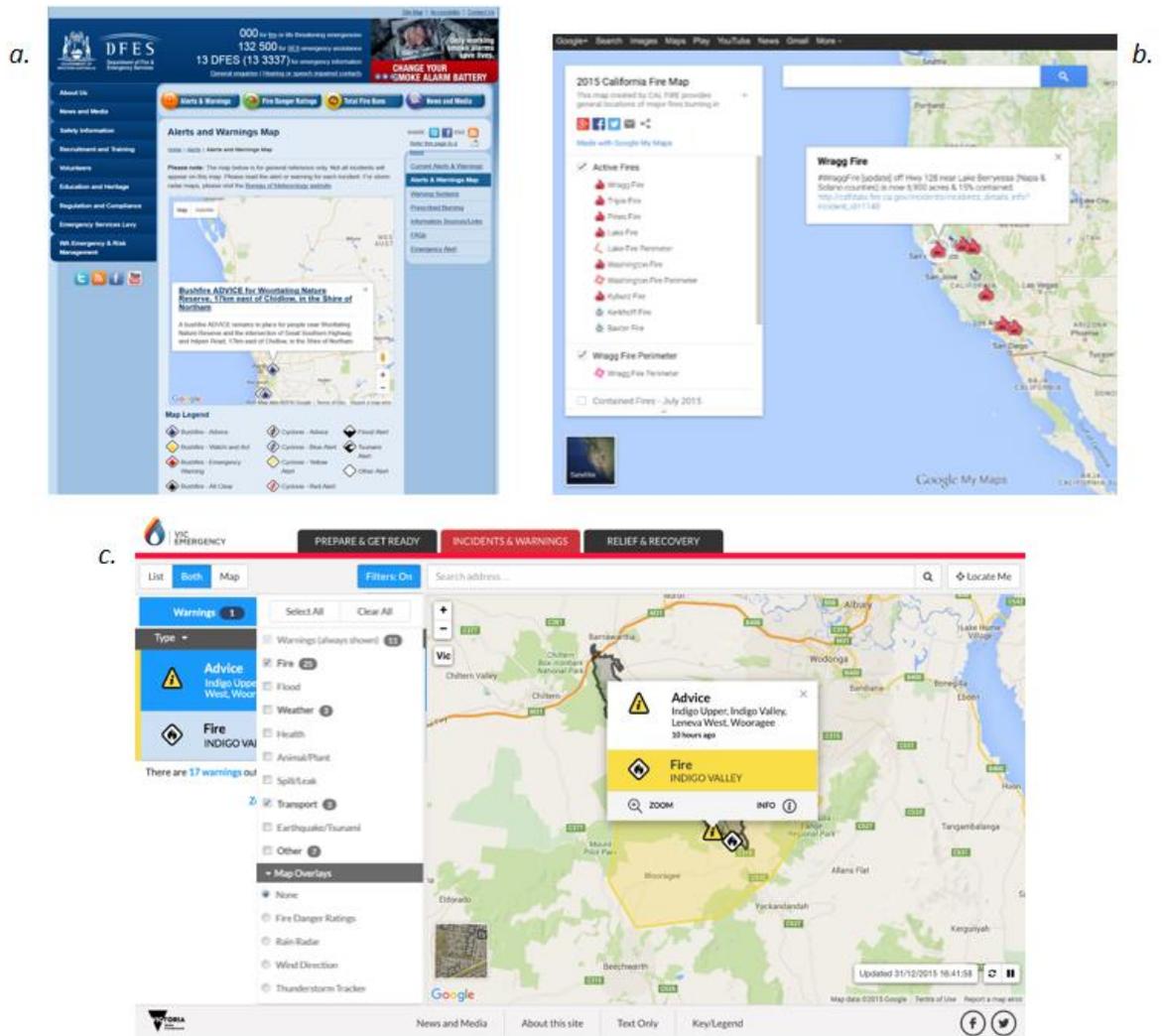
Figure 6.1 Examples of existing mapping approaches used to deliver wildfire warnings: a) Alerts and Warning maps provided by the Department of Fire and Emergency Services (Western Australia); b) California Fire Map provided by CAL Fire; and c) VicEmergency provided by Emergency Management Victoria and supported by fire authorities in the state of Victoria, Australia. The amount of spatial content provided by the maps escalates respectively.

The discrepancy in approaches used for delivering map based early warning information is attributable to two largely unanswered questions: 1) what is the effectiveness of using maps for delivering wildfire warnings compared to using text based warnings, and 2) what elements and designs constitute an effective wildfire warning map? The first question has been addressed by Cao et al. (Under revision) illustrating that communication of spatial related

wildfire warning information using appropriate cartographic representations can provide increased appeal, improved understanding and heightened risk perception when compared to similar text-based messages. However, this leaves open how interactive mapping applications can best be designed to improve the effectiveness of wildfire warnings.

To address this knowledge gap, a wildfire mapping application was prototyped, and an evaluation of the tool was conducted in the Australian context, to develop a blueprint for creating usable and effective map-based wildfire warnings. In this study, the map-based warning instrument is intended to serve as an alternative warning communication approach to text-based messages. Therefore, the mapping application had to provide access to sufficient warning information such that citizens who prefer visual depictions of wildfire information over text would not need to seek additional information. However, in reality a map-based approach does not necessarily exclude the use of text-based warnings as well, and both options can be provided to suite varied predilection of the users. Furthermore, 'effectiveness' of a warning instrument in this paper is defined as achieving its communication goals, that is, to provide information that can promote timely and appropriate decisions regarding protective behaviours in response to an impending threat (Quarantelli, 1984). To this end, this study sought to address two specific questions: i) what information should be included in a wildfire warning mapping tool to facilitate decision-making; and ii) how an interactive mapping interface can best be designed to present this information to ensure usability and ease of information access.

In the remainder of this paper, we first present a review of the key information elements necessary for effective warnings, as well as the general principles for designing usable, interactive mapping interfaces for non-experts. The current public response to wildfire emergencies in the Australian context is then introduced, followed by a demonstration of the methods for designing, prototyping, and evaluating an Australian-based wildfire mapping application. Findings from the evaluation study are then presented and discussed, identifying the imperative content for map-based wildfire warnings whilst highlighting some of the

principles for effective mapping interface design. The study results provide valuable empirical evidence with respect to how to design effective and usable tools to truly harness advanced mapping technologies to benefit the general public in the face of wildfires, potentially saving lives by providing adequate information and facilitating appropriate decision-making.

6.2 Important warning information for effective warning

Whilst there has been an absence of literature discussing the appropriate content of effective warning maps, the content of text-based warnings has been a topic of interest for decades. Based on a review of public response to hazard warnings, Mileti and colleagues (Mileti and Sorensen, 1990, Mileti and Peek, 2000) developed a generic formula for effective warning messaging, specifying several crucial components, including the hazard and its consequences (*hazard*), the location and effective time of the warning (*warning location* and *time*), guidance for protective actions (*guidance*), and a credible source for the information (*source*). In the context of contemporary location-based SMS alert services, an experimental study by Bean et al. (2014) further reinforced the relative significance of communicating specific *hazard* and *guidance* information for motivating behaviours by facilitating risk personalisation and providing instructions for taking appropriate responses. Moreover, the study reported the advantage of comprehensive messaging (using 1380 characters) in yielding optimised warning outcomes when compared with brief messaging (using 90 and 140 characters), despite warning receivers' reduced satisfaction with the longer communications (Bean et al., 2014). However, the specific recipe for effective warning messages may vary within and across hazard types (Bean et al., 2014), and environmental, social, and risk perception contexts (Mileti and Sorensen, 1990).

With specific regards to wildfires, the Common Alerting Protocol Australian Profile (CAP-AU standard) stipulates the provision of *location* and *time* for each warning issued, along with information detailing the exact location of the fire and its likely impact, direction of fire movement, wind conditions, and time remaining before impact for a community (*hazard*), as well as guidance for protective behaviours (*guidance*). Other countries such as the U.S. often

deliver analogous text-based wildfire warnings encompassing a similar range of information, irrespective of the diversity in wordings.

In contrast to the comprehensive protocols available for the delivery of text-based warnings, a paucity of systematic guidance exists for the provision of effective warning maps, leading to large discrepancies in the content of existing maps used for public warnings: some warning maps only provide simplistic visual information, whereas others attempt to offer more enriched visualisation of the hazard and warning. Specifically, simplistic warning maps often focus on the visualisation of one selected aspect of information, such as those that provide cursory incident locations (*hazard*; e.g. Figure 6.1.*a*) *or* designated warning areas (location; e.g. NWS, 2008), serving as a supplement to textual warnings. However, the visual communication of only one warning element may not yield positive effects on warning comprehension and responses. For instance, the communication of *warning location* maps (i.e. depicting warning polygons) alone was found to result in erroneous risk interpretation and decisions (Ash et al., 2014, Lindell et al., 2015a), potentially ascribable to the inadequacy of the information provided for elucidating the spatial heterogeneity of the hazard and risk situation. Enriched visual warnings, on the contrary, often attempt to provide a relatively more comprehensive picture of the hazard and warning context by offering visual details regarding both the *hazard* and *warning location*. Yet, diversity continues to exist in the specific map content adopted for portraying hazards and warnings. For example, tornado warnings in the United States employ real-time radar imagery to provide visual evidence of the location and extent of advancing tornados (*hazard*), in association with warning polygons maps to delineate *warning locations* (NWS, 2008). By contrast, the 'cone of uncertainty' (COU) maps widely used for hurricane warnings provide an example of how maps are used to represent a more complex range of *hazard* and *warning location* related information, involving the current location of the tropical cyclone centre, its predicted track, statistical errors associated with the prediction, and warning polygons (NHC 2015). However, studies have identified the deficiency of both mapping approaches in providing appropriate information to facilitate comprehension and decision-making. First, Casteel and Downing (2013) demonstrated the

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lack of effectiveness of radar imagery in enhancing people's risk perception and motivating behaviours, raising the question of how useful this information is in warnings. Furthermore, the communication of prediction uncertainty in COU maps was found to result in confusion and misinterpretation of areas that may be impacted (Broad et al., 2007), warranting re-consideration of the necessity of including probability information on hurricane warning maps. These discussions highlight the importance of identifying both the most useful information elements and the most useful method of their delivery for providing holistic, yet effective visual warnings. When supplying insufficient or inappropriate visual information, warning maps may have no added, or even adverse effect on public's comprehension and responses when compared to text based warnings.

In the specific context of wildfire warnings, much of the information identified in the CAP-AU standard for text-based warnings is geographic in nature and *can* be visualised using maps. Specifically, Cao et al. (Under revision) identified seven spatial elements from typical Australian textual wildfire warnings following the CAP-AU standard, including: 1) fire location/perimeter (*hazard*), 2) fire suppression status (i.e. location of active/contained fire edge; *hazard*), 3) current and forecast wind condition (*hazard*), 4) predicted fire movement (*hazard*), 5) fire warning areas and associated warning levels (*warning location*), 6) closed roads (*guidance* for evacuation), and 7) evacuation centre locations (*guidance* for evacuation). Analogous to the diverse visual warning approaches used for other hazards, maps currently used for wildfire warnings have adopted varied selections of these seven spatial information elements but not necessarily all. For instance, the California Fire Map provided by CAL FIRE (2016) delivers both cursory wildfire locations and accurate fire perimeters (element 1); and the VicEmergency and Alert SA supplied by two Australian state agencies (EMV 2015, Government of South Australia, 2015) provide maps of warning polygons (element 5), fire perimeters (element 1) and wind conditions (part of element 3). However, a search of scholarly literature to date has unearthed a paucity of research examining the effectiveness of existing wildfire warning maps for eliciting appropriate public responses, or contemplating

which of these spatial information elements are important and *should* be included in map-based warnings to facilitate decision-making.

6.3 Usable map interactivity designs for information access

Web-based mapping technologies allow for active control of spatial information through interactive displays (Crampton, 2002). Fundamental functions of interactive maps include the ability to search locations, turn map layers on and off, zoom in and out and pan across a map view, retrieve additional information pertinent to particular features, and measure distances (Steinmann et al., 2005). Whilst the general public's ability to use interactive maps is mediated by experience, expertise, motivation, and spatial cognition, interactive features can be designed in a way that caters to a wide audience with varying abilities (Roth, 2013). Generally, interactive maps designed for novice and non-expert users should follow several heuristics, including simple functionalities (Roth and Harrower, 2008), intuitive presentation of information (Hagemeier-Klose and Wagner, 2009), and flexibility to support a diversity of users' habits (Nivala et al., 2008, Roth and Harrower, 2008). Moreover, an introduction to interactive controls, or short training, was found to have a significant influence in enhancing people's ability to use sophisticated mapping tools (Andrienko et al., 2002). Whilst training of general users on the Internet is challenging, adequate 'tool usage' instructions delivered through effective interface design, such as tooltips and explanatory text (Roth and Harrower, 2008), may heighten users' ability to interact with advanced functionalities. In the context of hazard risk visualisation, a particular challenge is the presentation of data at a scale that captures the extent of the hazard 'footprint' whilst allowing for individual contextualisation (Lieske, 2012). For instance, a regional flood map often conceals local information related to one's particular location, preventing risk personalisation (Lieske, 2012). Theoretically, this problem can be alleviated through interactive manipulation of map scales enabled by web-based applications (Lieske, 2012); however, empirical evidence regarding user ability to personalise risk through dynamic map viewing is currently lacking.

6.4 Individuals' decision-making and response to wildfires in the Australian context

In this section we present an overview of Australian wildfire management and the Australian public's likely response in case of wildfire emergencies to provide the context for which the wildfire mapping application presented in this study was designed and evaluated. Australian wildfire management is renowned for its unique national policy which directs citizens to decide between staying and actively defending their property and leaving early when a wildfire threatens (Tibbits et al., 2008). Both actions can ensure the safety of humans, but can be significantly dangerous if not conducted appropriately. Specifically, evacuation at the last minute has accounted for significant wildfire fatalities in Australia (Haynes et al., 2010), and staying and defending without adequate preparation is likely to result in failed defence, leaving the defenders in severe peril (Tibbits and Whittaker, 2007, Handmer et al., 2010, Cao et al., 2016). The national policy therefore stresses the importance of establishing a 'fire-plan' with an explicit decision between the two response strategies at the start of a wildfire season (Llewellyn, 2012). Moreover, adequate preparation and planning beforehand is crucial for assuring safe execution of an intended action (Llewellyn, 2012). For instance, those who plan to leave early are requested to assemble an emergency kit as well as specify a trigger for evacuation, such as the issuance of a severe weather warning (e.g. CFA, 2013b); those who plan to stay and defend need to make sufficient physical and psychological preparation for actively defending their property throughout a wildfire, coupled with contingency plans for when defence fails (Llewellyn, 2012). Ideally, with explicit and adequate planning, householders can be prepared for various emergency scenarios, and make easy, timely and safe decisions regarding either leaving early or staying and defending when a prospective wildfire threat is identified.

In reality however, whilst many Australian citizens have alleged a 'fire-plan' to either 'stay and defend' or 'leave early', the planned actions are often not adequately deliberated or prepared. Specifically, research has found that many of the individuals who plan to leave early

are unable to identify an explicit trigger for evacuation prior to an emergency (McLennan et al., 2015). Those individuals are therefore likely to not enact prompt evacuation upon receiving a warning. Rather, they often demonstrate a desire to assess the fire situation and contemplate whether, and at what point, evacuation is warranted, resulting in delayed evacuation (Tibbits and Whittaker, 2007). In a similar vein, many of those who have decided to stay and defend are found to not be fully committed to active defence, and they intend to evacuate if they 'feel threatened', such as when a possible passage of fire front is identified (Tibbits and Whittaker, 2007, p.289). However, without sufficient information, it is difficult, if not impossible, for residents to make an accurate assessment of the prospective fire threat at an early stage. Those who plan to stay and defend until they feel threatened thus are essentially planning to wait before making a final decision, and are likely to evacuate late, when it is no longer safe to do so (Tibbits and Whittaker, 2007).

Moreover, an appreciable proportion of Australian residents are found to not be able to make an explicit choice between 'staying and defending' and 'leaving early' prior to an emergency (Heath et al., 2011, McLennan et al., 2015, Trigg et al., 2015b). Many communicate a plan to 'wait and see', and intend to leave the decision to the day of an event (Rhodes, 2007a, Whittaker et al., 2010, McLennan and Elliott, 2012, McLennan et al., 2015). However, when a potential wildfire threat is identified, those residents often still cannot make the decision (McLennan, 2014). Such a reluctance, and/or difficulty, in deciding between 'staying and defending' and 'leaving early' is driven by residents' desire to both save properties and protect the lives of family members (McLennan and Elliott, 2012, McNeill et al., 2015). McLennan (2014, p.5) hence has characterised the response of these types of residents in wildfire events as 'wait, seek more information, and hope for the best that the fire will not impact their property and they will not have to make a choice'.

In summary, a deficient 'fire-plan' prior to an event, meaning either an underprepared plan to 'stay and defend' or 'leave early', or a deliberate plan to 'wait and see', entails a complex psychological process of contemplation and decision-making for implementing the 'fire-plan'

when a wildfire actually strikes. This often results in delayed decisions and responses, putting residents in significant peril. Therefore, given the inadequacy of many Australian residents' fire plan, effective warning information is critical for aiding decision-making during a wildfire event. However, specific needs tied to warning information may vary by individual and intended action (i.e. 'staying and defending', 'leaving early', or 'waiting and seeing'), as each approach requires a unique type of situational reasoning and decision-making. Guided by this assumption, the current study sought to identify the most important information elements for providing effective map-based wildfire warnings for people with various fire-plans. Details of the methodology are introduced in the next section.

6.5 Method

To understand what constitutes an 'effective' map-based warning approach, a preliminary wildfire mapping tool was prototyped and evaluated. A formative evaluation approach (Kaplan and Maxwell, 2005) was used to identify how the mapping tool could best be designed to achieve the goal of facilitating individual decision-making and easy information access. Specifically, the evaluation focused on exploring the important information elements to be communicated, and identifying optimal design characteristics for presenting warning information through an interactive mapping interface. In the following we introduce the prototyped tool and evaluation procedure in detail.

6.5.1 The prototyped mapping tool

The wildfire mapping tool prototype was designed to serve as a comprehensive portal for citizens who prefer the visual communication of wildfire warning information. 'Comprehensiveness' was achieved by supplying an inclusive array of information (Table 6.1) identified from examples of text-based warnings currently disseminated across Australia. The information content first included spatial information elements identified by Cao et al. (Under revision) concerning *hazard*, *warning location*, and response *guidance* (Table 6.1). Results from Cao et al. (Under revision) suggest however, that a combination of appropriately

Table 6.1 All the spatial and non-spatial information elements provided by the prototyped wildfire mapping application.

Element ID	Name of information element	Presentation method
Spatial Information		
Hazard		
1	Burnt area	Map
2	Number of hectares of burnt area	Static text annotation on the map of burnt area
3	Fire origin	Map
4	Fire control status (i.e. active and contained fire edges)	Map
5	Description of fire control status (i.e. 'the fire is currently out of control')	Text in the legend of the map of fire control status
6	Wind now	Map
7	General description of current wind direction and speed	Text in the legend of the map of wind now
8	Wind forecast in XX hours	Map
9	General description of forecast wind direction and speed in XX hours	Text in the legend of the map of wind forecast
10	Fire spread estimation	Map
Warning location		
11	Warning areas	Map
12	Description of warning areas	Dynamic text annotation next to the map of warning areas
Response guidance		
13	Closed roads	Map
14	Description of closed roads	Dynamic text annotation next to the map of closed roads
15	Evacuation centres	Map
16	Description of evacuation centre (names and addresses)	Dynamic text annotation next to the map of evacuation centres
Personalised information		
17	One's home	Map
18	Distance from the nearest fire front to one's home	Text in the table of map layers beneath the title of the corresponding fire
Non-spatial Information		
Hazard		
19	Fire Danger Rating in one's area	Graph and text in a separate information section, and details accessible through a hyperlink
Response Guidance		
20	Action advice for one's associated warning areas	Text in a separate information section, and details accessible through a hyperlink
Basemap		
21	Google street map	Map
22	Google satellite map	Map
23	Google terrain map	Map

designed map elements and text based descriptors may provide for an optimal communication strategy. Therefore, the prototyped mapping tool adhered to these design characteristics by coupling spatial information elements (e.g. burnt area represented using a map in Table 6.1) with text-based descriptors (e.g. number of hectares of the burnt area in Table 6.1). The map representations of spatial warning information were designed based on the most effective symbols and design principles identified by Cao et al. (Under revision).

In addition to the spatial-related *hazard*, *warning location*, and response *guidance* information communicated in current text-based warnings disseminated across Australia (Table 6.1), the prototyped mapping tool delivered two additional pieces of spatial information, namely a map-based indicator of the user's home and text-based descriptions highlighting the distance from the user's home to the nearest fire front (i.e. *personalised information* in Table 6.1). The user's home was mapped based on an address search and depicted by marking the location using a blue house symbol. The marked location was used to centre the map view, with the map scale adapted to show details of the local extent whilst ensuring the inclusion of all necessary wildfire information. The distance between the nearest active fire edge and the marked location was then calculated and displayed to the user.

In addition to spatial information elements, the prototyped mapping tool also conveyed non-spatial information delivered in Australian text-based warnings, including Fire Danger Rating (FDR) and specific action advice provided for areas under warning (Table 6.1). The FDR information is provided to indicate fire weather severity, and can be related to one's decision to 'stay and defend' or 'leave early'. That is, under severe FDRs, agencies' recommendation is that 'leaving early' is a safer option, and those with a plan to 'stay and defend' need to re-evaluate their decision (DFES, 2015c). The action advice provided by wildfire warnings often suggests the appropriate timing (e.g. immediately) for activating one's fire plan (i.e. 'staying and defending' or 'leaving early'). Notably, the prototyped wildfire mapping tool aimed to provide personalised FDR and action advice information by identifying and presenting information associated with one's search location (Table 6.1). Finally, several Google base-

maps were provided to users during the assessment process (Table 6.1) to help identify

preferences. These included the Google Street Map as a default background, and the Google

Satellite Image and Google Terrain Map as options.

The prototyped tool also allowed for fundamental interactive functionalities such as address

search and map manipulation as supported by Google Maps, control of map layer visibility,

retrieval of text-based descriptors through callout boxes enacted by clicking on pertinent map

features (see footnote for Figure 6.2 for more details). The web-based mapping tool (Figure

6.2) was prototyped using open source web-GIS development tools including OpenLayers

(2015; version 2.13.1) and GeoServer 2.4.4 (2015; version 2.4.4).
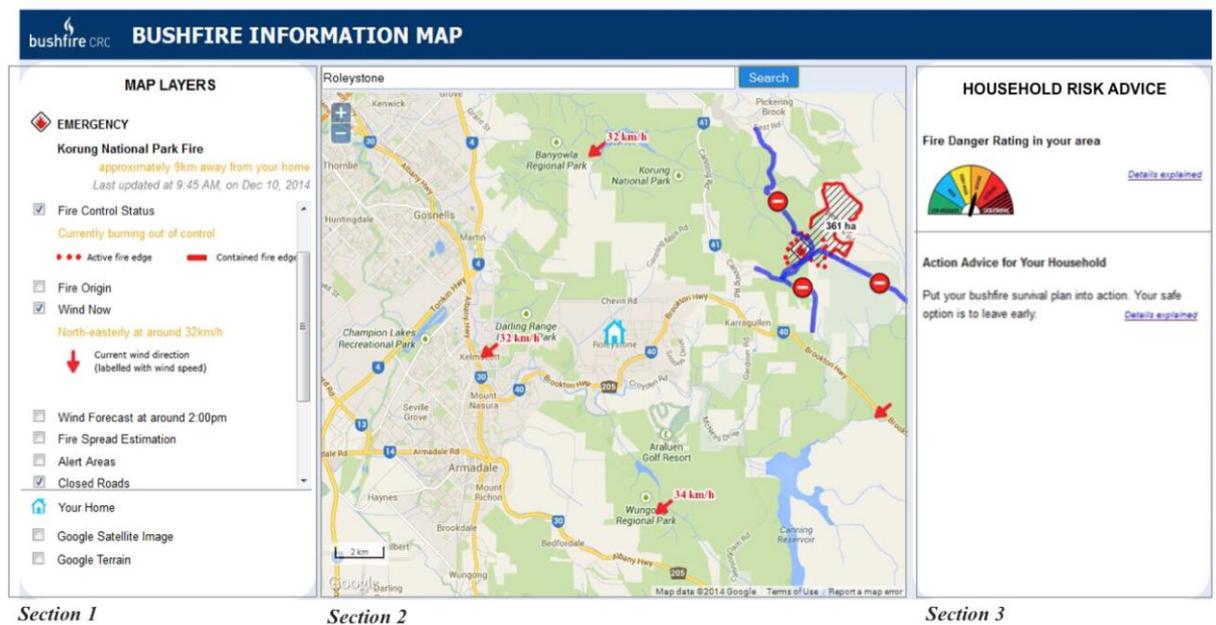
Figure 6.2 A screenshot of the prototyped interactive mapping tool used for communicating wildfire warnings. The interface contains three sections: a map table of contents (*section 1*) and a map view section (*section 2*) conjointly showing information elements 1-18 and 21-23 (Table 6.1), and a Household Risk Advice section showing information elements 19 and 20. Interactive control of map visibility allowed for the presentation of all wildfire related map layers and the two additional base maps (i.e. Google Satellite Image and Terrain Map). In the current image, three wildfire related map layers are visible on the map: fire control status, current wind conditions, and closed roads. Textual descriptors associated with the spatial information elements are shown in the map legend or as map annotation. *Personalised* spatial information (Table 6.1), including the map of a user's home and its distance to the nearest fire front, is automatically shown following the search of one's address: the legend of the former is shown in the map table of contents, and the latter is presented in text under the name of the fire at the top of the same section.

6.5.2 Participants

Participants for the current study were elicited from respondents of a previous survey-based study conducted in three wildfire prone suburbs within Western Australia (Cao et al., Under revision). Out of those previous respondents (N = 264), 168 survey respondents expressed an interest in engaging in a subsequent interview study through a question asked at the end of the survey. The final interview sample was selected from these survey respondents. With an

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intention to identify varied information needs by residents with distinctive fire plans, a purposive sampling approach was adopted to obtain a mixed sample involving residents with different fire plans. The survey responses revealed that 28.9% of the previous survey participants (N = 235[3]) planned to 'defend as much as they can but leave if it's too severe', and 41.7% planned to 'stay and defend or leave early depending on the day,' both indicating a strategy to 'wait and see'. Furthermore, 10.2% of the survey participants planned to 'stay and defend throughout the fire', 13.2% planned to 'leave early', and the remaining 6.0% did not identify a plan. To represent the distribution of fire plans revealed by the survey responses, 12 survey respondents with a plan to 'defend as much as they can but leave if it's too severe' (representing those who plan to 'wait and see'), six participants with a plan to 'stay and defend throughout the fire' and six participants with a plan to 'leave early', were approached, resulting in 24 interview participants. In addition, each group was sampled to contain a mixture of rural and urban residences, with different gender, education levels and e-map use habits, to represent the population with varied characteristics. Out of the 24 sampled interviewees, 21 consented to participate, and their demographics are demonstrated in Table 6.2.

Table 6.2 Demographics of the 21 interviewees**.**

	Total = 21
Male, *n (%)*	10 (48%)
Mean age, *yr (SD)*	54 (8)
Residence, *n (%)*	
Rural	10 (48%)
Urban	11 (52%)
Education level, *n (%)*	
University degrees	13 (62%)
Trade certificate/diploma	5 (24%)
School qualification	3 (14%)
Frequency of using computers, *n (%)*	
Daily	20 (95%)
2-3 times a week	1 (5%)
Frequency of using digital maps (e.g. Google Maps, navigation systems)	
More than once a week/daily	9 (42%)
≤ once a week	6 (29%)
≤ once a month	6 (29%)

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[3] The number does not equal to the total number of survey respondents (i.e. 264) because some participants did not respond to the question regarding their 'fire-plan'.

6.5.3 Test scenarios

As an individual's decision-making may differ under different emergency circumstances, three test scenarios were devised to simulate three escalating wildfire warning levels currently employed within Australia (Advice, Watch and Act, Emergency – in order of escalation). The mapping tool presented information for each scenario that corresponded with fire characteristics associated with each warning level (National Bushfire Warnings Taskforce, 2009, Table 3). One of the three test scenarios was randomly assigned to each participant, whilst ensuring that an equal number of participants were provided with each of the three test scenarios respectively within each fire plan group (i.e. 'wait and see', 'stay and defend', or 'leave early').

Table 6.3 Specification of the simulated scenario for each warning level

Warning level	Distance between the fire and one's home	Estimated time to reach one's home	FDR in one's area	Current wind speed	Forecast wind speed in 4 hours	General action advice
Emergency	4 – 7 km	0-4 hours	Severe	42-45 kph	50-52 kph	It is too late to leave.
Watch and Act	8 – 11 km	4-8 hours	Severe	32-35 kph	40-42 kph	Leave immediately or prepare to stay and defend.
Advice	15 – 20 km	12-16 hours	High	23-25 kph	30 -32 kph	Stay informed and prepare to activate your fire plan.

6.5.4 Interview procedure and usability tasks

The study adopted a formative evaluation approach to identify the important information elements and optimal interactivity design by observing and analysing users' interaction with the prototyped mapping tool (Hix and Hartson, 1993). A set of tasks was designed and used to

guide and prompt participants' navigation through the tool whilst engaging in a semi-structured interview, in order to explore whether the objectives of 'effectiveness' were met (Gabbard et al., 1999). Verbal protocol analysis (VPA), a means of capturing user experiences as participants "think aloud" (Ericsson and Simon, 1993) was employed throughout the interview process to assess user needs and expectations as they 'talked through' their interactions (Nielsen, 1993, Gabbard et al., 1999).

The semi-structured interview procedure comprised four sections. In the first section, participants were asked to complete three sub-tasks including: 1) finding your home on the map; 2) identifying the fire's location in relation to your home (how far it is from one's home, and how the fire might threaten one's property); and 3) making an evacuation plan by identifying at least one safe destination and egress route. The completion of the three sub-tasks required an exploration of all information presented in section 1 and 2 of the mapping tool (Figure 6.2). In cases where participants overlooked certain information elements, their user behaviour was recorded, followed by a prompt to explore the missed information.

The second portion of the interview began with participants reviewing the FDR for their area, and the suggested protective actions for the corresponding warning level (i.e. section 3 of the mapping tool as shown in Figure 6.2). This was followed by questions focused on the particular wildfire scenario that had been presented to them: 'in this current mock scenario, how do you intend to respond to the wildfire now?'. Participants were given time to re-familiarise themselves with the scenario they were presented with, and were then asked to describe the protective action they would take and explain the reason for their decision, highlighting the information elements their decision was based on. Participants' perception of the threat in relation to their own home was ascertained during this section of the interview if not voluntarily communicated by a participant in order to help understand the decision-making process. This was achieved by asking two final questions: 'on a scale from 1 to 7, how likely is it that the fire will impact your property and why do you believe this?,' and 'on a

scale from 1 to 7, how severe do you think the impact will be if the fire does reach your property and why?'.

In the third section of the interview, participants were given a stack of index cards, each representing one of the 23 information elements shown on the mapping tool (Table 6.1), and were asked to rate the importance of each on a Likert scale from 1 to 5 (5 = critical, and 1= not important at all). Following the rating of each information element, the participants were prompted to explain their rating, if the usage of the information element for one's decision-making had not been discussed during the previous interview sections. In the final section (section 4), participants were asked a series of demographic questions and asked to indicate their self-rated wildfire knowledge, their level of household preparedness, and their past fire experience.

Individual interviews were conducted in a private room at local community centres, and took approximately one hour. Participants were informed about the location and duration of the interviews, and permission was obtained prior to the interviews. Each interview was video and audio recorded, with one web camera in front of the participant for recording facial expressions and audio, and one camera behind the interviewee recording laptop use patterns.

6.5.5 Data analysis

The audio recordings of the 21 interviews were first transcribed. The video recordings were then examined to identify user interaction with the mapping tool. Interactions were documented in words. A scissor-and-sort technique (Stewart and Shamdasani, 2014) was employed to analyse the qualitative interview content by identifying sub-themes, establishing a coding schema, and grouping and analysing similarities and differences in participants' responses to address the research questions. Specifically, the qualitative interview content was analysed in relation to the two research questions respectively. The first research question, i.e. what information should be included in a wildfire warning mapping tool to facilitate individual decision-making, was addressed by understanding participants' rationale for using

the heterogeneous information presented and making decisions in response to the advancing wildfire. The second question, i.e. how an interactive mapping interface can best be designed to present this information to ensure usability and ease of information access, was informed by observing participants' interaction with the mapping application in completing each task. The specific themes that emerged and were coded for the two research question are introduced in the next section. In addition, the third section of the interview process also yielded quantitative results regarding the importance of each information element as subjectively rated by the participants. This data was used to complement the qualitative results in understanding the significance of the content delivered by the prototyped wildfire warning mapping tool.

6.6 Findings and Discussion

Generally, all participants complimented the mapping application for how informative, comprehensive, explicit and visually efficient it was:

> *When you read (textual) information, you got to stop and visualise it, you have to imagine where the roads is, so this is really quick and easy, and you can choose what information you want.*
>
> *(Subject 8, female)*

> *To me, the most important is to have all the information on the map. Because you can have too much text, and it's too hard to correlate information and link ideas from one paragraph to something said somewhere else down here, or across different pages. So to me, map is one way of having all the information clear, all in the same place at the same time.*
>
> *(Subject 10, male)*

Interestingly, the only participant who declared her general dislike of maps and abstract visual communication at the beginning of the interview, reversed her attitude after exploring the mapping application:

That (the interactive mapping tool) is far far better (than textual warnings). There is so much information there to help you make decisions. And it's far more informative than those text messages. So that is mindset changed when I looked at that.

(Subject 17, female)

However, as results from the study by Cao et al. (Under revision) suggested, participants' subjective preference may not align with objective measurement in indicating warning effectiveness. Therefore, we strongly focused on the objective findings regarding participants' usage of the information supplied by the prototyped mapping application for decision-making, and their interaction with the mapping interface for information accessing.

6.6.1 Content for facilitating decision-making

Qualitative results

Participants' description regarding how to respond to the mock wildfire scenario in the interviews revealed three different types of logical approaches to decision-making. These decision-making approaches were linked to participants' response intention: many intended to delay their decision deliberately as they experienced difficulties in making an explicit choice between staying and defending and leaving early at an early stage, and their decision-making approach was identified as '*indecisive*'; some participants were found to have a commitment to defending their property against any possible threat, and their decision-making approach was categorised as '*committed defending*'; the remainder intended to evacuate the property well before the fire threat without attempting to defend their property, and their decision-making approach was categorised as '*committed leaving*'. When comparing these approach categories to participants' alleged 'fire plans' as stated in the previous survey study, the interview results exhibited that participants' decision-making characteristics in the face of an impending threat were generally consistent with their alleged 'fire-plans' (Table 6.4).

Table 6.4 Number of interviewees adopting the three different logical approaches to decision-making in the face of the simulated wildfire threats in comparison with their alleged fire plans

Logical approaches to decision-making adopted in the interviews	Fire plans			*Total*
	Do as much as possible to defend their property but leave if the fire threat becomes too severe	Stay and defend throughout the fire	Evacuate the property well before the fire threatened their home without attempting to defend their property	
Indecisive	10	2	X	*12*
Committed defender	1	2	X	*3*
Committed leaver	X	X	6	*6*

Due to distinctive response intentions, the three types of decision processes demonstrated varied usage of the wildfire warning information presented. First, the '*indecisive*' decision makers, with a reluctance to make an early decision, often intended to wait and closely monitor the specific fire location and condition prior to enacting any response. Such an intention was often driven by two reasons: the first was a desire to protect their home from embers despite a lack of sufficient physical or psychological preparedness for defence against an intensive ember attack or a massive fire front; the second was a perception that late evacuation would be safe and one or more evacuation routes would be available. These two reasons contributed collectively to a decision to wait and see whilst defending against small embers and leaving when 'it is really necessary'. However, decisions regarding the 'necessity' for evacuation were essentially subjective judgements of how severe an ember attack might be or the likelihood of a major fire front reaching their property. Moreover, the *indecisive* decision makers could only feel 'certain' about making such subjective judgements of fire threat severity when the fire reached into their close proximity due to their understanding of the capriciousness of wildfires. For instance, many indicated a plan to make the final decision to leave if the fire was to jump a major road (acting as a fire barrier) 1-3 km away from their home. Some mentioned the use of time related information provided by the fire spread estimation map to make an evacuation decision, such as leaving when the fire was predicted to

reach the property within 1-2 hours. However, most *indecisive* decision makers ignored the warning levels and action advice suggested by agencies.

> *So I would really want to see whether fire crews can contain the fire, especially because the wind is going to change to the east (based on the map of wind forecast). If it comes past the Brookton Highway (1.5km away), and the wind is going to change, it's going to blow it towards my house. But if it gets as far as Brookton Highway before the wind changes, it's going to blow north of it. So it is not going to burn directly in my direction. So I think that information (on the maps) would be useful for me. (It) would give me a great sense of confidence in my own decision-making process when that information is visually available like this. I think again text is rubbish.*
>
> *(Subject 4, Male)*

> *I guess what I kept seeing here is estimated time 0-4 hours (based on the map of fire spread estimation). So if I've got everything ready to go, if my wife and daughter have fled, it's really just me deciding to leave. When I look at this map, I can see my escape routes. There are three main routes (I can take). I will probably wait until I was told the fire was an hour away, and make a decision then, because an hour gives me a lot of time. I don't know. I have to admit, when it came down to only one hour away, how do I decide it's worth staying or not?*
>
> *(Subject 15, Male)*

Second, with respect to the decision-making process shown by those in the category of '*committed defending*', the three committed defenders also identified a need to keep monitoring the fire situation for a purpose of obtaining a sense of 'timing' for getting prepared for active defence. They therefore depended on the information regarding the specific location of the active fire front, its distance to their home, and wind impact. In addition, two of the committed defenders intended to subject their decision regarding staying and defending to the

weather conditions on the day, and would abandon the plan of defence on a 'hot windy day', suggesting the importance of communicating FDR levels.

Finally, the decision-making process shown by those in the category of '*committed leaving*' was one that focused on deciding the timing of evacuation. A profound distinction was revealed in the reasoning concerning this decision across the six committed leavers, indicating their varied information needs. Specifically, one committed leaver demonstrated a high level of vigilance, attributable to a high level of perceived fire impact on human health and lives. Her plan was to leave as soon as the fire was 'close'. Simple awareness of an official suggestion of 'immediate evacuation' for her area stimulated a perception of the impact likelihood being 'definitive', and an intention to leave 'immediately'. With this said, the communication of fire location and predicted fire course provided essential knowledge regarding the safe egress routes or which side of the house would provide the safest shelter if it is too late to leave and she needs to shelter in place.

> *I don't care if my house burns down. To me it's just a house at the end of the day.*
>
> *(Subject 14, Female)*

The other five committed leavers, whilst intending to leave if there was 'any potential threat', were unlikely to be motivated to leave by simply receiving a warning suggesting 'immediate evacuation'. Rather, explicit communication of the fire location and predicted fire movement was essential to facilitate evacuation related decision-making. In their past experiences with fire, when such specific fire information was absent, most participants (4/5) drove around to ascertain the exact fire location and direction of spread. Generally, a fire 7-9 km away moving in the direction of one's home was sufficient to trigger an immediate evacuation. One participant also intended to use the time of impact related information indicated by the fire spread estimation to make his evacuation decision, as he intended to evacuate as soon as the fire was predicted to reach his home within 6 hours.

A further analysis of the information required for the three types of decision-making approaches revealed two distinctive patterns. That is, despite decision approach dependent differences in the use of information, a majority of the participants (18/21) mainly relied on *hazard* information such as the wildfire location, wind conditions, and fire spread estimations. The decisions of these 18 participants appeared to be partially informed by, but not necessarily steered by the *guidance* provided by emergency management officials. Rather, they tended to weigh their decisions on their own assessment of the *hazard* information, and hence were referred to as '*self-reliers*'. A closer examination identified that the majority of the '*self-reliers*' (15/18) only valued their own risk assessment, whereas the other three participants intended to use the *warning* and *guidance* as a general reference (Figure 6.3); however, when the self-reliers' own assessment of the *hazard* situation conflicted with what was suggested by the *warning* and *guidance*, the latter was overruled. Such self-reliance appeared to be caused by the mistrust of the warnings and action advice provided by officials, a sentiment ascribable to participants' perception of the warnings as being too general or inaccurate in describing a fire threat for one's specific location.

> *A lot of the alert information is sort of general. You think yeah, but what's happening to me now? What's happening to my house? You want to come and have a more detailed look.*
>
> *(Subject 8, Female)*

In contrast, a minority of the participants (3/21) trusted the *warning* and *guidance* provided by the agencies, and depended on such information for making their decisions (Figure 6.3). These three participants were thus categorised as '*advice followers*'. Upon viewing an agency's advice to 'leave immediately', all three participants desired to follow the suggestion. Still, it has to be noted that two of these participants were identified as '*indecisive*' in their actual decision-making (Figure 6.3). This indecision was caused by contradictory aspirations of their partners (both husbands) to 'always stay and defend', even though their partners were not present at the interviews.
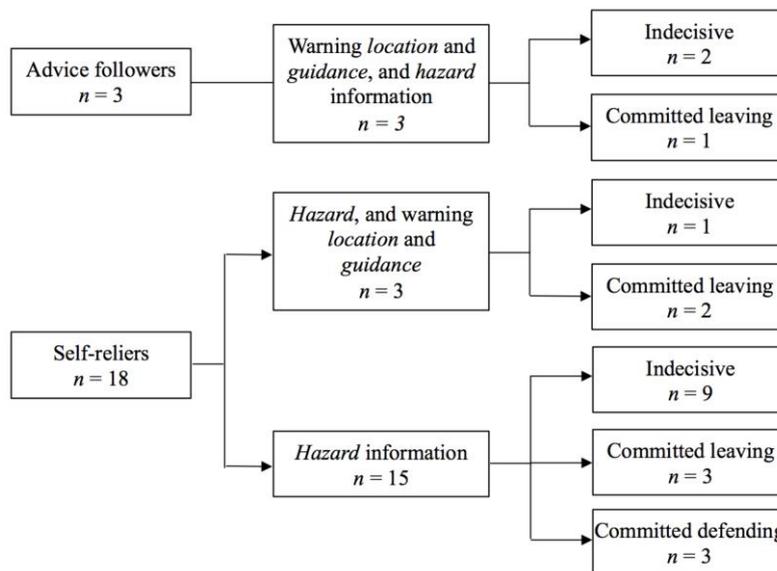
Figure 6.3 Diagram showing the needs of information by participants with varied types of personalities (i.e. *advice followers* and *self-reliers*), and their relationships with their decision-making types.

These general results regarding the information needs of interviewees suggest varied information prioritisation for different population groups. Specifically, warning levels for an individual's area and associated *guidance* should be prioritised for '*advice followers*', whereas *hazard* information involving specific locations of the active fire front and wind conditions should be prioritised for '*self-reliers*'. However, this does not mean an exclusion of *hazard* information for the former group, and *warning* and *guidance* information for the latter group. Rather, relative prominence of the presentation of the information may be deliberated on the account of its relative importance. For instance, *warning* and *guidance* for one's area may be promoted as the first elements through the warning interface for '*advice followers*'. For '*self-reliers*', the map of warning areas may be supplied as an optional map layer or replaced by a text-based description of the warning level for an individual's area to reduce visual complexity, as the visual specificity regarding the general warning area did not impact participants' decisions.

Furthermore, a closer examination of the usage of *hazard* information by '*self-reliers*' exhibited differences in their reliance on the map for fire-spread estimation. Specifically, only four of the 18 participants used the fire-spread estimation to identify evacuation triggers. The other participants (14/18) used the hazard information depicting the known wildfire conditions, including the existing wildfire locations, and current and forecast wind conditions, but did not use the fire spread estimation for making evacuation decisions. Many did not completely trust the modelled prediction, due to the uncertainty (i.e. the 4-hour time window) it comprised. Some participants also were concerned with its accuracy, and would trust their own assessment of 'time' more than the modelled results. Nevertheless, it was found that participants' self-assessment were not always accurate. For instance, a number of participants ($n = 5$) mistook the wind speed as the speed of fire spread and used it to infer the time of fire arrival for their location, resulting in significant errors. This indicates that appropriate communication of the primary hazard information concerning the wildfire location and wind condition is vital, particularly for '*self-reliers*', whereas fire spread estimations may also be necessary to aid accurate interpretation of the situation.

It can be seen from Figure 6.3 that there appears to be a relationship between decision-making types and one's personality in terms of information needs. Specifically, committed defenders were likely to be '*self-reliers*'. By contrast, committed leavers and indecisive decision makers were either '*self-reliers*' or '*advice followers*'; however, a majority of the participants in these two decision-making categories (5/6 committed leavers, and 10/12 indecisive decision makers) were '*self-relieres*'. Furthermore, as people's decision-making type was closely related to their prior fire plans (Table 6.4), the implication is that people's 'fire-plan' may be an indicator of their warning information preferences. For instance, all four participants who alleged a plan to 'stay and defend throughout the fire' in this study were identified as '*self-reliers*'. Since two of them were labelled as indecisive decision makers and the other two were labelled as committed defenders based on the interviews, initial fire plan thus seemed to be a more consistent indicator of their information preferences than their expressed action plan in response to the fire scenario (Table 6.4). However, a fire-plan to 'evacuate well before the fire

threatened one's home' and one to 'do as much as possible to defend one's property but leave if the fire threat becomes too severe' may not be as accurate in predicting an individual's warning information preferences, as participants with those two fire-plans were identified as either '*self-reliers*' or '*advice followers*' based on the interviews. Results from this study revealed that other demographic and psychological factors may conjointly serve to better indicate one's needs for warning information, such as gender, desire to save house, and influence of partners' contradictory decision. If identified and validated by more large-scale studies, these indicators of an individual's warning information needs can be employed to provide personality dependent warnings by supplying and/or underscoring the desired and effective information elements for different types of residents through the mapping interface.

Subjective ratings of information importance

Given the small sample size of this study, participants' quantitative ratings of the importance of each information element was interpreted using their descriptive values, rather than through statistical analyses. The quantitative results (Table 6.5) were generally consistent with the patterns revealed by the qualitative findings. First, most maps providing information on the *hazard* itself were rated as critical (mean ratings >4.5 on the 1-5 Likert scale) with strong inter-rater agreement (IRA > .7; see the footnote of Table 6 for more details). The maps of current wind (mean rating = 5) and locations of active and contained fire edges (mean rating = 4.9) provided the most imperative information. The map of forecast wind was relatively less important (mean rating = 4.7), as several participants were concerned with its accuracy and uncertainty. Sharing similar problems, the map of fire spread estimation (mean rating = 4.6) was also considered as relatively less important. Furthermore, the maps of burnt area (mean rating = 3.9) and fire origin (mean rating = 3.2) were deemed as not important, and may be excluded from the mapping tool. This is because the map of active and contained fire edges demonstrated in the study also depicted the fire shape and provided more accurate fire location information.

Table 6.5 Mean ratings of the importance of each information element (on a Likert-scale of 1-5, anchored by 1 = not important at all and 5 = critical), and the associated inter-rater agreement (IRA), listed in descending ordered by the mean rating.

Element ID	Name of information element	Mean rating	IRA (r_{wg})*
6	Map of current wind	5.0	1.0
4	Map of active and contained fire edges	4.9	0.9
13	Map of road closure	4.8	0.9
17	Map of one's home	4.8	0.8
21	Google street map	4.7	0.9
8	Map of wind forecast	4.7	0.9
18	Approximate distance from the fire to one's home	4.6	0.8
5	Description of fire control status	4.6	0.8
10	Map of fire spread prediction	4.6	0.8
11	Map of warning areas	4.3	0.7
20	Action advice for one's area	4.1	0.5
1	Map of burnt area	3.9	0.5
7	Description of current wind	4.0	0.6
9	Description of forecast wind	4.0	0.6
14	Description of closed roads	3.9	0.7
15	Map of evacuation centre	3.7	0.3
16	Description of evacuation centre location	3.5	0.2
19	FDR in one's area	3.5	-0.1
12	Description of alert areas	3.4	0.5
22	Google satellite map	3.3	0.2
3	Map of fire origin	3.2	0.4
2	Number of hectares of burnt area	3.0	0.3
23	Google terrain map	2.2	0.5

* IRA analysis is used to test the absolute agreement among human judges for rating a subject (Richardson 2010). In this study the r_{wg} index (c.f. James et al., 1984) was calculated for the ratings of each information element. As suggested by (LeBreton and Senter, 2008), a r_{wg} > .7 denotes a strong agreement, between .5 and .7 denotes a moderate agreement, between .3 and .5 suggests a week agreement, and < .3 suggests no agreement.

Second, consistent with the qualitative findings, the map of warning areas (*location*) was rated as important (mean rating = 4.3), but less imperative than many of the *hazard* maps. Moreover, the IRA measurement (= .7) showed a relatively higher degree of discrepancies in participants' sentiments towards the importance of the *warning location* map in comparison to the *hazard* maps (IRA ≥ .8 for maps of current wind, active and contained fire edges, wind forecast, and

fire spread prediction). Third, *personalised* information, including the map of an individual's home (mean rating = 4.8) and the calculated distance (mean rating = 4.6), was considered important. During the interviews, a number of participants expressed their preference for such information as it significantly facilitated contextualisation of the fire and warning information. Fourth, most participants regarded the map of closed roads as critical (mean rating = 4.8), as it 'comes in handy' for planning evacuation routes, especially when the wildfire is nearby and surrounding roads are affected. In contrast, the map of evacuation centres was not as valued by the participants (mean rating = 3.7), as most identified they would not use the facility. Finally, the detailed action advice communicated in text form was generally rated as important (mean rating = 4.1), but with a higher importance rating by '*advice followers*' (= 5.0) than by '*self-reliers*' (= 3.8), resonating with the previous discussion regarding their divergent information needs. The other non-spatial information element, namely FDR for one's area, was not viewed as an indicator of the potential fire severity by most participants, resulting in a low mean rating.

Additionally, with regard to the textual descriptors of the mapped information, most descriptors were identified as not imperative except the description of fire control status. As Cao et al. (Under revision) identified, the narration of 'out of control' provided irreplaceable meaning for people to attain a sense of urgency. Finally, out of the three background maps evaluated, most participants indicated that Google Street map provided sufficient and explicit contextual information (mean rating = 4.7).

6.6.2 Interactive interface design for information accessing

In addition to the identification of important information for inclusion in a wildfire warning mapping tool to facilitate decision-making, the interview results were also analysed to understand what constitutes an optimal design of an interactive mapping interface for easy usability and information access. Generally, participants in the interviews all demonstrated fundamental capability in using the interactive features of the mapping tool. However, several issues presented themselves throughout participants' performance of the different tasks, which

hindered the access to and understanding of certain information elements by some participants. An analysis of these issues revealed five themes: a) address search; b) access to map layers; c) access to non-visual information via the mapping interface; d) map scales; and e) prior education. Specific results for each sub-theme are discussed below.

Address search

The first testing task was to identify one's home on the map. Upon this request, approximately half of the participants (12/21) found and used the address search bar to complete the task, whilst the others (9/21) attempted to pinpoint their location on the map by manipulating map scale and extent and identifying familiar landmarks. After being prompted with the alternative search option, four of the nine participants who did not originally use the search function expressed favour for the function, whilst the remaining five participants preferred the manual search solution due to lack of trust in the accuracy of the automatic search function.

In addition, six of the participants who liked the search function ($N = 16$) did not enter their full street address (e.g. omitting street number or suburb name), and five expected a drop-down list of matching options while entering their address, a technique employed by Google Maps. As suggested by Nivala et al. (2008), flexible functionalities are needed to cater to varied users' needs. In this specific context, accurate address searches are critical for risk comprehension and personalisation. Therefore, complete address search may be prompted and mandated by the system through appropriate design to preclude inaccurate mapping of one's home.

Access to map layers

The prototyped mapping tool allowed users to turn map layers on and off by clicking on the corresponding checkboxes in the map table of contents. Associated legend was also shown in the map table of contents when a map layer was turned on (Figure 6.2). A majority (17/21) of the participants instinctively turned map layers on and off to complete the second task in the

interviews, i.e. to identify the fire's location in relation to one's home, how far it was from one's home, and how the fire might threaten one's property. However, with nine optional map layers communicating the wildfire situation, several participants (6/21) did not examine one or more layers during the initial exploration. This is potentially caused by the excessive length of the map table of contents when three or more map layers are turned on, as the legend associated with each visible map layer is displayed. Such a lengthy map table of contents necessitates the use of the scroll bar to access the entire map list, which was not noticed by several of the participants.

Despite most interviewee's competence in turning on map layers to seek additional wildfire information, only six (6/17) were able to fluently manipulate map layer visibility. Many participants did not think about changing the layers' visibility when having difficulties in understanding the excessively overlaid maps. Three participants considered turning off certain layers, but forgot the names of the layers and could not identify them in the map table of contents.

These results thus suggest the need for several design principles related to the presentation of the map table of contents to facilitate users' access to the visual information. First, critical layers should be prioritised in the map table of contents, especially when the list of legends is likely to become lengthy and a scroll bar is inevitable. Second, closely related information should be combined as one layer, and indicated using intuitively understandable names. In the current case, the map of burnt area, fire origin, and fire control status (i.e. active and contained fire edges) could be amalgamated as one layer named 'fire location'. The current and forecast winds may also be integrated into one layer through proper symbology design and legend expression. Spatial information that is not critical to be visualised, such as the fire origin map identified in section 6.1, should be eliminated from the visual presentation.

Access to non-visual information

Five approaches were employed to deliver the diversified text-based information elements through the mapping interface: i) static map annotation; ii) dynamic map annotation accessible by clicking on a map feature; iii) description in map legend; iv) text in the table of content underneath the name of the fire; and v) text in separate windows accessible through hyperlinks. The information elements presented using each method are specified in Table 6.1.

It was found that method i and iii were both easy for the interview participants to use, whilst the other approaches were not. First, dynamic annotation in relation to a map feature through the callout box (method ii) was not noticed by a majority (15/21) of participants, despite the change from normal to hand cursor when hovering over the associated map features, which appeared during most participants' exploration procedure. After a demonstration by the interviewer, most participants liked this presentation approach. However, prominent tooltips are needed to showcase the functionality for novice users. Second, text information displayed under the title of the fire (method iv) showing the personalised distance and updating time (Figure 6.2), was largely neglected (19/21). Third, information displayed in a separate information window (method v) that was not identifiable through the main map interface, may have been difficult to access. In the interviews, such information, including the FDR and detailed action advice, was explained to the participants by the interviewers, rather than being voluntarily explored, meaning that the information was mandatorily accessed. However, several participants forgot where it was presented when they tried to re-access the information provided in the separate information window. Users' ignorance of the text information displayed with certain separation from visual content using method iv and v suggests that users are likely to focus on the visual features and directly adjacent elements (visual or textual) when interacting with a mapping interface. This implies the challenge in designing a balanced map interface to present and facilitate access to large amounts of both visual and non-visual information. One potential solution is to reduce the amount of visual and textual information that needs to be highlighted through the interface by identifying elements that are essential for users' decision-making, and present such critical information with prominence using the effective methods (e.g. method i, ii, and iii discussed above).

Map scale

Following an address search, the prototyped system would centre the map on that location and enlarge the map scale to 1:100,000. Such a scale was deliberately selected to include at least a part of the wildfire information associated with each map layer whilst displaying as much local detail as possible. This means an increment of the map scale by one level would result in potential exclusion of wildfire information in the displayed map extent. For instance, wind conditions were marked by dispersedly distributed arrows, simulating real weather data yielded by observation stations. An increase in map scale would thus carry the risk of not showing any wind arrows in the map. Given this design, the interviews revealed that more than half (12/21; male $= 7$, and female $= 5$)) of participants examined local details by zooming in on the map. Specifically, six of those participants attempted to confirm the accuracy of the automatic address search by examining the surrounding roads in a scale of 1:25,000 to 1:50,000, and eight participants sought more specific local context when interpreting wildfire risks in relation to themselves with a map scale of 1:10,000 to 1:50,000. When map layers such as wind conditions were turned on for the first time on an enlarged map scale, the information was likely to fall outside the borders of the visible map. In such cases, a majority of the participants intuitively reduced the map scale to look for information, whilst four participants did not realise the pitfall of enlarged map scales for information displaying, resulting in failed information access and profound confusion. In addition to the prevalent preference for large map scales, three other participants (3/21) were inclined to examine wildfire information on a small map scale displaying a regional area, despite the fluency they demonstrated in managing map scales. Such small map scales concealed details of both the local context and wildfire information, and hence hindered their understanding. Notably, one other participant (1/21) appeared to get lost whilst inadvertently changing map scales. The remaining five participants (5/21) stayed at the default map scale throughout the information exploration.

Evidently, users' access to wildfire information through interactive maps is subject to not only the displaying of a proper default map scale that includes all delivered information, but also an agile control of map scales to facilitate the exploration and interpretation of risk in a balanced local and regional context. In this study, eight participants (8/21) failed to access all information in an adequate manner due to misuse of map scales. These include four participants who preferred large map scales but failed to access all information, three participants who preferred small map scales and did not refer to local details, and one who lost the view of pertinent map extent as a result of amateurish map control skills. Consequently, mapping systems designed for warning communication should provide a prominent shortcut that allows for and promote users' accessing the default 'proper' map scale when necessary. Moreover, when mapped information is beyond the viewed extent, the system could furnish a warning to guide the users to search for the information by changing map scales. A more intelligent solution for displaying non-locational information such as wind conditions would be the dynamic placement of map symbols to ensure their inclusion in the viewed map extent at all times.

Prior education

In general, most participants were able to use the interactive features, including address search, information visibility and access controls, and map manipulation tools. Their competence in using these features were enhanced as the interviews proceeded, highlighting in some cases a need for prior education to familiarise users with such a mapping application. For instance, four participants who did not notice the address search function stated that relevant guidance upon initial entry into the system would help. Four participants described a feeling of being overwhelmed by the complex interactivities and 'did not know what to do' in the beginning, but felt comfortable accessing the map layers and manipulating the maps after introduction and practice. In an online environment, guided interactions should thus be implemented by providing tooltips, especially for novice users. If widely employed, the wildfire mapping

portal could be publicised so individuals can familiarise themselves with the tool prior to a real fire event.

6.7 Summary and Conclusions

The current study evaluated the use of a mapping application by residents in the face of simulated imminent wildfire threats for understanding and responding to warnings. The results shed light on how to effectively design map-based wildfire warning instruments to provide necessary and important information content through properly designed interactive mapping interfaces.

In respect to information content, the study results revealed that not all information elements were equally essential for participants' decision-making. Despite the participants' diverse wildfire survival plans and decision-making objectives, the following information elements were identified as generally the most important: i) the accurate location of active fires, ii) prevailing winds and potentially its forecast change, iii) closed roads, iv) a description of the fire control status (e.g. 'out of control'), v) the personalised mapping of one's home location, vi) calculated distance between one's home to the closest fire front, vii) warning levels for one's area, and viii) action advice provided by agencies for the designated warning areas. However, it was found that people's specific needs for information vary based on their personality. Specifically, most participants demonstrated a stronger degree of trust in their own risk assessment over suggestions by agencies, and they mainly relied on their own decision-making using the provided *hazard* information (aforementioned element i – vi). By contrast, a minority of participants were identified as '*advice followers*' who trusted official warnings and wanted to comply with agencies' action advice without specific inspection of the risk situation. For this latter group the information regarding warning levels and action advice (aforementioned element vii and viii) were thus of relatively higher importance. The implication is that a wildfire mapping tool built for the wider audience should deliver all the critical information elements to accommodate users' varied needs. An alternative and further improved approach may be to develop tools that can customise the information presented and

highlighted based on personality profiling. For example, a resident who is identified as a '*self-relier*' may be provided with the important hazard maps as default information, and the warning levels and action advice as optional information. For '*advice followers*', the warning levels and agency advice for one's area may be highlighted as the most important. However, such an approach requires further investigation to identify significant indicators (e.g. fire-plan, demographic characteristics, and psychological intentions in terms of responding to wildfires) of people's information needs.

With respect to interactivities of the mapping interface, the study results underscored the need to allow for flexible search functions, to explicitly and intuitively present the names of map layers, and to provide adequate tooltips to enhance information access. Furthermore, judicious design is required to supply a balanced mapping interface to highlight not only the critical visual information, but also the imperative elements depicted in text. In addition, inadequate control of map scales may lead to significant errors in information interpretation, necessitating the provision of restriction or assistance for controlling map scales, such as by providing a prominent widget for restoring the default map scale, and by dynamically updating the location of wind symbols to ensure its inclusion in the map extent. Finally, as adequate guidance of tool usage may be critical for novice users, such map-based warning applications, if implemented, should be propagated at the beginning of wildfire seasons to allow for practice by the residents.

To conclude, results from this study have provided a general guidance for building effective map-based wildfire warning tools by identifying important information content and optimal interactive design characteristics. However, it needs to be highlighted that even for basic *hazard* information such as fire locations, timeliness of the data is crucial, as it provides heightened accuracy. This is especially important given that most participants expected to refer to the map-based information for close monitoring of the situation and identifying decision triggers. Without a capability to update the maps half hourly or hourly, maps of the *hazard* will become useless for the individual decision makers. Moreover, a reliance on and

use of out-dated mapped information will lead to warning disasters. Current updating

frequency for text-based warnings, i.e. ranging from one hour to half days (DFES, 2015b), is

thus not sufficient. In fact, semi-/automated updating capacity can now be implemented to

incorporate more timely spatial information from the emergency management system (Cao et

al., In prep). Agencies that determine to opt for the more advanced map-based warning

approach should therefore endeavour to enhance their technical capacity for providing

updated information in the meantime.

Chapter 7. General Discussion and Conclusion

7.1 Summary of research findings

Web- and mobile- based mapping technologies have become ubiquitous over the last decade and they have been changing the way we receive and perceive geographic information. In spite of the salient 'spatial' nature of hazards and disasters, however, the use of maps has not yet become a common communication approach for warning the public of impending emergencies. In fact, agencies appear reluctant in employing map-based approaches for delivering public early warnings, a sentiment that might be attributable to the lack of a scientific understanding regarding the role of maps in improving the public's warning responses. Indeed, researchers have started to theoretically contend the potential benefits of map-mediated risk communication methods for increasing vividness, facilitating risk assessment, and promoting personal risk perceptions (Dransch et al., 2010). Still, an empirical understanding regarding the extent to which maps can actually enhance public response to emergencies in comparison with conventional text-based communication is lacking. In addition, it remains unclear how mapping instruments can best be developed to maximise the advantage of visual communication. As science and technological advancements continue to provide new, timely and accurate spatial information concerning hazards and their impacts, it is a logical step to evaluate the potential of map-based warnings, and identify optimal graphical approaches by harnessing advanced mapping technologies.

To this end, this thesis presented an innovative body of research examining the effectiveness of maps for wildfire warnings, and exploring suitable ways to harness webGIS technologies for enhanced warning communication in an Australian context. Findings and contributions of the research can be encapsulated into three major aspects. First, an empirical study was conducted (Chapter 5), offering evidence of the relative effectiveness of maps over text-based messaging for facilitating accurate understanding, raising risk perceptions and increasing warning appeal. Maps thus provide a promising pathway for improving wildfire public warnings, and researchers and practitioners should begin the transition from text-based

warnings to map-based approaches. To achieve optimum results, systematic investigations are needed to identify the appropriate and effective ways to employ maps in this particular domain.

For this purpose, the second, and the most prominent contribution of this research was to provide concrete insights into how to develop effective map-mediated wildfire warnings by exhibiting the conceptualisation and operationalisation of a *personalised* visual warning tool conceived and designed from a user-centred perspective. First, a *personalised* warning framework was presented, which underscores two aspects of individualised information communication that can facilitate personal risk perception and decision-making: i) the location-based visual presentation of the spatial context of hazards and warnings using maps, and ii) the provision of tailored advice for protective actions through household-specific vulnerability and risk assessment. Based on this conceptual framework, three studies were conducted to collectively contribute to the identification of an effective design for building a *personalised* wildfire visual warning. Specifically, the study presented in Chapter 4 developed a tangible definition of the required levels of household preparedness for active defence against wildfires, serving as a key component for providing tailored action advice in a *personalised* warning. This was followed by two evaluative studies (Chapter 5 and 6) identifying the important information elements to be communicated, as well as the effective cartographic representations and optimal design characteristics for presenting the spatial and non-spatial information elements through interactive mapping interfaces. Together these findings provide a straightforward and valuable first step towards the development of 'effective' map-based warning applications that can provide a personal and appropriate picture of the hazard and warning context. Emergency management agencies who have started releasing wildfire warning maps can also refer to the effective warning content, representations and design aspects identified in these chapters to improve and refine their own tools.

The third and final contribution of the overall research was to illustrate a cohesive, user-centred research framework that can be adapted to direct the design of map-mediated public warnings for other analogous hazards, such as floods and tsunami. Specifically, the methodology presented in Chapter 2 could serve to clarify the overarching design objectives and questions (i.e. the identification of effective content, representations and design), and provide transferrable evaluation techniques for developing useful map-based warning tools for other hazards. Whilst answers to specific research questions may vary for different types of hazards, the existence of such hands-on guidance may facilitate and boost the creation of truly 'effective' visual warnings by providing the users with a central role in the design.

7.2 Recommendations for future work

7.2.1 Further evaluation and refinement

This research identified effective map designs for wildfire warnings using evidence-based system design approaches. Specifically, initial designs for a map-based wildfire warning tool were proposed, followed by an evaluation by end-users to identify necessary improvements with respect to the information content, representations, and system interface and functionality. Further research needs to assess whether a refined system based on the current research findings can garner additional improvement in warning outcomes. In fact, user-centred designs for computer programs and geovisualisation tools often require an iterative design-evaluation-refinement process in an attempt to approach optimisation (Nielsen, 1993, Robinson, 2005). Likewise, evaluation iterations will also be crucial for designing effective mapping applications for public warnings. Such secondary assessment and system refinement is especially necessary since the current research is the first of its kind and thereby exploratory in nature. Moreover, to adapt the proposed visual warning tool to local contexts, further appraisal and revision of the content, representations and functionalities need to account for the specific cultural and demographic characteristics, and relevant emergency management policies.

It should also be highlighted that the evaluative studies presented in this thesis were conducted in experimental settings. This means that it remains unclear whether the proposed mapping tool will effectively motivate individuals to perform improved responses in the real world. During experimental scenarios, participants have sufficient time to process information, inspect risk situations, and contemplate response decisions. In real life scenarios however, people's ability to understand, perceive and use the visual and spatial information may be influenced by a more pressing timeframe and by adverse emotional reactions such as panic. In addition, during actual emergencies, Internet based warning communication is unlikely to work in isolation. Rather, in the current warning system, Australian residents have been found to rely on other information outlets, including radio communication and social network (e.g. family, friends, and social media), for their decision-making in wildfires (Heath et al., 2011, McLennan, 2014, Trigg et al., 2015a). Information obtained from the various sources is likely to be of different specificity and accuracy and describe the event from distinct angles. It remains to be seen how the specific and accurate spatial information offered by maps will interact with textual and informal information by other sources, and whether the former will assist or confuse the public in their decision-making. Consequently, future evaluation and improvement of map-based warning tools need to be conducted in real world situations to build visual warnings that can effectively contribute to the dynamics of a complete (i.e. including formal and informal sources) warning system.

7.2.2 Development of a visual warning protocol

To promote and assist the employment of effective map-based wildfire warnings, it is critical for emergency management authorities to start developing national visual warning protocols (EMV, 2014b) that explicitly define the content to be communicated, and the representations and interface designs to be employed. Visual warning protocols can be analogous to, or be a part of, the Common Alerting Protocols that have been developed in many countries such as the U.S., Canada and Australia. The standardisation of the design for map-based warnings can aid local agencies in building consistent and effective visual warning solutions in spite of the

diversity of their spatial data and technological capacity (EMV, 2014b). Furthermore, the adoption of consistent mapping approaches across a country can accelerate citizen's acceptance of, and familiarisation with, new warning information and formats, maximising the chances of visual warnings leading to more appropriate response decisions.

7.2.3 Advancing data capacity

The increased effectiveness of maps over text in motivating appropriate warning responses, as exhibited by this research, was to a large extent ascribable to the heightened specificity and accuracy of the spatial information communicated by maps. For example, the more accurate understanding of the location, distance and direction of a fire hazard yielded by maps as compared to text (reported in Chapter 5) was grounded in the more explicit and accurate delineation of spatial information by the former. This implies that if the spatial data underpinning the maps is inaccurate, participants' understanding would also be erroneous. Furthermore, the study presented in Chapter 6 revealed that the raised spatial specificity and accuracy offered by maps improved participants' ability in making decisions by reducing uncertainty. That is, with no explicit and certain knowledge regarding the fire location and its likely direction, participants who referred to text-based warnings in their past experience were inclined to delay responding and seek more information instead (e.g. by driving around to look for the fire). The implication is that, if map-based warnings cannot offer accurate spatial information, they will essentially be similar to text-based warnings and be unlikely to enhance response.

In the changing situation of an emergency, the accuracy of the warning information communicated is contingent upon its timeliness. In the current Australian wildfire warning system, text-based warnings are updated at varied frequencies, depending on the warning levels: every hour for 'Emergency' warnings, every two hours for 'Watch and Act' warnings, and every half day for 'Advice' warnings (DFES, 2015b). By contrast, existing map-based warning tools, including the VicEmergency developed by EMV (2015) and Alert SA provided by the Government of South Australia (2015), update their hazard maps in a less reliable

manner. For example, based on the author's observation, the maps of fire perimeters presented by both applications are often updated only on a daily basis. Such a frequency cannot accommodate users' needs of specific and accurate wildfire information. Many interview participants in the final study (Chapter 6) expressed a desire to refer to the hazard related maps half-hourly or hourly, even at 'Advice' or 'Watch and Act' warning levels. Such a requirement may be unfeasible. More realistic approaches to updating hazard maps could be similar to the existing strategy for text-based warnings, namely, varied updating frequencies dependent upon warning levels. However, information regarding when a hazard map was last published and when it is due to be updated needs to be explicitly communicated and emphasised through the mapping interface to ensure correct interpretation of the map and appropriate decision-making for response.

In fact, hourly updating of spatial wildfire information during emergency situations is not technologically impractical. To the author's knowledge, the limited updating frequency of existing map-based warnings in Australia is not caused by the inaccessibility of spatial data. Rather, during fast-migrating wildfire events, hazard information such as fire perimeters are often tracked and updated half-hourly to hourly for operational use. A semi-/automated GIS could therefore be constructed to translate operational maps into public information maps in a short window of time. The actualisation of such efficient updating for visual warnings only requires short-term investment of the agencies to establish the aforementioned visual protocols that define the appropriate information content and representation methods for public consumption, and set up the GIS infrastructures for semi-/automated transformation from operational maps to public information maps.

7.2.4 Development of user-dependent warnings

The final study (Chapter 6) reported different information needs across participants, indicating the necessity of developing user-dependent warnings to provide varied information to accommodate distinctive users' needs. Specifically, the study results suggested the significance of providing specific hazard information for '*self-reliers*', and the need of

highlighting warning levels and action advice for '*advice followers*'. Given the limited sample size of the interview study however, further research is needed to assess the validity of the reported results at a larger scale. Furthermore, evaluation studies are needed to determine whether the provision and underscoring of user desired information is truly beneficial for motivating 'appropriate' responses, such as early evacuation. For instance, the delivery of specific hazard information for the '*self-reliers*' may result in constant attention to exploring the information rather than taking action. If this is the case, reconsideration is warranted to identify whether specific hazard information desired by those residents can truly improve their response, or what the best strategy is to communicate such information to satisfy the demands of '*self-reliers*' whilst promoting 'appropriate' decision-making. Finally, if the importance of such a user-dependent warning approach is corroborated, investigations are needed to identify significant indicators (e.g. fire-plan, demographic characteristics) of people's personalities in terms of warning information needs to categorise users and provide warnings that underscore the information elements (i.e. hazard related information or agencies' action advice) that will motivate the optimum response.

To summarise, this research has provided tangible answers to the question of how to map wildfire warnings in an appropriate and 'effective' way. The information content, cartographic representations and interface design that have been identified as optimal can be used to guide the improvement of existing mapping applications, or the development of new mapping instruments. If local agencies resolve to adopt map-based solutions to improve warnings, however, the supply of user-centred mapping instruments must be coupled with adequate investment in improving the capacity to feed accurate and timely data into the warning system. Moreover, at a national or regional level, the provision of 'effective' map-based warnings needs to be incorporated into the holistic warning strategy to assure appropriate applications and optimal outcomes.

List of References

ACT EMERGENCY SERVICES AGENCY (ESA). 2009. *Prepare. Act. Survive.* [Online].
Available: http://cdn.esa.act.gov.au/wp-content/uploads/prepare-act-survive.pdf
[Accessed Mar. 11 2015].

ALEXANDER, D. 1991. Information technology in real-time for monitoring and managing
natural disasters. *Progress in Physical Geography,* 15**,** 238-260.

ALEXANDER, D. E. 2002. *Principles of emergency planning and management*, Oxford
University Press.

AMBROSIA, V. G., BUECHEL, S. W., BRASS, J. A., PETERSON, J. R., DAVIES, R. H.,
KANE, R. J. & SPAIN, S. 1998. An integration of remote sensing, GIS, and
information distribution for wildfire detection and management. *Photogrammetric
engineering and remote sensing,* 64**,** 977-986.

ANDERSON, W. A. 1969. Disaster Warning and Communication Processes in Two
Communities. *Journal of Communication,* 19**,** 92-104.

ANDRIENKO, N., ANDRIENKO, G., VOSS, H., BERNARDO, F., HIPOLITO, J. &
KRETCHMER, U. 2002. Testing the Usability of Interactive Maps in CommonGIS.
Cartography and geographic information science, 29**,** 325-342.

ARLIKATTI, S., LINDELL, M. K., PRATER, C. S. & ZHANG, Y. 2006. Risk Area
Accuracy and Hurricane Evacuation Expectations of Coastal Residents. *Environment
and Behavior,* 38**,** 226-247.

ASH, K. D., SCHUMANN III, R. L. & BOWSER, G. C. 2014. Tornado Warning Trade-Offs:
Evaluating Choices for Visually Communicating Risk. *Weather, Climate, and Society,* 6**,**
104-118.

AUSTRALASIAN FIRE AND EMERGENCY SERVICE AUTHORITIES COUNCIL
(AFAC) 2010. Position Paper on Bushfires and Community Safety, Version 4.1.
Melbourne: Australasian Fire and Emergency Service Authorities Council (AFAC).

AUSTRALIAN BUREAU OF STATISTICS (ABS). 2011a. *2074.0 - Census of Population
and Housing: Mesh Block Counts* [Online]. Available:

http://www.abs.gov.au/ausstats/abs@.nsf/Lookup/2074.0main+features12011

[Accessed Oct 03 2014].

AUSTRALIAN BUREAU OF STATISTICS (ABS). 2011b. *Community Profiles* [Online].

Available: http://www.abs.gov.au/websitedbs/censushome.nsf/home/communityprofiles

[Accessed Apr 20 2015].

AUSTRALIAN BUREAU OF STATISTICS (ABS). 2014. *8146.0 - Household Use of*

Information Technology, Australia, 2012-13 [Online]. Available:

http://www.abs.gov.au/AUSSTATS/abs@.nsf/Lookup/8146.0Main+Features12012-

13?OpenDocument [Accessed Oct 23 2015].

AUSTRALIAN GOVERNMENT BUREAU OF METEOROLOGY (BOM). 2015.

Interactive Weather and Wave Forecast Maps [Online]. Available:

http://www.bom.gov.au/australia/charts/viewer/index.shtml?type=windbarb&level=10

m&tz=AEDT&area=Au&model=CG&chartSubmit=Refresh+View [Accessed May 10

2015].

BAKER, E. J. 1991. Hurricane evacuation behavior. *International Journal of Mass*

Emergencies and Disasters, 9**,** 287-310.

BEAN, H., SUTTON, J., LIU, B. F., MADDEN, S., WOOD, M. M. & MILETI, D. S. 2015.

The Study of Mobile Public Warning Messages: A Research Review and Agenda.

Review of Communication, 15**,** 60-80.

BEAN, H., WOOD, M., MILETI, D., LIU, B., SUTTON, J. & MADDEN, S. 2014.

Comprehensive Testing of Imminent Threat Public Messages for Mobile Devices.

Report to the Homeland Security Advanced Research Projects Agency, Science and

Technology Directorate, U.S. Department of Homeland Security. College Park, MD:

National Consortium for the Study of Terrorism and Responses to Terrorism.

BELL, H. M. & TOBIN, G. A. 2007. Efficient and effective? The 100-year flood in the

communication and perception of flood risk. *Environmental Hazards,* 7**,** 302-311.

BENNETT, D., PHILLIPS, B. D., THOMAS, D. S., GRUNTFEST, E. & SUTTON, J. 2013.

New Ideas for Practitioners. *In:* THOMAS, D. S. K., PHILLIPS, B. D., LOVEKAMP,

W. E. & FOTHERGILL, A. (eds.) *Social vulnerability to disasters.* Boca Raton, Florida:
CRC Press.

BLAIKIE, P. M., CANNON, T., DAVIS, I. & WISNER, B. 1994. *At Risk: Natural Hazards,
People's Vulnerability, and Disasters,* London, Routledge.

BLANCHI, R. & LEONARD, J. 2005. Investigation of bushfire attack mechanisms resulting
in house loss in the ACT bushfire 2003. *Report for Bushfire CRC.* Highett, VIC,
Australia: CSIRO Manufacturing and Infrastructure Technology.

BLANCHI, R., LEONARD, J., LEICESTER, R., LIPKIN, F., BOULAIRE, F. &
MCNAMARA, C. Assessing vulnerability at the urban interface. The 5th International
Wildland Fire Conference, 2011 Sun City, South Africa.

BLANCHI, R., LEONARD, J. E. & LEICESTER, R. H. 2006. Lessons learnt from post-
bushfire surveys at the urban interface in Australia. *Forest Ecology and Management,*
234**,** S139-S139.

BLANCHI, R., LUCAS, C., LEONARD, J. & FINKELE, K. 2010. Meteorological conditions
and wildfire-related houseloss in Australia. *International Journal of Wildland Fire,* 19**,**
914-926.

BOARD ON NATURAL DISASTERS OF THE NATIONAL RESEARCH CONCIL 1999.
Mitigation Emerges as Major Strategy for Reducing Losses Caused by Natural
Disasters. *Science,* 284**,** 1943-1947.

BOSTROM, A., ANSELIN, L. & FARRIS, J. 2008. Visualizing seismic risk and uncertainty.
Annals of the New York Academy of Sciences, 1128**,** 29-40.

BOWDITCH, P. A., SARGEANT, A. J., LEONARD, J. E. & MACINDOE, L. 2006. Window
and glazing exposure to laboratory-simulated bushfires. *Report to Bushfire CRC,
Confidential CMIT Document 205.* Melbounre, Australia.

BRESSEN, T. 2007. Consensus decision making. *The Change Handbook: The Definitive
Resource on Today's Best Methods for Engaging Whole Systems.* 2nd ed. San Francisco,
CA: Berrett-Koehler Publishers.

BROAD, K., LEISEROWITZ, A., WEINKLE, J. & STEKETEE, M. 2007. Misinterpretations of the "cone of uncertainty" in Florida during the 2004 hurricane season. *Bulletin of the American Meteorological Society,* 88**,** 651-667.

BURGMAN, M. A., MCBRIDE, M., ASHTON, R., SPEIRS-BRIDGE, A., FLANDER, L., WINTLE, B., FIDLER, F., RUMPFF, L. & TWARDY, C. 2011. Expert status and performance. *PLoS One,* 6**,** e22998.

BUTLER, B. W. & COHEN, J. D. 1998. Firefighter safety zones: a theoretical model based on radiative heating. *International Journal of Wildland Fire,* 8**,** 73-77.

BUXTON, M., HAYNES, R., MERCER, D. & BUTT, A. 2011. Vulnerability to bushfire risk at Melbourne's urban fringe: the failure of regulatory land use planning. *Geographical Research,* 49**,** 1-12.

CALIFORNIA DEPARTMENT OF FORESTRY AND FIRE PROTECTION (CAL FIRE). 2015. *Valley Fire Incident Information* [Online]. Available: http://cdfdata.fire.ca.gov/incidents/incidents_details_info?incident_id=1226 [Accessed Nov 10 2015].

CALIFORNIA DEPARTMENT OF FORESTRY AND FIRE PROTECTION (CAL FIRE). 2016. *California Fire Map* [Online]. Available: https://www.google.com/maps/d/u/0/viewer?ll=37.055177%2C-120.454102&spn=17.505593%2C18.720703&hl=en&msa=0&z=5&source=embed&ie=UTF8&mid=zp8nK_5H0MFQ.kzTmU5XK-qJQ [Accessed April 8 2016].

CAMPBELL, C. S. & EGBERT, S. L. 1990. Animated cartography/Thirty years of scratching the surface. *Cartographica: The International Journal for Geographic Information and Geovisualization,* 27**,** 24-46.

CAO, Y., BORUFF, B. J. & MCNEILL, I. M. "Should I Stay or Should I Go?" Defining the Preparatory Conditions in Support of Active Defence for Different Fire Danger Ratings. *In:* WRIGHT, L. J., ed. Proceedings of Bushfire CRC & AFAC 2013 Conference Research Forum, 2013 Melbourne, Australia. Bushfire CRC, 38-52.

CAO, Y., BORUFF, B. J. & MCNEILL, I. M. 2016. Defining Sufficient Household Preparedness for Active Wildfire Defence: Toward an Australian Baseline. *Natural Hazards Review,* 17.

CAO, Y., BORUFF, B. J. & MCNEILL, I. M. In prep. Towards Personalised Public Early Warnings: Harnessing Technological Advancements to Promote Better Individual Decision Making.

CAO, Y., BORUFF, B. J. & MCNEILL, I. M. Under revision. Is a picture worth a thousand words? Evaluating the effectiveness of maps for delivering wildfire warning information. *International Journal of Disaster Risk Reduction*.

CASTEEL, M. A. & DOWNING, J. R. 2013. How individuals process NWS weather warning messages on their cell phones. *Weather, Climate, and Society,* 5**,** 254-265.

COHEN, J. D. Structure Ignition Assessment Model (SIAM). *In:* WEISE, D. R. & MARTIN, R. F., eds. Proceedings of the Biswell Symposium: Fire Issues and Solutions in Urban Interface and Wildland Ecosystems, 1994 February 15-17 1995 Walnut Creek, CA. Albany, CA: USDA Forest Service, Pacific Southwest Research Station.

COHEN, J. D. 2000. Preventing Disaster: Home Ignitability in the Wildland-Urban Interface. *Journal of Forestry,* 98**,** 15-21.

COHEN, J. D. 2004. Relating flame radiation to home ignition using modeling and experimental crown fires. *Canadian Journal of Forest Research,* 34**,** 1616-1626.

COLLINS, T. W. 2005. Households, forests, and fire hazard vulnerability in the American West: A case study of a California community. *Environmental Hazards,* 6**,** 23-37.

COPPOLA, D. P. 2006. *Introduction to international disaster management*, Butterworth-Heinemann.

COUNTRY FIRE AUTHORITY (CFA). 2009. *Household Self-Assessment Tool Online,* [Online]. State of Victoria. Available: http://www.cfa.vic.gov.au/plan-prepare/house-bushfire-assessment-tool/ [Accessed May. 1 2015].

COUNTRY FIRE AUTHORITY (CFA) 2013a. Fire Ready Kit. http://www.cfa.vic.gov.au/fm_files/attachments/plan_and_prepare/frk_2013/4713_CFA_2014_FireReadyKit_web.pdf.

COUNTRY FIRE AUTHORITY (CFA). 2013b. *Leaving Early. Bushfire Survival Planning Template* [Online]. Victoria, Australia. Available: http://www.cfa.vic.gov.au/fm_files/attachments/plan_and_prepare/frk_2013/4713_CFA _Pullout_LEAVING_web.pdf [Accessed Dec 01 2015].

COUNTRY FIRE SERVICE (CFS). 2014. *Prepare For Bushfire* [Online]. South Australia. Available: http://www.cfs.sa.gov.au/site/prepare_for_bushfire.jsp [Accessed Mar. 11 2015].

COVA, T. J. 1999. GIS in emergency management. *In:* LONGLEY, P. A., GOODCHILD, M. F., MAGUIRE, G. J. & RHIND, D. W. (eds.) *Geographical information systems: Principles, Techniques, Applications, 2nd Edition: Management Issues and Applications.* New York/Chichester: John Wiley.

COVA, T. J., DREWS, F. A., SIEBENECK, L. K. & MUSTERS, A. 2009. Protective actions in wildfires: evacuate or shelter-in-place? *Natural Hazards Review,* 10**,** 151-162.

COVELLO, V. T. 1990. A Review of Obstacles to Public Understanding and Effective Risk Communication. *In:* LEISS, W. (ed.) *Prospects and Problems in Risk Communication.* Waterloo: University of Waterloo.

CRAMPTON, J. W. 2002. Interactivity types in geographic visualization. *Cartography and geographic information science,* 29**,** 85-98.

CRICHTON, D. 1999. The Risk Triangle. *In:* INGLETON, J. (ed.) *Natural Disaster Management.* Tudor Rose, London.

CUTTER, S. L. 2003. GI science, disasters, and emergency management. *Transactions in GIS,* 7**,** 439-446.

DAVIS, J. B. 1990. The wildland-urban interface: paradise or battleground? *Journal of forestry (USA),* 88**,** 26-31.

DAVIS, P. O. & DOTSON, C. O. 1987. Physiological aspects of fire fighting. *Fire technology,* 23**,** 280-291.

DEPARTMENT OF FIRE AND EMERGENCY SERVICES (DFES) 2014. Prepare. Act. Survive. Version 5.

http://www.dfes.wa.gov.au/safetyinformation/fire/bushfire/BushfireManualsandGuides/
DFES_Bushfire-Prepare_Act_Survive_Booklet.pdf.

DEPARTMENT OF FIRE AND EMERGENCY SERVICES (DFES). 2015a. *Alerts and Warnings Map* [Online]. Available:
http://www.dfes.wa.gov.au/alerts/Pages/alertsmap.aspx [Accessed Oct 20 2015].

DEPARTMENT OF FIRE AND EMERGENCY SERVICES (DFES). 2015b. *Bushfire warnings: what should you do?* [Online]. Available:
http://www.dfes.wa.gov.au/safetyinformation/fire/bushfire/BushfireChecklists/DFES_Bushfire-Warning_Levels.pdf [Accessed Oct 20 2015].

DEPARTMENT OF FIRE AND EMERGENCY SERVICES (DFES). 2015c. *Fire Danger Rating and What It Means To You* [Online]. Western Australia: Government of Western Australia. Available:
http://www.dfes.wa.gov.au/safetyinformation/fire/bushfire/BushfireChecklists/DFES_Bushfire-Fire_danger_ratings.pdf [Accessed Feb 10 2016].

DOW, K. & CUTTER, S. L. 1998. Crying wolf: Repeat responses to hurricane evacuation orders.

DRABEK, T. E. 1999. Understanding disaster warning responses. *The Social Science Journal,* 36**,** 515-523.

DRANSCH, D., ROTZOLL, H. & POSER, K. 2010. The contribution of maps to the challenges of risk communication to the public. *International Journal of Digital Earth,* 3**,** 292-311.

DUNLOP, P. D., MCLENNAN, J., ELLIOTT, G., KELLY, L., RISEBOROUGH, K., TYLER, M. & FAIRBROTHER, P. 2011. Capturing Community Members' Bushfire Experiences: The Lake Clifton (WA) Fire. *In:* THORNTON, R. P. (ed.) *'Proceedings of Bushfire CRC & AFAC 2010 Conference Science Day' 1 September 2011, Sydney Australia, Bushfire CRC.*

DUNLOP, P. D., MCNEILL, I. M., BOYLAN, J. L., MORRISON, D. L. & SKINNER, T. C. 2014. Preparing... for what? Developing multi-dimensional measures of community

wildfire preparedness for researchers, practitioners and households. *International Journal of Wildland Fire,* 23**,** 887-896.

EMERGENCY MANAGEMENT AUSTRALIA (EMA) 2004. Emergency Management in Australia. *Australian Emergency Manual Series.* ACT, Australia.

EMERGENCY MANAGEMENT SPATIAL INFORMATION NETWORK AUSTRALIA (EMSINA) 2010. All Hazards Symbology Project Report. Australia.

EMERGENCY MANAGEMENT VICTORIA 2014a. National Review of Emergency Alert: Consolidated Report of Findings December 2014. Melbourne: Ipsos.

EMERGENCY MANAGEMENT VICTORIA 2014b. National Review of Warnings and Information: Final Report. Melbourne: Victorian Government.

EMERGENCY MANAGEMENT VICTORIA (EMV). 2015. *VicEmergency* [Online]. Available: http://emergency.vic.gov.au/map#now [Accessed Oct 10 2015].

ERICSSON, K. A. & SIMON, H. A. 1993. *Protocol analysis: Verbal reports as data (rev. ed.)*, Cambridge, MA, US: The MIT Press.

FEDERAL EMERGENCY MANAGEMENT AGENCY (FEMA). 2000. *Avoiding Wildfire Damage: A Homeowners Checklist* [Online]. Available: http://www.fema.gov/pdf/hazard/wildfire/wdfrdam.pdf [Accessed Jan. 12 2012].

FISCHHOFF, B. 1995. Risk Perception and Communication Unplugged: Twenty Years of Process. *Risk Analysis,* 15**,** 137-145.

FLANNIGAN, M. D., AMIRO, B. D., LOGAN, K. A., STOCKS, B. & WOTTON, B. 2006. Forest fires and climate change in the 21st century. *Mitigation and adaptation strategies for global change,* 11**,** 847-859.

FLOYD, D. L., PRENTICE-DUNN, S. & ROGERS, R. W. 2000a. A Meta-Analysis of Research on Protection Motivation Theory. *Journal of Applied Social Psychology,* 30**,** 407-429.

FLOYD, D. L., PRENTICE‐DUNN, S. & ROGERS, R. W. 2000b. A meta‐analysis of research on protection motivation theory. *Journal of applied social psychology,* 30**,** 407-429.

FOOTE, E. I. D. 1994. *Structure Survival on the 1990 Santa Barbara" Paint" Fire: A Retrospective Study of Urban-wildland Interface Fire Hazard Mitigation Factors.* M.S. thesis, University of California at Berkeley.

FOSTER, B. 2016. WA fires: Yarloop residents 'given 25 minutes notice' before fire wiped out town. *WA Today*, p.Feb 17.

GABBARD, J. L., HIX, D. & SWAN, J. E. 1999. User-centered design and evaluation of virtual environments. *IEEE Computer Graphics and Applications,* 19**,** 51-59.

GEOSCIENCE AUSTRALIA. 2005. *SENTINEL,* *http://sentinel.ga.gov.au/acres/sentinel/index.shtml* [Online]. [Accessed 13/09/11].

GEOSERVER. 2015. Available: http://geoserver.org/ [Accessed].

GLADWIN, H., LAZO, J. K., MORROW, B. H., PEACOCK, W. G. & WILLOUGHBY, H. E. 2007. Social science research needs for the hurricane forecast and warning system. *Natural Hazards Review,* 8**,** 87-95.

GOOGLE CRISIS RESPONSE. 2015. *Google Crisis Map, US Wildfires* [Online]. Available: https://google.org/crisismap/us-wildfires [Accessed May 15 2015].

GOVERNMENT OF SOUTH AUSTRALIA. 2015. *Alert SA* [Online]. Available: https://www.alert.sa.gov.au/map [Accessed Oct 10 2015].

GOVERNMENT OF WESTERN AUSTRALIA 2011. A Shared Responsibility: The Report of the Perth Hills Bushfire February 2011 Review. Western Australia.

GUHA-SAPIR, D., BELOW, R. & HOYOIS, P. 2015. EM-DAT: International Disaster Database – www.emdat.be Brussels, Belgium: Universit éCatholique de Louvain.

GUTTELING, J. M. & WIEGMAN, O. 1996. *Exploring risk communication*, Springer Science & Business Media.

HAGEMEIER-KLOSE, M. & WAGNER, K. 2009. Evaluation of flood hazard maps in print and web mapping services as information tools in flood risk communication. *Natural Hazards and Earth System Sciences,* 9**,** 563-574.

HAMMER, B. & SCHMIDLIN, T. W. 2002. Response to warnings during the 3 May 1999 Oklahoma City tornado: Reasons and relative injury rates. *Weather and Forecasting,* 17**,** 577-581.

HAMMER, R. B., STEWART, S. I. & RADELOFF, V. C. 2009. Demographic trends, the wildland–urban interface, and wildfire management. *Society and Natural Resources,* 22**,** 777-782.

HANDMER, J. Floodplain maps: uses and limitations as public information. 13th New Zealand Geographical Society Conference, Hamilton, New Zealand, 1985.

HANDMER, J., O'NEIL, S. & KILLALEA, D. 2010. Review of fatalities in the February 7, 2009, bushfires. *Prepared for the Victorian Bushfires Royal Commission April 2010.* Melbourne: Centre for Risk and Community Safety RMIT University & Bushfire CRC.

HANDMER, J. & TIBBITS, A. 2005. Is staying at home the safest option during bushfires? Historical evidence for an Australian approach. *Environmental Hazards,* 6**,** 81-91.

HARTNETT, T. 2011. *Consensus Oriented Decision Making,* Gabriola Island, New Society Publishers.

HAYNES, K., BARCLAY, J. & PIDGEON, N. 2007. Volcanic hazard communication using maps: an evaluation of their effectiveness. *Bulletin of Volcanology,* 70**,** 123-138.

HAYNES, K., COATES, L., LEIGH, R., HANDMER, J., WHITTAKER, J., GISSING, A., MCANENEY, J. & OPPER, S. 2009. 'Shelter-in-place'vs. evacuation in flash floods. *Environmental Hazards,* 8**,** 291-303.

HAYNES, K., HANDMER, J., MCANENEY, J., TIBBITS, A. & COATES, L. 2010. Australian bushfire fatalities 1900-2008: exploring trends in relation to the 'Prepare, stay and defend or leave early' policy. *Environmental Science & Policy,* 13**,** 185-194.

HEATH, J., NULSEN, C., DUNLOP, P., CLARKE, P., BURGELT, P. & MORRISON, D. 2011. The February 2011 Fires in Roleystone, Kelmscott and Red Hill. Melbourne, Australia: Bushfire CRC.

HENNESSY, K., LUCAS, C., NICHOLLS, N., BATHOLS, J., SUPPIAH, R. & RICKETTS, J. 2005. Climate change impacts on fire-weather in south-east Australia. *Consultancy report by CSIRO Marine and Atmospheric Research, Bureau of Meteorology and Bushfire CRC.* Melbourne, Australia: CSIRO Marine and Atmospheric Research.

HINES, F., TOLHURST, K. G., WILSON, A. A. & MCCARTHY, G. J. 2010. *Overall fuel hazard assessment guide,* Melbourne, Victorian Government Department of Sustainability and Environment.

HIX, D. & HARTSON, H. R. 1993. *Developing user interfaces: ensuring usability through product & process*, John Wiley & Sons, Inc.

HOWARD, R. A., NORTH, D. W., OFFENSEND, F. L. & SMART, C. N. 1973. Decision Analysis of Fire Protection Strategy for the Santa Monica Mountains: An Initial Assessment. Menlo Park, CA: Stanford Research Institute.

HUANG, S.-K., LINDELL, M. K. & PRATER, C. S. 2015. Who leaves and who stays? A review and statistical meta-analysis of hurricane evacuation studies. *Environment and Behavior,* 0013916515578485.

JAMES, L. R., DEMAREE, R. G. & WOLF, G. 1984. Estimating within-group interrater reliability with and without response bias. *Journal of applied psychology,* 69**,** 85-98.

JOHNSTON, P., KELSO, J. & MILNE, G. J. 2008. Efficient Simulation of Wildfire spread on an irregular grid. *International Journal of Wildland Fire,* 17**,** 614-627.

KAIN, D. & COVI, M. 2013. Visualizing complexity and uncertainty about climate change and sea level rise. *Communication Design Quarterly Review,* 1**,** 46-53.

KAPLAN, B. & MAXWELL, J. A. 2005. Qualitative research methods for evaluating computer information systems. *Evaluating the organizational impact of healthcare information systems.* New York: Springer.

KJELLGREN, S. 2013. Exploring local risk managers' use of flood hazard maps for risk communication purposes in Baden-Württemberg. *Natural Hazards and Earth System Science,* 13**,** 1857-1872.

KRAJEWSKI, W. F., KRUGER, A., SMITH, J. A., LAWRENCE, R., GUNYON, C., GOSKA, R., SEO, B.-C., DOMASZCZYNSKI, P., BAECK, M. L. & RAMAMURTHY, M. K. 2011. Towards better utilization of NEXRAD data in hydrology: an overview of Hydro-NEXRAD. *Journal of hydroinformatics,* 13**,** 255-266.

KRIMSKY, S. 2007. Risk communication in the internet age: The rise of disorganized skepticism. *Environmental hazards,* 7**,** 157-164.

LAZARUS, G. & ELLEY, J. 1984. A study of the effect of household occupancy during the Ash Wednesday bushfire in Upper Beaconsfield, Victoria, February, 1983. *National Centre for Rural Fire Research Technical Paper No. 3.* Victoria, AU: Chisholm Institute of Technology.

LEBRETON, J. M. & SENTER, J. L. 2008. Answers to 20 Questions About Interrater Reliability and Interrater Agreement. *Organizational Research Methods,* 11**,** 815-852.

LEIK, R. K., CARTER, T. M., CLARK, J. P., KENDALL, S. D. & GIFFORD, G. A. 1981. Community Response to Natural Hazard Warnings. DTIC Document.

LEONARD, J. 2009. Report to the 2009 Victorian Bushfires Royal Commission Building performance in Bushfires. VIC, Australia: CSIRO Sustainable Ecosystem.

LEONARD, J. E., BLANCHI, R., WHITE, N., BICKNELL, A., SARGEANT, A., REISEN, F., CHENG, M. & HONAVAR, K. 2006. Research and investigation into the performance of residential boundary fencing systems in bushfires. Clayton South, Victoria, Australia: CSIRO Manufacturing & Infrastructure Technology, Fire Science & Technology Laboratory, Bushfire Research and BlueScope Steel Limited.

LIESKE, D. J. 2012. Towards a framework for designing spatial and non-spatial visualizations for communicating climate change risks. *Geomatica,* 66**,** 27-36.

LIESKE, D. J., WADE, T. & RONESS, L. A. 2014. Climate change awareness and strategies for communicating the risk of coastal flooding: a Canadian Maritime case example. *Estuarine, Coastal and Shelf Science,* 140**,** 83-94.

LILLESAND, T., KIEFER, R. W. & CHIPMAN, J. 2015. *Remote sensing and image interpretation,* New York, John Wiley & Sons.

LIN, P.-H. & LEE, C.-S. 2008. The eyewall-penetration reconnaissance observation of Typhoon Longwang (2005) with unmanned aerial vehicle, Aerosonde. *Journal of Atmospheric and Oceanic Technology,* 25**,** 15-25.

LINDELL, M. K. 2000. An overview of protective action decision-making for a nuclear power plant emergency. *Journal of hazardous materials,* 75**,** 113-129.

LINDELL, M. K. & BROOKS, H. 2013. An Integrated Agenda for Research on Severe Storms. *International Journal of Mass Emergencies and Disasters,* 31.

LINDELL, M. K., HUANG, S.-K., WEI, H.-L. & SAMUELSON, C. D. 2015a. Perceptions and expected immediate reactions to tornado warning polygons. *Natural Hazards*, 1-25.

LINDELL, M. K., LU, J.-C. & PRATER, C. S. 2005. Household decision making and evacuation in response to Hurricane Lili. *Natural hazards review*.

LINDELL, M. K. & PERRY, R. W. 2004. *Communicating environmental risk in multiethnic communities,* Thousands Oaks, CA, Sage.

LINDELL, M. K. & PERRY, R. W. 2012. The protective action decision model: theoretical modifications and additional evidence. *Risk Analysis,* 32**,** 616-632.

LINDELL, M. K., PRATER, C. S., GREGG, C. E., APATU, E. J., HUANG, S.-K. & WU, H. C. 2015b. Households' immediate Responses to the 2009 American Samoa Earthquake and Tsunami. *International Journal of Disaster Risk Reduction,* 12**,** 328-340.

LINDELL, M. K. & WHITNEY, D. J. 2000. Correlates of household seismic hazard adjustment adoption. *Risk Analysis,* 20**,** 13-26.

LLEWELLYN, R. 2012. Bushfires and Community Safety: Australasian Fire and Emergency Service Authorities Council (AFAC) Version 5.0. Melbourne: AFAC.

LLOYD, R. 1997. *Spatial Cognition, Geographic Environments,* Dordrecht, Kluwer Academic Publishers.

LUKE, R. H. & MCARTHUR, A. G. 1978. *Bush Fires in Australia,* Canberra, ACT, Australia, Australian Government Publishing Service.

MACEACHREN, A. M. 1995. *How Maps Work: Representation, Visualisation, and Design,* New York, The Guilford Press.

MARTIN, I. M., BENDER, H. & RAISH, C. 2007. What Motivates Individuals to Protect Themselves from Risks: The Case of Wildland Fires. *Risk Analysis,* 27**,** 887-900.

MCLENNAN, J. 2014. Capturing Community Members' Bushfire Experiences: Interviews With Residents Following the 12 January 2012 Parkerville (WA) Fire. *Bushfire & Natural Hazards Cooperative Research Centre, East Melbourne*.

MCLENNAN, J., DUNLOP, P., KELLY, L. & ELLIOTT, G. 2011a. Lake Clifton Fire 10 January 2011: Field interview task force report – community bushfire safety. Melbourne: School of Psychological Science La Trobe University and Bushfire CRC.

MCLENNAN, J. & ELLIOTT, G. 2011. Checklist Items For Researchers: Householder

   Preparations For Bushfires. Melbourne, Australia: Bushfire Cooperative Research

   Centre and School of Psychological Science La Trobe University.

MCLENNAN, J. & ELLIOTT, G. 'Wait and See': The Elephant in the Community Bushfire

   Safety Room? Proceedings of Bushfire CRC & AFAC 2012 Conference Research

   Forum, 2012.

MCLENNAN, J., ELLIOTT, G. & OMODEI, M. 2011b. Issues in Community Bushfire

   Safety: Analyses of Interviews Conducted by the 2009 Victorian Bushfires Research

   Task Force. Melbourne, Australia: School of Psychological Science, La Trobe

   University.

MCLENNAN, J., ELLIOTT, G. & OMODEI, M. 2012. Householder decision-making under

   imminent wildfire threat: stay and defend or leave? *International Journal of Wildland*

   Fire, 21**,** 915-925.

MCLENNAN, J., ELLIOTT, G., OMODEI, M. & WHITTAKER, J. 2013. Householders'

   safety-related decisions, plans, actions and outcomes during the 7 February 2009

   Victorian (Australia) wildfires. *Fire Safety Journal,* 61**,** 175-184.

MCLENNAN, J., OMODEI, M., ELLIOTT, G., MCNEILL, I., DUNLOP, P. & SUSS, J.

   Bushfire survival-related decision-making: what the stress and human performance

   literature tells us. *In:* THORNTON, R. P., ed. Proceedings of the Bushfire Cooperative

   Research Centre & AFAC 2011 Conference Science Day, 2011c Sydney, Australia.

   Bushfire CRC, East Melbourne, VIC, Australia, 307-319.

MCLENNAN, J., PATON, D. & WRIGHT, L. 2015. At-risk householders' responses to

   potential and actual bushfire threat: An analysis of findings from seven Australian post-

   bushfire interview studies 2009–2014. *International Journal of Disaster Risk Reduction,*

   12**,** 319-327.

MCNEILL, I. M., DUNLOP, P. D., HEATH, J. B., SKINNER, T. C. & MORRISON, D. L.

   2013. Expecting the unexpected: predicting physiological and psychological wildfire

   preparedness from perceived risk, responsibility, and obstacles. *Risk analysis,* 33**,** 1829-

   1843.

MCNEILL, I. M., DUNLOP, P. D., SKINNER, T. C. & MORRISON, D. L. 2015. Predicting delay in residents' decisions on defending v. evacuating through antecedents of decision avoidance. *International Journal of Wildland Fire,* 24**,** 153-161.

MEYER, V., KUHLICKE, C., LUTHER, J., FUCHS, S., PRIEST, S., DORNER, W., SERRHINI, K., PARDOE, J., MCCARTHY, S. & SEIDEL, J. 2012. Recommendations for the user-specific enhancement of flood maps. *Natural Hazards and Earth System Science,* 12**,** 1701-1716.

MILETI, D. S. 1999. *Disasters by design: A reassessment of natural hazards in the United States*, National Academies Press.

MILETI, D. S. & FITZPATRICK, C. 1992. The causal sequence of risk communication in the Parkfield earthquake prediction experiment. *Risk Analysis,* 12**,** 393-400.

MILETI, D. S. & O'BRIEN, P. W. 1992. Warnings during disaster: Normalizing communicated risk. *Social Problems,* 39**,** 40-57.

MILETI, D. S. & PEEK, L. 2000. The social psychology of public response to warnings of a nuclear power plant accident. *Journal of Hazardous Materials,* 75**,** 181-194.

MILETI, D. S. & SORENSEN, J. H. 1990. Communication of emergency public warnings: A social science perspective and state-of-the-art assessment. TN, USA: Oak Ridge National Lab.

MILLS, J. W. & CURTIS, A. 2008. Geospatial approaches for disease risk communication in marginalized communities. *Progress in community health partnerships: research, education, and action,* 2**,** 61-72.

MOORE, H. E., BATES, F. L., LAYMAN, M. V. & PARENTON, V. J. 1963. BEFORE THE WIND. A STUDY OF THE RESPONSE TO HURRICANE CARLA. DTIC Document.

MORGAN, M. G. 2002. *Risk communication: A mental models approach*, Cambridge University Press.

NAGELE, D. E. & TRAINOR, J. E. 2012. Geographic specificity, tornadoes, and protective action. *Weather, Climate, and Society,* 4**,** 145-155.

NATIONAL BUSHFIRE WARNINGS TASKFORCE 2009. Australia's revised arrangements for bushfire advice and alerts - 2009/2010 Fire Season.

NATIONAL HURRICANE CENTER (NHC). 2015. *Definition of the NHC Track Forecast Cone* [Online]. Available: http://www.nhc.noaa.gov/aboutcone.shtml [Accessed Aug 12 2015].

NATIONAL RESEARCH COUNCIL 1989. *Improving Risk Communication,* Washington, DC, National Academy Press.

NATIONAL WEATHER SERVICE (NWS). 2008. *Why Store-Based Warnings?* [Online]. Available: http://www.nws.noaa.gov/sbwarnings/ [Accessed Aug 12 2015].

NEUWIRTH, K., DUNWOODY, S. & GRIFFIN, R. J. 2000. Protection motivation and risk communication. *Risk Analysis,* 20**,** 721-734.

NIELSEN, J. 1993. *Usability engineering,* Boston, Massachusetts, Academic Press, Inc.

NIGG, J. M. 1995. Risk Communication and Warning Systems. *In:* HORLICK-JONES, T., AMENDOLA, A. & CASALE, R. (eds.) *Natural Risk and Civil Protection.* London: E & FN Spon.

NIVALA, A.-M., BREWSTER, S. & SARJAKOSKI, T. L. 2008. Usability Evaluation of Web Mapping Sites. *The Cartographic Journal,* 45**,** 129-138.

NOAA. 2014. *Hazard Mapping System* [Online]. [Accessed 2014].

NOBLE, I., GILL, A. & BARY, G. 1980. McArthur's fire‐danger meters expressed as equations. *Australian Journal of Ecology,* 5**,** 201-203.

NSW RURAL FIRE SERVICE (RFS) 2012. New National Mapping Symbology for incidents. *Bushfire bulletin.*

OPENLAYERS. 2015. Available: http://openlayers.org/two/ [Accessed].

PARKER, D. J., PRIEST, S. J. & TAPSELL, S. M. 2009. Understanding and enhancing the public's behavioural response to flood warning information. *Meteorological applications,* 16**,** 103-114.

PATON, D. 2006. Warning Systems: Issues and considerations for warning the public. *Douglas Paton*.

PAVEGLIO, T., CARROLL, M. S. & JAKES, P. J. Advancing the discussion of shelter-in-place as a means of protecting public safety during wildland Fire. Proceedings of Does

Evacuation Always Put Fire Safety First? Presented at the Backyards and Beyond Conference, 2007 Denver, Colorado.

PAVEGLIO, T., CARROLL, M. S. & JAKES, P. J. 2008. Alternatives to evacuation—Protecting public safety during wildland fire. *Journal of Forestry,* 106**,** 65-70.

PENMAN, T., ERIKSEN, C., BLANCHI, R., CHLADIL, M., GILL, A., HAYNES, K., LEONARD, J., MCLENNAN, J. & BRADSTOCK, R. A. 2013. Defining adequate means of residents to prepare property for protection from wildfire. *International Journal of Disaster Risk Reduction,* 6**,** 67-77.

PERRY, R. W., GREENE, M. R. & LINDELL, M. K. 1980. ENHANCING EVACUATION WARNING COMPLIANCE: SUGGESTIONS FOREMERGENCY PLANNING*. *Disasters,* 4**,** 433-449.

PERRY, R. W. & LINDELL, M. K. 1991. The effects of ethnicity on evacuation decision-making. *International journal of mass emergencies and disasters,* 9**,** 47-68.

PERRY, R. W., LINDELL, M. K. & GREENE, M. 1981. *Evacuation planning in emergency management*, LexingtonBooks.

PERRY, R. W., LINDELL, M. K. & GREENE, M. R. 1982. Crisis communications: Ethnic differentials in interpreting and acting on disaster warnings. *Social Behavior and Personality: an international journal,* 10**,** 97-104.

PIÑOL, J., TERRADAS, J. & LLORET, F. 1998. Climate warming, wildfire hazard, and wildfire occurrence in coastal eastern Spain. *Climatic change,* 38**,** 345-357.

POLLINO, M., FATTORUSO, G., DELLA ROCCA, A. B., LA PORTA, L., CURZIO, S. L., AROLCHI, A., JAMES, V. & PASCALE, C. 2011. An open source GIS system for earthquake early warning and post-event emergency management. *Computational Science and Its Applications-ICCSA 2011.* Springer.

POWELL, G. 2015. WA bushfires: Esperance bushfire warning downgraded as firefighters make progress. *ABC*.

PREPARING FOR DISASTER 2005. Editorial. *Nature,* 438**,** 889.

PRIOR, T. & ERIKSEN, C. 2012. What Does Being "Well Prepared" For Wildfire Mean? *In:* PATON, D. & TEDIM, F. (eds.) *Wildfire and Community: Facilitating Preparedness and Resilience.* Springfield, Illinois: Charles C Thomas Publishers, Ltd.

PROCHASKA, J. O., REDDING, C. A. & EVERS, K. E. 2008. THE TRANSTHEORETICAL MODEL AND STAGES OF CHANGE. *In:* KAREN GLANZ, B. K. R., AND K. VISWANATH (ed.) *Health behavior and health education: theory, research, and practice* 4th ed. San Francisco, CA: John Wiley & Sons, Inc.

QUARANTELLI, E. L. 1984. Perceptions and reactions to emergency warnings of sudden hazards. *EKISTICS-THE PROBLEMS AND SCIENCE OF HUMAN SETTLEMENTS,* 51**,** 511-515.

RAMSAY, G. C., MCARTHUR, N. A. & DOWLING, V. P. 1987. Preliminary results from an examination of house survival in the 16 February 1983 bushfires in Australia. *Fire and Materials,* 11**,** 49-51.

RHODES, A. The Australian "Stay or Go" approach: Factors influencing householder decisions. *In:* S. MCCAFFREY, P. W., M. ROBINSON, ed. Extended abstracts from the Human Dimensions of Wildland Fire conf, Oct 23-25 2007a Fort Collins, Colorado. International Association of Wildland Fire.

RHODES, A. What's Happening? An Australian Perspective on keeping the Community Informed during Major Wildfires. *In:* S. MCCAFFREY, P. W., M. ROBINSON, ed. Extended abstracts from the Human Dimensions of Wildland Fire conf, Oct 23-25 2007b Fort Collins, Colorado. International Association of Wildland Fire.

ROBINSON, A. C. 2005. Geovisualization and Epidemiology: A General Design Framework. *Proceedings of the 22nd International Cartographic Conference.* A Coru ña, Spain.

RODRÍGUEZ, H., QUARANTELLI, E. L., DYNES, R. R., RODR´ıGUEZ, H. A., D´ıAZ, W., SANTOS, J. M. & AGUIRRE, B. E. 2007. Communicating Risk and Uncertainty: Science, Technology, and Disasters at the Crossroads. *Handbook of Disaster Research.* Springer New York.

ROHRMANN, B. 1992. The evaluation of risk communication effectiveness. *Acta Psychologica,* 81**,** 169-192.

ROHRMANN, B. 2003. The utility of the World-Wide-Web for fire preparedness of residents. *Australian Journal of Emergency Management,* 18**,** 20-28.

ROTH, R. E. 2013. Interactive maps: What we know and what we need to know. *Journal of Spatial Information Science***,** 59-115.

ROTH, R. E. & HARROWER, M. 2008. Addressing map interface usability: learning from the Lakeshore Nature Preserve interactive map. *Cartographic Perspectives***,** 46-66.

RURAL FIRE SERVICE QUEENSLAND (RFSQ). 2012. *Are you bushfire prepared? Prepare. Act. Survive pamphlets* [Online]. Queensland. [Accessed].

SALMON, C. T. & NICHOLS, J. S. 1983. The next-birthday method of respondent selection. *Public opinion quarterly,* 47**,** 270-276.

SANDMAN, P. M. 1987. Risk communication: facing public outrage. *EPA J.,* 13**,** 21.

SEEDS FOR CHANGE 2013. *A consensus handbook,* UK, Seeds for Change Lancaster Co-operative Ltd.

SHARMA, U., PATWARDHAN, A. & PARTHASARATHY, D. 2009. Assessing adaptive capacity to tropical cyclones in the East coast of India: a pilot study of public response to cyclone warning information. *Climatic change,* 94**,** 189-209.

SHAW, R. & GUPTA, M. 2009. Information, education, and communication for urban risk reduction. *In:* SHAW, R., SRINIVAS, H. & SHARMA, A. (eds.) *Urban Risk Reduction: An Asian Perspective (Community, Environment and Disaster Risk Management , Volume 1).* Bingley, UK: Emerald Group Publishing Limited.

SHERMAN-MORRIS, K., ANTONELLI, K. B. & WILLIAMS, C. C. 2015. Measuring the effectiveness of the graphical communication of hurricane storm surge threat. *Weather, Climate, and Society,* 7**,** 69-82.

SHRODER, J. F. & PATON, D. 2014. *Wildfire Hazards, Risks, and Disasters*, Elsevier.

SLOVIC, P., FINUCANE, M. L., PETERS, E. & MACGREGOR, D. G. 2004. Risk as analysis and risk as feelings: Some thoughts about affect, reason, risk, and rationality. *Risk analysis,* 24**,** 311-322.

SMITH, C. F. & KAIN, D. J. 2010. Making sense of hurricanes: Public discourse and perceived risk of extreme weather. *Critical Approaches to Discourse Analysis across Disciplines,* 4**,** 180-196.

SORENSEN, J. 2000. Hazard Warning Systems: Review of 20 Years of Progress. *Natural hazards review,* 1**,** 119-125.

SORENSEN, J. H. 1991. When shall we leave? Factors affecting the timing of evacuation departures. *International Journal of Mass Emergencies and Disasters,* 9**,** 153-165.

STANDARDS AUSTRALIA 2009. A.S.3959-2009 Construction of Buildings in Bushfire-prone Areas. Sydney, Australia.

STATE EMERGENCY MANAGEMENT COMMITTEE (SEMC) 2014. Parkerville Stoneville Mt Helena Bushfire Review. Western Australia.

STEBER, M., ALLEN, A., JAMES, B. & MOSS, K. Aurora: Enhancing the capabilities of Landgate's FireWatch with fire-spread simulation. *In:* THORNTON, R. P. & WRIGHT, L. J., eds. Proceedings of Bushfire CRC & AFAC 2012 Conference Research Forum, 2012 Perth, Australia. Bushfire CRC, 115-123.

STEINMANN, R., KREK, A. & BLASCHKE, T. 2005. Can online map-based applications improve citizen participation? *E-Government: Towards Electronic Democracy.* Springer.

STEINMETZ, T., RAAPE, U., TEßMANN, S., STROBL, C., FRIEDEMANN, M., KUKOFKA, T., RIEDLINGER, T., MIKUSCH, E. & DECH, S. 2010. Tsunami early warning and decision support. *Natural Hazards and Earth System Science,* 10**,** 1839-1850.

STEWART, D. W. & SHAMDASANI, P. N. 2014. *Focus groups: Theory and practice*, Sage Publications.

SYPHARD, A. D., BRENNAN, T. J. & KEELEY, J. E. 2014. The role of defensible space for residential structure protection during wildfires. *International Journal of Wildland Fire,* 23**,** 1165-1175.

TASMANIA FIRE SERVICE (TFS). 2009. *Prepare to survive* [Online]. Available: http://www.fire.tas.gov.au/Show?pageId=colprepareHome [Accessed Apr. 12 2012].

TASMANIA FIRE SERVICE (TFS). 2012. *Bushfire Survival Plan* [Online]. Available: http://www.fire.tas.gov.au/userfiles/stuartp/file/Publications/121055-TFS-Bushfire-Survival-Booklet_lr.pdf [Accessed Dec. 10 2014].

TEAGUE, B., MCLEOD, R. & PASCOE, S. 2010. 2009 Victorian Bushfires Royal Commission: Final Report. Melbourne, Australia: State Government of Victoria.

TERPSTRA, T. & VREUGDENHIL, H. Filling in the blanks: Constructing effective flood warning messages using the Flood Warning Communicator (FWC). Proc of the 8th International ISCRAM Conference, 2011.

THOMAS, D. S. K., ERTUGAY, K. & KEMEC, S. 2007. The role of geographic information systems/remote sensing in disaster management. *In:* RODRIGUEZ, H., QUARANTELLI, E. L. & DYNES, R. (eds.) *Handbook of disaster research.* New York: Springer.

THOMPSON, M. A., LINDSAY, J. M. & GAILLARD, J. C. 2015. The influence of probabilistic volcanic hazard map properties on hazard communication. *Journal of Applied Volcanology,* 4**,** 1-24.

TIBBITS, A., HANDMER, J., HAYNES, K., LOWE, T. & WHITTAKER, J. 2008. Prepare, stay and defend or leave early: Evidence for the Australian approach. *In:* HANDMER, J. & HAYNES, K. (eds.) *Community Bushfire Safety* Collingwood: CSIRO.

TIBBITS, A. & WHITTAKER, J. 2007. Stay and defend or leave early: policy problems and experiences during the 2003 Victorian bushfires. *Environmental Hazards,* 7**,** 283-290.

TOLHURST, K. 2009. Report On Assessing Defendable Space Around Houses In Bushfire-Prone Environments. University of Melbourne, Victoria, Australia.

TOLHURST, K. & HOWLETT, K. House ignition likelihood index—An hazard assessment method for land managers in the wildland-urban interface. 10th AFAC Conference and 3rd International Wildland Fire Conference, 2-6, October 2003 2003 Sydney, Australia.

TOLHURST, K. G., SHIELDS, B. J. & CHONG, D. M. 2008. Phoenix: Development and Application of a Bushfire Risk Management Tool. *Australian Journal of Emergency Management,* 23**,** 47.

TRIGG, J., RAINBIRD, S., THOMPSON, K., BEARMAN, C., WRIGHT, L. & MCLENNAN, J. 2015a. Capturing community experience: South Australian bushfires January 2014. Australia: Bushfire and Natural Hazards CRC.

TRIGG, J., RAINBIRD, S., THOMPSON, K., BEARMAN, C., WRIGHT, L. & MCLENNAN, J. 2015b. Capturing community experiences: South Australian bushfires January 2014. Melbourne, Australia: Bushfire and Natural Hazards CRC.

TUFTE, E. R. & GRAVES-MORRIS, P. R. 1983. *The visual display of quantitative information,* Cheshire, CT, Graphics Press.

U.S. GEOLOGICAL SURVEY. 2012. *USGS Flood Inundation Mapping Program* [Online]. Available: http://water.usgs.gov/osw/flood_inundation/ [Accessed Oct 2014].

UNITED NATIONS INTERNATIONAL STRATEGY FOR DISASTER REDUCTION (UNISDR). Hyogo framework for action 2005–2015: Building the resilience of nations and communities to disasters. World Conference on Disaster Reduction, January 18-22 2005 Kobe, Hyogo, Japan.

VICROADS. 2014. *VicTraffic* [Online]. Available: http://traffic.vicroads.vic.gov.au/ [Accessed Oct 10 2015].

WAHLQUIST, C. 2016. Firefighters criticise Yarloop bushfire inquiry, saying it should be broader. *The Guardian*.

WEBSTER, J. 2000. *The complete bushfire safety book,* Sydney, Random House.

WESTERLING, A. L., HIDALGO, H. G., CAYAN, D. R. & SWETNAM, T. W. 2006. Warming and Earlier Spring Increase Western U.S. Forest Wildfire Activity. *Science,* 313**,** 940-943.

WHITAKER, R. 2010. *The Complete Book of Australian Weather,* Sydney, Allen & Unwin.

WHITTAKER, J. & HANDMER, J. 2010. Community bushfire safety: a review of post-Black Saturday research. *Australian Journal of Emergency Management, The,* 25**,** 7.

WHITTAKER, J., HAYNES, K., HANDMER, J. & MCLENNAN, J. 2013. Community safety during the 2009 Australian 'Black Saturday' bushfires: an analysis of household preparedness and response. *International Journal of Wildland Fire*.

WHITTAKER, J., HAYNES, K., MCLENNAN, J., HANDMER, J. & TOWERS, B. 2010. Household mail survey. Research Results from February 7th Victorian Fires Second Report on: Human Behaviour & Community Safety. Melbourne, Australia: Bushfire CRC.

WHITTAKER, J., MACLENNAN, J., ELLIOTT, G., GILBERT, J., HANDMER, J., HAYNESM, K. & COULISHAW, S. 2009. Victorian 2009 Bushfire Research Response: Final Report. Bushfire CRC Post-fire Research Program in Human Behaviour. Melbourne, Australia: Bushfire Cooperative Reserach Center.

WILLIAMS, A. A. J., KAROLY, D. J. & TAPPER, N. 2001. The sensitivity of Australian fire danger to climate change. *Climatic change,* 49**,** 171-191.

WILSON, A. A. & FERGUSON, I. S. 1984. Fight or flee?—a case study of the Mount Macedon bushfire. *Australian Forestry,* 47**,** 230-236.

WILSON, A. A. G. 1988. A Simple Device for Calculating the Probability of a House Surviving a Bushfire. *Australian Forestry,* 51**,** 119-123.

WOOD, M. M., BEAN, H., LIU, B. F. & BOYD, M. 2015. Comprehensive Testing of Imminent Threat Public Messages for Mobile Devices: Final Report. *Report to the Homeland Security Advanced Research Projects Agency, Science and Technology Directorate, U.S. Department of Homeland Security.* College Park, MD: National Consortium for the Study of Terrorism and Responses to Terrorism.

YOON, J.-H., KRAVITZ, B., RASCH, P. J., SIMON WANG, S.-Y., GILLIES, R. R. & HIPPS, L. 2015. Extreme Fire Season in California: A Glimpse Into the Future? *Bulletin of the American Meteorological Society,* 96**,** S5-S9.

ZHANG, Y., PRATER, C. S. & LINDELL, M. K. 2004. Risk area accuracy and evacuation from Hurricane Bret. *Natural Hazards Review,* 5**,** 115-120.

Appendix 1: Examined preparatory actions, criticality ratings adopted for the baseline instrument, and the responses from all three small groups

	Baseline rating (the most conservative response)	Small group responses*
Section 1. Critical actions with consensual ratings		
[a] Within the *Inner Zone,* clear dry grass, leaf litter, bark and twigs from around the house.	All FDRs	
[a] Within the *Inner Zone,* cut long grass.	All FDRs	
[a, b] Within the *Inner Zone,* remove flammable shrubs from under and between trees.	Very High	
[a] Within the *Inner Zone,* make sure that no large shrubs are next to or below a window.	All FDRs	
[a] Within the *Inner Zone,* ensure that no trees are overhanging the roofline.	All FDRs	
[a] Within the *Inner Zone,* remove flammable vines from the walls of the house.	All FDRs	
Ensure that roof gutters and valleys are clear of leaves and bark.	All FDRs	
[c] Clear leaves, bark and combustible materials in the area under decking.	All FDRs	
Remove any wood piles, timber, fuel containers, flammable rubbish and old junk lying within 20m of the house.	All FDRs	
Keep BBQs and gas cylinders on the side of the house furthest away from the likely direction of a fire (where the bush is), and ensure the areas (e.g. 5m) around them are clear of ground fuel.	All FDRs	
Ensure that the pressure relief valves on LPG cylinders near the house face outwards (so flames are not directed toward the house).	All FDRs	
Seal roof junctions, gaps around roof lights, ventilators and evaporative cooler with non-combustible materials.	All FDRs	

	Baseline rating (the most conservative response)	Small group responses*
Obtain and prepare equipment to put out spot fires and sparks, such as rakes, shovels, and mops.	All FDRs	
Obtain a portable battery operated AM/FM radio.	All FDRs	
Obtain full-length protective clothing (wool, cotton) for all the family members who are staying to defend. This should include gloves, eye protection, smoke mask, work boots, and a broad brimmed hat.	All FDRs	

Section 2. Critical actions with no consensus concerning the FDRs under which they are critical

	Baseline rating (the most conservative response)	Small group responses*
[c] Clear vegetation and debris from all supporting posts, columns, stumps, piers, and poles in the flooring system and beneath the floor.	All FDRs	All FDRs / Very High
Ensure that any mulch around the house or in the garden is non-flammable, that is, any flammable mulch is kept well away from the house, or well treated or watered.	All FDRs	All FDRs / Severe
Seal gaps in all joins between external walls and cladding.	All FDRs	All FDRs / Very High
Seal gaps around window frames.	All FDRs	All FDRs / Very High
Ensure that garage doors are tight fitting to door frame if a garage is attached to the house.	All FDRs	All FDRs / Very High / Severe
Enclose eaves and seal all gaps between fascias or rafters.	All FDRs	All FDRs / Very High / Severe
[d] Enclose under floor spaces with screens or shutters.	All FDRs	All FDRs / Very High / Severe
Ensure the roofing material on the house is fire-resistant (e.g. metal, tile, composition).	All FDRs	All FDRs / Very High
Ensure that there is no combustible material on the deck adjacent to the house.	All FDRs	All FDRs / Extreme
Acquire firefighting hoses and pump which can reach all parts of the house (including roof), and ensure they are operational.	All FDRs	All FDRs / Very High
If a diesel or petrol firefighting pump is not portable or mobile, cover it or place it where it can be protected from radiant heat and direct flame contact.	All FDRs	All FDRs / Very High

	Baseline rating (the most conservative response)	Small group responses*
		Severe
Acquire a generator for use as a backup power supply if using an electric pump.	**All FDRs**	**All FDRs** **Very High**
Acquire ladders that are long enough to allow for checking the roof cavity and eaves and to put out spot fires sparks on the roof.	**All FDRs**	**All FDRs** **Very High**
For pipes that are essential to water delivery, ensure that they are metal; or bury non-metal pipes to a depth of at least 300mm below the finished ground level.	**All FDRs**	**All FDRs** **Very High**
Obtain a sufficient independent water supply (quantity depends on specific regulations) for firefighting purposes only, such as tank, dam or pool.	**All FDRs**	**All FDRs** **Very High**
Locate water tanks (particularly plastic) for firefighting use on the non-hazard side of the building, and ensure there is no vegetation or combustible material around them.	**All FDRs**	**Very High** **Severe**
Ensure no person has disability that will prevent him/her from actively defending.	**Very High**	**All FDRs** **Severe**
Ensure those staying are fully committed to defending the home.	**All FDRs**	**All FDRs** **Very High** **Severe**
Decide beforehand under which specific conditions (e.g. the fire danger rating, whether or not there are visitors over) individuals will defend and under which they will evacuate.	**All FDRs**	**All FDRs** **Severe**
Ensure that every person who intends to stay and defend (under pre-defined conditions) is clear on, and have practiced the fire response plan together with other household members who will be defending.	**All FDRs**	**All FDRs** **Very High** **Severe**
Prepare a contingency plan for if the initial plan to defend fails, including an appropriate spot for sheltering-in-place.	**All FDRs**	**All FDRs** **Very High**

Section 3. Critical actions with no consensus concerning their criticality

[a, e, f] Within the *Outer Zone,* rake up and remove leaf litter and twigs under trees.	**All FDRs**	**All FDRs** **Severe** **Not Critical**

	Baseline rating (the most conservative response)	Small group responses*
[a, e] Within the *Outer Zone,* cut long grass.	All FDRs	All FDRs / Severe / Not Critical
[a, g] Within the *Outer Zone,* cut dead material (e.g. detached branches or bark) on at least 50% of the outer zone.	Extreme	Extreme / Not Critical
[a] Within the *Outer Zone,* selectively remove shrubs and small trees to create clumps, and maintain distance between clumps and larger trees.	Very High	Very High / Severe / Not Critical
[a, h] Within the *Inner Zone,* thin a 4m space between tree crowns.	Very High	Very High / Severe / Not Critical
[a] Within the *Inner Zone*, ensure that all trees on or near the property are away from overhead utility lines.	All FDRs	All FDRs / Severe / Not Critical
[a] Within the *Inner Zone,* replace all highly-flammable plants with low-flammable plants.	All FDRs	All FDRs / Severe / Not Critical
Maintain the paint on window sills so there is no flaking or exposed wood.	All FDRs	All FDRs / Not Critical
Seal gaps around external doors using non-combustible weather strips and draught stoppers.	All FDRs	All FDRs / Very High / Not Critical
Block all vents and weepholes (e.g. chimneys, stovepipes) with wire mesh screens 2.0mm (not aluminium).	All FDRs	All FDRs / Severe / Not Critical
Ensure that windows exposed to radiant heat sources (e.g. vegetation, sheds and woodpiles) are protected by window shutters.	Extreme	Extreme / Not Critical
Cover windows not protected by shutters with wire mesh screens 2.0mm (not aluminium).	Severe	Severe / Extreme / Not Critical
Fit roller shutters with an ember guard at the top of the garage door if the garage is attached to the house.	Severe	Severe / Extreme / Not Critical
Install non-combustible sarking (lining) under roofing.	Very High	Very High / Not Critical

	Baseline rating (the most conservative response)	Small group responses*
Ensure that decking is made of fire-retardant timber or non-combustible materials.	Severe	Severe / Not Critical
[i] Have a non-combustible doormat, or remove the doormat when there is a fire danger.	All FDRs	All FDRs / Severe / Not Critical
Prepare buckets that allow you to move water quickly and easily.	Very High	Very High / Not Critical
Ensure there are at least two adults staying and actively defending.	Very High	Very High / Severe / Not Critical
[j] Ensure there is no elderly who is not fit to defend being involved in the defending process.	All FDRs	All FDRs / Severe / Not Critical
[j] Ensure there is no child under 16 staying and actively defending.	Severe	Severe / Not Critical
[j] Ensure there is no frail/vulnerable person staying and actively defending.	All FDRs	All FDRs / Severe / Not Critical
[j] Ensure there is no person with mental health conditions staying and actively defending.	All FDRs	All FDRs / Very High / Not Critical
[k] Take into account that active defence could last for many hours to days.	Severe	Severe / Not Critical
[k] Prepare themselves emotionally for the possibility that their home may still be destroyed, even if they defend it.	All FDRs	All FDRs / Severe / Not Critical
[k] Prepare themselves emotionally for the possibility that staying and defending their homes may cause emotional trauma, injury and death.	All FDRs	All FDRs / Severe / Not Critical
Plan what will be done with pets and/or livestock.	All FDRs	All FDRs / Very High / Not Critical
[l] Ensure their neighbours know about their household's intended fire plan.	All FDRs	All FDRs / Severe / Not Critical

	Baseline rating (the most conservative response)	Small group responses*	
Have a fire shelter or bunker built in the home which can provide for shelter-in-place if necessary. (It must comply with building regulations for private bushfire shelters, regarding things such as accessing and exiting the shelter and tenability of air supply.)	Severe	Severe	Not Critical

Section 4. Non-critical Items with full consensus

[a] Within the *Outer Zone,* ensure that any trees and shrubs that are planted are low in oil content, making them less likely to ignite.	Not Critical	
[a] Within the *Outer Zone,* retain established trees to trap embers and reduce wind speeds.	Not Critical	
[a] Within the *Outer Zone,* conduct controlled burning on your property to reduce the fuel load within the last 6 months.	Not Critical	
[a] Within the *Inner Zone,* prune lower tree branches (up to 2m off the ground).	Not Critical	
[a] Within the *Inner Zone,* chemically treat the area around outbuildings and sheds to prevent the regrowth of vegetation.	Not Critical	
Clear vegetation along the boundary of the property to create a firebreak.	Not Critical	
Establish a landscaped garden, vegetable garden, cultivated soil or gravelled areas on the fire-prone side of the home.	Not Critical	
Build wide paths, paving, driveways, or tennis court that can provide fuel breaks.	Not Critical	
Locate any dams, pools and any effluent disposal areas on the side of buildings facing the most likely direction of fire.	Not Critical	
Create radiation shields and windbreaks such as stone or metal fences and hedges using low-flammability plants.	Not Critical	
[m] If gutter protection is installed, ensure it is made of non-flammable materials (e.g. metal).	Not Critical	
Ensure that external house timbers have a sound coat of paint.	Not Critical	
Install wire mesh screens 2.0mm (not aluminium) over all external doors.	Not Critical	
Ensure that decking has a minimum 8mm gap between timber planks.	Not Critical	
Ensure that shade cloth is made from non-combustible materials, or remove the shade cloth when there is a fire danger.	Not Critical	
Know the maximum operating temperature as specified for the pump by the manufacturer.	Not Critical	
Acquire at least one fire extinguisher for inside the home.	Not Critical	

	Baseline rating (the most conservative response)	Small group responses*
Ensure that smoke alarms are fitted on every level of the house as required under legislation.	Not Critical	
Prepare knapsack spray or garden backpack spray to help you put out spot fires. If using a garden backpack make sure it has been cleaned out before using it in a bushfire.	Not Critical	
Install a sprinkler system around the property.	Not Critical	
Install a roof-mounted sprinkler system.	Not Critical	
Obtain a waterproof torch.	Not Critical	
Obtain new spare batteries.	Not Critical	
Obtain first aid kit with manual.	Not Critical	
Obtain woollen blankets/towels.	Not Critical	
Ensure that home and content insurance is adequate.	Not Critical	
Display a prominent house number.	Not Critical	
Ensure there is adequate access for fire trucks to your property – 4m wide by 4m high with a turn-around area.	Not Critical	
Reduce vegetation loads along the access path.	Not Critical	
Obtain an emergency supply of drinking water (quantity needed will depend on specific recommendation by local agencies).	Not Critical	
Obtain sufficient canned or dried food (quantity needed will depend on specific recommendation by local agencies).	Not Critical	
Obtain a water container suitable for washing or cooking.	Not Critical	
Obtain a can opener, portable cooking gear and eating utensils.	Not Critical	

Note:

All FDRs = this item is critical at all FDR levels; Very High = this item is critical at Very High, Severe and Extreme FDR levels;

`Severe` = this item is critical at Severe and Extreme FDR levels; `Extreme` = this item is critical at the Extreme FDR level only;

`Not Critical` = this item is not critical at any FDR level.

* Small group responses are only shown for items in section 2 and 3, which did not obtain full consensus in the workshop.

a. The desired distance for the *Inner Zone* and *Outer Zone* need to be explicitly defined.

b. Argued by the experts is that the criticality of this action is 'contingent upon the amount and location of the vegetation'. Therefore further revision may be needed to restrict the conditions under which this action must be completed. An example of clarification could be to 'remove flammable shrubs from under and between trees within 10m of the house'.

c. One group originally rated this item as critical at `Very High` but agreed to change to `All FDRs`. However, comments were made that whether this item was critical or not 'depends on the amount' of leaves and barks, etc. This item may be altered to 'ensure there is not a large amount of vegetation, leaves, barks and combustible materials' in the associated areas.

d. This action may be an alternative to the item 'clear vegetation and debris around all supporting posts, columns, stumps, piers, and poles in the flooring system and beneath the floor' as recommended by one group, implying that these two items may be merged and the completion of either one is considered sufficient.

e. The group rating this action as critical at `All FDRs` considered it to be more critical for larger properties. Agencies that intend to include this action as a critical item may specify that it is only critical for large properties in rural areas.

f. Another argument of this action being critical at `Severe` is that the leaf litters can be blown into the inner zone.

g. The criteria of 50% may be reconsidered.

h. Jurisdictions may have different regulations regarding vegetation management, and therefore this item may be replaced and its critical nature should be reassessed.

i. The group rated this action as `Not Critical` because 'it can be completed on the day'. However, this item should remain in the checklist of critical actions as a decision-support tool for measuring preparedness during a fire danger. Householders will be reminded to remove the combustible doormat if have not done so at the time of use.

j. This action is related to people's capability of actively defending if planning to stay. Most experts agreed that the assessment should not be restrained to a set of generic indicators of age, disability or other characteristics. It may be sufficient to only ask people to make their own decision of their capability regarding active defence.

k. The group that rated this action as `Severe` commented that it was contingent on the location of the property. Further conditions may be given to define its criticality, such as highly risky areas surrounded by dense forest.

l. This action was identified as contingent upon proximity from people's house to the neighbours'. Further conditions should be given to clarify the distance within which the neighbours should be informed if considered as critical for staying and defending.

m. This action was considered as an alternative to the item 'ensure that roof gutters and valleys are clear of leaves and bark' in section 1 by one group. In such case, these two items should be merged. However, the other groups commented that some gutter protectors can be counterproductive and fuel clearance should still be prioritised. Therefore the application of this action should be re-examined.

Appendix 2.

"Should I Stay or Should I Go?" Defining the Preparatory Conditions in Support of Active Defence for Different Fire Danger Ratings

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Abstract.

In Australia, householders can stay and defend their properties during a bushfire if the household is adequately prepared. State (and territory) fire agencies have provided householders with checklists of desirable preparatory actions, including property preparation, judging ability of individuals, and acquiring equipment and resources for active defence. However, the lack of consistency in the existing checklists implies not all the listed preparatory actions are *critical* for making the decision of actively defending; in addition, agencies agree that the levels of desired preparedness should be associated with Fire Danger Ratings (FDR), the indicator of fire weather intensity. Still, no clarification exists concerning the exact levels to which a household should prepare to actively defend during different FDRs. This study therefore attempts to explore the *critical* nature of preparatory actions in relation to FDRs based on expert knowledge. To this aim, a survey was conducted with bushfire experts who were requested to rate whether each preparatory action is critical under different FDR conditions. Results from 36 experts confirmed our hypothesis that some preparatory items are not critical or only critical at certain FDRs. However, a more in-depth study with a range of experts is required to provide further consensus concerning the critical preparatory actions and to clarify discrepancies of opinions for items highlighted as controversial through the survey process.

Background

The AFAC policy (2010, p.11) on Bushfires and Community Safety states that 'people usually have two safe options when threatened by bushfire: leaving early or actively defending adequately prepared properties'. Therefore, it is important for householders to understand what is meant by 'being adequately prepared' when deciding on whether or not to defend their property. However, post-fire studies have indicated that many people who plan to stay and defend often overestimate their preparedness levels and capability to actively defend a property (Handme *et al.* 2010; McLennan *et al.* 2011; Whittaker *et al.* 2013). One major issue that may have contributed to the misjudgement is the lack of explicit explanation or guidelines for sufficient household preparedness for staying and defending.

The AFAC position paper (2010) has outlined two major aspects concerning household preparedness to enhance the chance of successfully staying and defending:

a) The defendability of a property. House defendability should be ensured by creating and maintaining a defendable space, within which bushfire fuels must be reduced to eliminate or significantly attenuate the ability of a fire to burn and spread to buildings, as well as ember-proofing the building structure to minimise the chance of its ignition (AFAC 2010).

b) Householders' competence in defending their home. The AFAC position paper (2010, p. 10) identified that 'for those planning to defend their homes, they must ensure that they are fit, and have personal protective equipment, adequate water supplies and firefighting equipment for the expected fire conditions'. In addition to physical fitness, defenders must also be psychologically ready to cope with trauma and injury and strategically plan for different circumstances and possible predicaments during the active defence (AFAC 2010).

Corresponding to these aspects of household preparedness, fire agencies across Australia have provided householders with checklists of desirable preparatory actions.

However, the existing checklists are only suggestive, and do not provide definitive insight into the required preparatory actions for staying and defending or whether completing a subset is sufficient. In addition, there is little consistency among the various agency-distributed preparation checklists across Australia. Although several studies have attempted to identify subsets of the more important preparatory activities (Paton *et al.* 2006; McLennan and Elliott 2011), these checklists were only developed as research instruments, and thus cannot serve as an indicator of sufficient preparedness in an operational setting. Further research is needed to investigate the operational significance of agency-listed preparatory actions in relation to households' safety for staying and defending.

Furthermore, the current risk communication materials distributed by Australian fire agencies (e.g. CFA 2010; DFES 2012) propose different required levels of preparedness depending on the Fire Danger Rating (FDR) levels. The current FDR system (as summarised in Table 1) is derived from the Fire Danger Index and intends to provide a scale to indicate potential fire behaviour (if started), and the difficulty of suppression given the forecasted weather conditions (Dowdy *et al.* 2009). Table 1 shows a sample of messages distributed by the Country Fire Authority (2010) concerning the meaning of FDRs and their relationships with the action of staying and defending. It illustrates that higher levels of preparedness are desired for actively defending a property at higher FDR levels. The terminology in the messages is abstract, however, in that it does not specify what being sufficiently prepared entails under different FDRs.

This study attempted to explore the *critical* nature of preparatory actions in relation to FDRs based on expert knowledge. A survey was conducted with relevant experts across Australia. In this paper, the following research questions are to be investigated via the analysis of experts' responses:

i. Are some preparatory actions critical for staying and defending whilst some are not so?

ii. Does the critical nature of a preparatory action for staying and defending vary at different FDR levels?

Table 1. Fire Danger Ratings and associated advices regarding household preparedness for staying and defending (adapted from Country Fire Authority 2010, *Prepare. Act. Survive. Fire Ready Kit.*)

FDR Categories	Fire Danger Index	What does it mean?	Staying and defending can only be considered if one's home is…
Catastrophic (Code Red)	100+	These are the worst conditions for a bush or grassfire. Homes are not designed or constructed to withstand fires in these conditions.	Never
Extreme	75 – 99	If a fire starts and takes hold, it will be uncontrollable and unpredictable. Spot fires will start, move quickly and come from many directions.	Situated and constructed or modified to withstand a bushfire, prepared to the *highest* level and can be actively defended.
Severe	50 – 74	If a fire starts and takes hold, it may be uncontrollable.	*Well prepared* and can be actively defended.
Very High	25 – 49	If a fire starts, it can most likely be controlled in these conditions.	Not stated
High	12 – 24		
Low to Moderate	0 – 11		

Throughout this paper, a '**critical**' preparatory action is referred to as an item that is essential for staying and defending in a bushfire; failing to complete a 'critical' item will dramatically decrease the chance of house survival or the possibility of properly defending the property, and thus actively defending is probably not a safe option under such circumstances. On contrary, some items may be helpful but not necessary, and thus should be regarded as non-critical. Failing to complete such items will have only a slight impact on the chance of successful defence if all the critical items have been assured. Theoretically, the clarification of the critical nature of the preparatory actions will provide better reference for residents to assess their preparedness level and make relatively sound and confident decisions regarding

active defence; however, it should be recognised that the safety of a household in a bushfire can never be guaranteed, especially during intensive fires.

An exploratory study of preparatory actions

Collection of preparatory items

A comprehensive checklist of preparatory actions was derived from a range of agency-distributed materials concerning household preparedness, including the 'Prepare. Act. Survive' pamphlets released by seven Australian state (and territory) agencies[4] and two materials from U.S. organisations[5].To integrate all materials, similar items were amalgamated, while omnibus items with multiple detailed actions were split to form an accurate and inclusive list of 100 items. Furthermore, the items were classified into sixteen categories (as shown in Table 2) that were created based on the important preparation aspects identified by the AFAC position paper (e.g. preparation for property defendability, judging ability of individuals, and acquiring equipment and resources for active defence) for the purpose of delineating the entire collection of preparatory actions.

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[4] North Territory was the only state excluded in this review because no specific Prepare. Act. Survive brochure was released online by the time of research.

[5] The two U.S. materials are 'Wildfire Preparedness' released by American Red Cross, and 'Checklist for Homeowners' developed by the Federal Emergency Management Agency.

Table 2. Categories of household preparatory actions included in the collective checklist

Categories			Code	Number of preparatory actions
PROPERTY DEFENDABILITY	To create defendable space, …	Create an *Outer Zone* by managing vegetation and reducing fine fuels.	D1	7
		Maintain vegetation and clear fine fuel within the *Inner Zone.*	D2	12
		Clear flammable materials within the *Inner Zone*.	D3	5
		Create fire breaks within the defendable space.	D4	5
	To Ember-proof the house, …	Clear fine fuels and combustible materials on the building.	D5	4
		Block all gaps in a structure and place metal fly wire mesh on all vents.	D6	13
		Use non-combustible building materials.	D7	9
PEOPLE, RESOURCE AND EQUIPMENT TO ACTIVELY DEFEND	Prepare equipment for actively defending.		D8	10
	Prepare water resource for actively defending.		D9	5
	Prepare food and water supply for people who are actively defending the home.		D10	4
	Prepare survival kit.		D11	7
	Ensure accessibility for firefighters.		D12	3
	Ensure coping capacity of those who are staying and defending the home.		D13	6
	Prepare psychologically for staying and defending.		D14	6
	Plan for staying and defending.		D15	3
	Prepare a fire shelter or bunker to shelter in home as a last resort.		D16	1

Questionnaire

In May 2012, a questionnaire based on the collective list of preparatory actions was deployed online. In the beginning of the survey, a self-assessment question was used to ensure only experts who are familiar with the pertinent subjects complete the survey. A snowball sampling strategy was employed to recruit preparedness experts from state (and territory) bushfire agencies as well as research institutions across Australia. A list of 48 contacts consisting of relevant experts from each organisation was initially constructed based on recommendations

by our personal network and identification through a web search. Emails were sent to each identified expert to request their participation in the survey if they held the necessary level of expertise; moreover, they were asked to help circulate the survey to or provide recommendations of the appropriate personnel within their organisations. Two reminders were sent in two-week intervals. A total of six additional experts were suggested during this process and were thus emailed following the same contact protocol. Besides this, some experts helped propagate the survey link within their personnel's email network. Eventually thirty-six valid responses were garnered. A majority of the participants (33/36) were agency-based emergency management officers and/or experienced fire fighters, and the other three responses came from bushfire community safety related researchers.

When examining overlap of items across the different materials, around 32% of items were mentioned by four or more of the nine reviewed materials. These items may be more important than others as they were more consistently mentioned. For instance, the item 'cut long grass within the inner zone' is probably critical to mitigate fire impact as it is mentioned by all nine agencies.

Within the questionnaire, fire experts were asked to identify 'at which FDR level(s) does each preparatory action become critical and therefore needs to be completed by the household in order to stay and defend', followed by the definition of '**critical'** preparatory actions. Logically, a preparatory action that is critical at low FDRs should also be critical at high FDRs; however, an action that is not necessary at low FDRs may turn out to be critical at high FDRs to fortify the protection against severe fire conditions. Therefore six options, as listed in Table 3, were given for the raters to choose from. This particular method was adopted to provide an understanding of whether an item is critical for staying and defending, and if yes, whether it is critical at all FDRs. The ratings associated with FDRs should be interpreted as a scale of how critical it is to complete a preparatory item for staying and defending. The items rated as critical at all FDRs are considered to be the most critical and should be completed under any bushfire condition to provide primary protection for active defence. The items rated

as critical at Extreme FDR only serve as vital protection for a property only under severe fire circumstances when the fire can easily become out of control. Furthermore, items rated as not critical at any FDR levels are not considered as necessarily critical, and failing to complete them should not influence the choice of staying and defending in any fire condition. The five viable answers were thus translated to an indicator representing how critical an item is based on a five-point ordinal scale from 0-4, where a larger value signifies a preparatory item is more critical to complete for staying and defending.

Table 3. Rating scale adopted in the Household Preparedness Survey and the coding values for analysis

Answers from the survey	Code
The preparatory item is critical at the FDR Levels of ...	
Low-Moderate, High and all levels above	4
Very High and all levels above	3
Severe and all levels above	2
Extreme level only	1
Not critical at any levels	0
Not sure	Missing Value

Analysis of Survey Results

Criticality ratings

Most preparatory actions obtained at least 32 valid rating values from the survey. All of the experts differentiated their ratings for the 100 items using the 0 to 4 spectrum identified in Table 3. Some experts adopted a more conservative approach than others by rating a large portion of the items as 4, but small clusters of 0 ratings were also observed for some items. This suggests that the experts acknowledged the different degrees of importance inherent in the preparatory actions, and there was relative agreement that some preparatory actions are not critical in making the decision of staying and defending.

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A calculation of the mean rating values for each preparatory item manifested that on average, 70/100 of the items were rated greater than 3 (M_{max} = 3.8), while 29/100 of them were between 2 and 3 and only one item was rated below 2 (M_{min} = 1.2). The average rating for each item was compared with the overall mean rating value ($M_{overall}$ = 3.11) through one sample t-tests. As shown in Table 4, 29 items obtained average ratings significantly higher than 3.11 and 15 items obtained average ratings significantly lower than that. The differences in ratings among the items are thus not due to chance, supporting the idea that the critical nature of the preparatory actions should vary at different FDRs. We then examined the relationship between the average rating values and the number of references. For the items referenced in less than four sources, 16 items were rated significantly higher than average (3.11) while 13 were rated significantly lower than 3.11; in contrast, the ratio is substantially larger for the items referenced by four or more sources (12 items significantly larger than 3.11 and one item significantly lower than that). This confirms our prediction that less referenced items may be less critical (i.e. lower rating scores) for staying and defending; however, 'number of sources' is not an explicit indicator of how critical a preparatory action is.

Table 4. **Comparison of item mean rating values with the overall mean value (3.11)**

Item mean rating value	Number of preparatory Items			
	From 1 -3 sources	From 4 - 9 sources	Other[a]	Total
$>= 3.11$	33	24	1	58
(significantly* >=3.11)	(16)	(12)	(1)	(29)
< 3.11	34	7	1	42
(significantly < 3.11)	(13)	(1)	(1)	(15)
Total	67	31	2	100
				(44)

* $p < 0.05$, based on one sample t-tests to compare the mean rating value of each item against overall mean value.
a. Two items were not sourced from the reviewed materials, and their average rating values are both significantly different from 3.11. The first one is 'have a fire shelter or bunker built in the home which can provide shelter for people', rated as 1.2 on average. The safety of this item has been a controversial, but its construction has been specifically regulated (ABCB 2010), and a well-designed bushfire shelter is recognised as a useful backup option (VBRC 2009). The second item, 'be fully committed to defending the home', was rated as 3.36 on average. Although not explicitly listed in the current materials, this item is proven to be an important facilitator for successfully staying and defending (Brennan 1998).

Interrater Agreement

The interrater agreement (IRA) was investigated to explore whether it is possible to build a national consensus on the identification of critical vs. non-critical preparatory actions at various FDR levels. Analysis of IRA is usually employed to test the absolute agreement among human judges for rating a subject (Richardson 2010). In the present case, two common indices, the r_{wg} (James *et al.* 1984) and Average Deviation (AD) index (Burke and Dunlap 2002), were calculated for each preparatory item. The r_{wg} derives from a comparison of the actual variance obtained from multiple raters and the variance expected in the case of no agreement (usually reflected by assuming a uniform response distribution). Values for r_{wg} should range between 0 and 1 with larger values indicating better agreement. However, negative values of r_{wg} can be observed when the actual variance exceeds the expected variance for a random response, suggesting a complete disputation (LeBreton and Senter 2008). According to the interpretation of r_{wg} statistics proposed by LeBreton and Senter (2008), 46/100 preparatory actions suggested moderate to high level of agreement with r_{wg} values larger than .50, and 27/100 were between .30 and .50, denoting a week agreement. The remaining 27/100 of the items showed discrepancy among experts' answers with r_{wg} values less than .30.

We further calculated AD, which estimates agreement in the metric of the original scale by averaging the absolute deviation of each rating from the overall mean rating. Accordingly, smaller values of AD indicate better agreement. The AD values calculated for the 100 items ranged from 0.28 to 1.30; 79/100 of the estimates were less than 1.01, the cut-off point for a five-point scale with 36 judges (Burke and Dunlap 2002), suggesting a high level of agreement.

By cross-referencing the IRA indices with the number of sources and mean rating values for the 27 controversial preparatory items (identified as lack of agreement by r_{wg}) in Table 5, we discovered that 23/27 (85%) items were collected from 1 to 3 source materials, and 18/27 (67%) items were with average rating values less than 3. This coincides with our initial

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conjecture that the controversial items are those less referenced in the sourced materials; however, not all the less recommended items were controversial. In addition, given that only 30/100 items in the overall checklist were rated below 3 on average, it is apparent that the items with low mean rating values occupy a larger proportion (67%) in the list of controversial items. It implies that discrepancy mostly happened when a group of experts provide an item with low rating scores, referring to a rating as critical only in severe fire scenarios or not critical at all.

One major reason for the disagreement is that some experts tended to adopt a conservative approach by rating most items to be critical at all FDR levels, whereas some experts employed a distinct strategy by distinguishing the preparatory items as related to the corresponding FDRs. For instance, item D6_13 'install wire mesh screens 1.5mm (not aluminium) over all external doors' obtained nine ratings of 4, ten ratings of 3, seven ratings of 2, three ratings of 1 and another three of 0. One expert supplemented his rating of 0 by commenting that this item is 'unnecessary if other listed actions undertaken'. Some raters may have held a similar position by rating it as 1 or 2, while the others probably took a more conservative approach. In fact, all the nine ratings of 4 in this case were served by conservative raters who rated more than 70% of the preparatory items as 4. A different type of discrepant distribution of ratings can be observed of item D10_9, 'ensure that smoke alarms are fitted on every level of the house'. Twenty-nine experts rated this item as 4 with a comment that 'this is part of a general requirement and not linked to a FDR', whilst three experts gave scores of 3, 2 and 1 respectively, and another three rated it as 0, coupled with a comment that it 'will not provide reliable warning of fire in the home due to presence of bushfire smoke'. It is evident in this case that most experts considered this item as highly critical, whereas several experts held extremely different opinions, which could not be fully explored through the survey process.

Thereby, an in-depth study with a taskforce of experts in an interactive environment is needed with the aim to obtain concrete consensus for rating the preparatory items, or explore the complex reasons for disputation. Given that nearly half of the items received moderate

agreement indicated by both r_{wg} and AD, it is promising that acquiring expert consensus is possible, at least for a subset of the checklist. The results would therefore be valuable to serve as a unanimous national starting point for bushfire agencies to start clarifying the checklist and identifying the critical items for different FDRs in local contexts so as to define the necessary preparatory conditions for staying and defending.

Table 5. Controversial preparatory items identified by r_{wg}

Preparatory Items	Mean ±SD	AD	r_{wg}	Sources[a]
D2_11: Within the Inner Zone, replace all highly-flammable plants with low-flammability plants.	3.1 ±1.26	0.97	0.20	FEMA. NSWRFS. TFS
D2_12: Within the Inner Zone, chemically treat the area around outbuildings and sheds to prevent the regrowth of vegetation.	3.0 ±1.26	0.95	0.20	CFS
D3_4: Within the Inner zone, keep the gas grill and propane tank at least 5 meters from house, and clear an area of 5 meters around the grill.	3.0 ±1.45	1.13	-0.05	ARC. FEMA
D4_2: Establish a landscaped garden, vegetable garden, cultivated soil or gravelled areas.	2.5 ±1.52	1.27	-0.16	DFES. CFS. TFS
D4_3: Build wide paths, paving, driveways, or tennis court that can provide fuel breaks.	2.6 ±1.52	1.27	-0.15	CFA. CFS. TFS
D4_4: Locate any dams, pools and any effluent disposal areas on the side of buildings facing the most likely direction of fire.	2.6 ±1.48	1.22	-0.09	CFA. DFES. CFS. TFS
D4_5: Create radiation shields and windbreaks such as stone or metal fences and hedges using low-flammability plants.	2.3 ±1.45	1.24	-0.05	DFES. NSWRFS. TFS
D5_2: Install metal gutter protection.	3.0 ±1.42	1.12	-0.02	ARC. NSWRFS. CFS
D6_4: Maintain the paint on windows sills so there is no flaking or exposed wood.	2.6 ±1.38	1.18	0.05	CFA
D6_6: Ensure that garage doors are tight fitting to door frame if garage is attached to the house.	2.7 ±1.24	1.06	0.23	CFA
D6_8: Ensure that external house timbers have a sound coat of paint.	2.7 ±1.39	1.17	0.03	FEMA
D6_10: Block all vents and weepholes (e.g. chimneys, stovepipes) with wire mesh screens 1.5mm (not aluminium).	2.7 ±1.19	1.06	0.30	DFES. ARC. FEMA. ACTF&R. CFS
D6_13: Install wire mesh screens 1.5mm (not aluminium) over all external doors.	2.6 ±1.27	1.04	0.20	CFA. ACTF&R. NSWRFS. QFRS. CFS
D7_2: Fit the roller shutters with an ember guard at the top of the garage door if the garage is attached to the house.	2.8 ±1.21	0.97	0.27	CFA

Continued

Table 5. Controversial preparatory items identified by r_{wg} *(Continued)*

Preparatory Items	Mean $\pm$ SD	AD	r_{wg}	Sources[a]
D7_8: For pipes that are essential to water delivery, ensure that they are metal, or non-metal pipes are buried to a depth of at least 300mm below the finished ground level.	2.7 $\pm$ 1.27	1.02	0.20	CFA. TFS
D7_9: Have a non-combustible doormat, or remove the doormat when there is a fire danger.	3.0 $\pm$ 1.35	1.03	0.09	ACTF&R. NSWRFS
D10_5: Know the maximum operating temperature as specified for the pump by the manufacturer.	3.1 $\pm$ 1.34	1.06	0.11	CFA
D10_9: Ensure that smoke alarms are fitted on every level of the house.	3.5 $\pm$ 1.25	0.85	0.22	ARC
D10_10: Prepare knapsack spray or garden backpack spray to help you put out spot fires. If using a garden backpack, make sure it has been cleaned out before using it in a bushfire.	3.3 $\pm$ 1.25	0.94	0.22	CFA. DFES
D11_4: Install a sprinkler system around the property.	2.3 $\pm$ 1.27	1.07	0.19	CFS
D11_5: Install a roof-mounted sprinkler system.	2.4 $\pm$ 1.31	1.11	0.14	CFA
D12_1: Obtain an emergency supply of drinking water (3L per person per day for four days).	2.4 $\pm$ 1.25	1.09	0.22	DFES. ACTF&R. TFS
D12_2: Obtain canned or dried food to last four days.	2.3 $\pm$ 1.28	1.12	0.18	DFES
D12_3: Obtain a water container suitable for washing or cooking.	2.0 $\pm$ 1.50	1.31	-0.13	DFES
D12_4: Obtain a can opener, cooking gear and eating utensils.	2.1 $\pm$ 1.48	1.29	-0.09	DFES
D14_3: No elderly who is not fit to defend.	3.0 $\pm$ 1.29	1.03	0.17	CFA. NSWRFS
D14_4: No children under 16 is staying and defending.	2.7 $\pm$ 1.42	1.22	-0.02	CFA. NSWRFS

N = 27

a. CFA = Country Fire Authority (VIC), QFRS = Queensland Fire and Rescue Service (QLD), DFES = Department of Fire and Emergency Services (WA), ACTF&R = ACT Fire & Rescue (ACT), NSWRFS = NSW Rural Fire Service (NSW), CFS = Country Fire Service (SA), TFS = Tasmania Fire Service (TAS), ARC = American Red Cross, FEMA = Federal Emergency Management Agency.

Checklist adjustment

In addition to the ratings, results suggested an adjustment of several existing items as well as enrichment of the list with several additional preparatory actions, resulting in a refined checklist of 104 items. Moreover, the qualitative comments coupling with missing values (i.e. 'not sure') or controversial ratings explained the obstacles in providing a confident rating and helped identify several types of potential adjustment needed for some items:

Type 1. The criteria of some preparatory items need to allow for adjustment according to jurisdiction policies. For instance, the item 'isolate clumps of shrubs and small trees from one another by at least 10 metres to avoid a continuous wall of trees within the Outer Zone' was claimed to be critical at all fires by one expert, but the criteria of isolation distance was regulated to be 'at least 1 (1.5) times the mature height of any in the clump' by his/her local government.

Type 2. Some preparatory items may be critical only under some circumstances. For example, the item 'clear vegetation along the boundary of the property to create a firebreak' was suggested to only be critical for certain types of properties, depending on 'the size of the property and distance from the boundary to the dwelling'. A lack of specification of such circumstances in the current survey caused a difficulty in rating.

Type 3. Some preparatory items may be compensatory for each other, and therefore only one of the actions has to be completed to allow active defence. One example is the item 'install metal gutter protection', which was suggested as not critical if the other item 'ensure that roof gutters and valleys are clear of leaves and bark' was completed. Therefore, the two actions may be combined as one critical action to allow householders' choice of at least one of them.

These three types of issues shed light on the potential difficulties that may be encountered whilst trying to further clarify if a preparatory item is critical when there is disagreement

between experts from different organisations. However, adjustment can be made to adapt the items relevant to these three issues to various local environments, jurisdictional regulations, or other specific conditions. Therefore the three types of potential adjustment suggested from the survey responses can be used as a guideline during future engagements with experts to help identify the issues for relevant preparatory items, solicit opinions to address these issues, and attain relative consensus upon the viable solutions for defining or explicating the critical nature of these complicated items for specific situations in different states.

Conclusion

Through an initial overview of the current communication materials within Australia, we identified a need to clarify the relationship between the necessity of different preparatory actions and FDR levels. This pilot study provides evidence that some but not all preparatory items are critical for making the decision of staying and defending, and in addition, their critical nature should be examined in relation to FDRs. Moderate to high interrater agreement was observed for approximately half of the items, with both high and low average rating values. However, statistics for the controversial items suggest that experts do employ diverse approaches during the individual rating process, and thus a more explicit study should be undertaken to understand the rationale of consensual ratings, to reconcile the different opinions as well as to investigate the specific reasons for disputation. Although the disparate physical and political context across Australia is likely to make it difficult to obtain a national consensus over many preparatory items, we believe this study is a breakthrough in clarifying the operational significance of the preparatory items. It provides a starting point from which a new instrument of household preparedness measure can be developed by bushfire agencies at different scales to assist residents' estimation of their preparedness levels and decision-making with respect to active defence. Nevertheless, it should be acknowledged that in a bushfire, although the completion of all the critical preparatory actions will substantially enhance the chance of successful defence, the safety of a household can never be guaranteed due to the complex nature of these types of events.

References

Australasian Fire and Emergency Service Authorities Council (AFAC) (2010) Position Paper
on Bushfires and Community Safety, Version 4.1. (Melbourne)

Australian Building Codes Board (ABCB) (2010) Performance Standard for Private Bush Fire
Shelters. (Canberra)

Brennan P (1998) 'Bushfire Threat: Response in a Small Community.' (Australian Emergency
Management Institute: Macedon, Vic)

Burke MJ, Dunlap WP (2002) Estimating Interrater Agreement with the Average Deviation
Index: A User's Guide. *Organizational research methods* **5**, 159-172.

Country Fire Authority (CFA) (2010) Prepare.Act.Survive. Fire Ready Kit.
(http://www.cfa.vic.gov.au/fm_files/attachments/plan_and_prepare/frk/fire-ready-kit-
complete.pdf)

Department of Fire and Emergency Services (DFES) (2012) Prepare. Act. Survive. Version 4.
(http://www.dfes.wa.gov.au/safetyinformation/fire/bushfire/BushfireManualsandGuides
/FESA_Bushfire-Prepare_Act_Survive_Booklet.pdf)

Dowdy AJ, Mills GA, Finkele K, Groot WD (2009) Australian fire weather as represented by
the McArthur Forest Fire Danger Index and the Canadian Forest Fire Weather Index.
CAWCR Technical Report No 10. (Centre for Australian Weather and Climate
Research: Victoria, Australia)

Handmer J, O'Neil S, Killalea D (2010) Review of fatalities in the February 7, 2009, bushfires.
Prepared for the Victorian Bushfires Royal Commission April 2010. (Centre for Risk
and Community Safety RMIT University & Bushfire CRC: Melbourne)

James LR, Demaree RG, Wolf G (1984) Estimating within-group interrater reliability with
and without response bias. *Journal of applied psychology* **69**, 85-98.

LeBreton JM, Senter JL (2008) Answers to 20 Questions About Interrater Reliability and
Interrater Agreement. *Organizational Research Methods* **11**, 815-852.

McLennan J, Elliott G (2011) Checklist Items For Researchers: Householder Preparations For Bushfires. (Bushfire Cooperative Research Centre and School of Psychological Science La Trobe University: Melbourne)

McLennan J, Elliott G, Omodei M (2011) Issues in Community Bushfire Safety: Analyses of Interviews Conducted by the 2009 Victorian Bushfires Research Task Force. (School of Psychological Science, La Trobe University: Melbourne)

Paton D, Kelly G, Burgelt PT, Doherty M (2006) Preparing for bushfires: understanding intentions. *Disaster Prevention and Management* **15**, 566-575.

Richardson JTE (2010) Perceived Academic Quality and Approaches to Studying in Higher Education: Evidence from Danish Students of Occupational Therapy. *Scandinavian Journal of Educational Research* **54**, 189-203.

Victorian Bush Fires Royal Commission (VBRC) (2009) Interim Report 2 – Priorities for Building In Bush Fire Prone Areas. (Parliament of Victoria: Melbourne)

Whittaker J, Haynes K, Handmer J, McLennan J (2013) Community safety during the 2009 Australian 'Black Saturday' bushfires: an analysis of household preparedness and response. *International Journal of Wildland Fire*.