bnhcrc.com.au

SCIENTIFIC KNOWLEDGE AND SCIENTIFIC UNCERTAINTY IN BUSHFIRE AND FLOOD RISK MITIGATION

Literature Review

Timothy Neale
Institute for Culture and Society, University of Western Sydney, NSW

TABLE OF CONTENTS

ACKNOWLEDGEMENT: THIS REPORT WAS FUNDED BY THE BUSHFIRE & NATURAL HAZARDS COOPERATIVE RESEARCH CENTRE (BNHCRC) AS PART OF THE 'SCIENTIFIC DIVERSITY, SCIENTIFIC UNCERTAINTY AND RISK MITIGATION POLICY AND PLANNING' PROJECT. THIS PROJECT IS A COLLABORATION BETWEEN THE INSTITUTE FOR CULTURE AND SOCIETY AT THE UNIVERSITY OF WESTERN SYDNEY, AND THE FENNER SCHOOL OF ENVIRONMENT AND SOCIETY AT THE AUSTRALIAN NATIONAL UNIVERSITY.

THANKS TO JOHN SCHAUBLE (LEAD END USER, EMERGENCY MANAGEMENT VICTORIA), ED PIKUSA (END USER, SOUTH AUSTRALIAN FIRE AND EMERGENCY SERVICES COMMISSION), CHRIS IRVINE (END USER, STATE EMERGENCY SERVICE, TASMANIA), MICHEAL RUMSEWICZ (BNHCRC) AND JESSICA WEIR (INSTITUTE FOR CULTURE AND SOCIETY, UWS) FOR THEIR COMMENTS ON A DRAFT OF THIS REPORT. THANKS ALSO TO HELEN BARCHAM (INSTITUTE FOR CULTURE AND SOCIETY, UWS) FOR EDITORIAL CORRECTIONS. ALL ERRORS REMAIN THE AUTHOR'S OWN.

PROJECT TEAM: LEAD RESEARCHER: DR JESSICA WEIR, UNIVERSITY OF WESTERN SYDNEY; PRINCIPAL INVESTIGATOR: DR TIMOTHY NEALE, UNIVERSITY OF WESTERN SYDNEY**;** PROJECT RESEARCHER: DR CHRISTINE HANSEN, AUSTRALIAN NATIONAL UNIVERSITY AND UNIVERSITY OF GOTHENBURG, SWEDEN; PROJECT RESEARCHER: ASSOCIATE PROFESSOR TARA MCGEE, UNIVERSITY OF ALBERTA, CANADA**;** PROJECT RESEARCHER: ASSOCIATE PROFESSOR MICHAEL EBURN, AUSTRALIAN NATIONAL UNIVERSITY; PROJECT RESEARCHER: PROFESSOR STEPHEN DOVERS, AUSTRALIAN NATIONAL UNIVERSITY; PROJECT RESEARCHER: PROFESSOR JOHN HANDMER, RMIT UNIVERSITY

ISBN: 978-1-74108-354-5

COVER PHOTO: MOGGS CREEK (PHOTO: TIMOTHY NEALE)

BARWON-OTWAY COAST (PHOTO: TIMOTHY NEALE)

EXECUTIVE SUMMARY

The Scientific Diversity, Scientific Uncertainty and Risk Mitigation Policy and Planning (RMPP) project aims to investigate the diversity and uncertainty of bushfire and flood science, and its contribution to risk mitigation policy and planning. The project investigates how policy makers, practitioners, courts, inquiries and the community differentiate, understand and use scientific knowledge in relation to bushfire and flood risk. It uses qualitative social science methods and case studies to analyse how diverse types of knowledge are ordered and judged as salient, credible and authoritative, and the pragmatic meaning this holds for emergency management across the PPRR spectrum.

This research report is the second literature review of the RMPP project and was written before any of the case studies had been completed. It synthesises approximately 250 academic sources on bushfire and flood risk science, including research on hazard modelling, prescribed burning, hydrological engineering, development planning, meteorology, climatology and evacuation planning. The report also incorporates theoretical insights from the fields of risk studies and science and technology studies (STS), as well as indicative research regarding the public understandings of science, risk communication and deliberative planning.

This report outlines the key scientific practices (methods and knowledge) and scientific uncertainties in bushfire and flood risk mitigation in Australia. Scientific uncertainties are those ‘known unknowns’ and ‘unknown unknowns’ that emerge from the development and utilisation of scientific knowledge. Risk mitigation involves those processes through which agencies attempt to limit the vulnerability of assets and values to a given hazard.

The focus of this report is the uncertainties encountered and managed by risk mitigation professionals in regards to these two hazards, though literature regarding natural sciences and the scientific method more generally are also included where appropriate. It is important to note that while this report excludes professional experience and local knowledge from its consideration of uncertainties and knowledge, these are also very important aspects of risk mitigation which will be addressed in the RMPP project’s case studies.

Key findings of this report include:

- Risk and scientific knowledge are both constructed categories, indicating that attempts to understand any individual instance of risk or scientific knowledge should be understood in light of the social, political, economic, and ecological context in which they emerge.
- Uncertainty is a necessary element of scientific methods, and as such risk mitigation practitioners and researchers alike should seek to ‘embrace uncertainty’ (Moore et al., 2005) as part of navigating bushfire and flood risk mitigation.

- There are common methodological uncertainties across scientific practices used to understand and mitigate a given hazard. For bushfire and flood risk mitigation, these uncertainties largely derive from the inherent biases of methods and their reliance on incomplete historic data to anticipate and mitigate rare and extremely rare hazard events within a changing climate.
- Flood science and flood mapping are central to current flood risk mitigation policies and practices such as engineering works, development planning and evacuation planning. These require the management of key uncertainties relating to flood history, meteorological prediction, climate change and human behaviour.
- Fire behaviour science and fire risk prediction are central to current bushfire risk mitigation policies and practices such as prescribed burning and development planning. These require the management of key uncertainties relating to fuel conditions, model validation, biodiversity and human behaviour.
- The scientific uncertainties encountered in bushfire and flood risk mitigation can be categorised as historicist, instrumental and interventionist uncertainties:
    - i) *historicist uncertainties* are those uncertainties which emerge from the reliance of scientific knowledge on archives of historical data;
    - ii) *instrumental uncertainties* are those uncertainties which emerge from the limitations of a given apparatus, heuristic or theory;
    - iii) *interventionist uncertainties* are those uncertainties which emerge from a given mitigation intervention.

This report's categorisation of uncertainties encountered and managed by bushfire and flood risk mitigation professionals will facilitate the methods of this project, including ensuring that the research is engaged with industry practice and policy priorities, as well as being useful to other people and institutions more broadly:

- First, the categorisation of uncertainties developed will be useful to this project and other social science research projects engaging with the complex and technical practices of risk mitigation professionals. Framing these uncertainties categorically as well as technically will prove useful to analysing the management of uncertainty across and between case studies.
- Second, it is anticipated that risk professionals will express differing opinions about the different uncertainties in mitigation practice in terms of their relative influence, changeability, volatility, and so on. Increased knowledge about the importance of different categories of uncertainties to mitigation practice will facilitate management of these uncertainties, for example, in terms of resourcing and design of risk mitigation training, and communications and education.
- Third, this categorisation of diverse forms of scientific knowledge and their uncertainties supports the capacity of risk mitigation professionals to explain risk and justify mitigation practices both to other risk mitigation professionals and to the public. Being able to describe a scientific uncertainty

is a vital aspect of internal and external risk communication and, as such, these categories will prove useful in communicating the origins and character of an uncertainty.

- Fourth, this report will be of particular use to non-scientists, including those engaged in research and industry roles, in generating an understanding of some of the key causes and consequences of scientific uncertainty in bushfire and flood risk mitigation. Such an understanding is necessary to any investigation of how individuals and agencies use and understand diverse scientific evidence and other forms of knowledge in their risk mitigation roles.

INTRODUCTION

The Scientific Diversity, Scientific Uncertainty and Risk Mitigation Policy and Planning (RMPP) project investigates the diversity and uncertainty of bushfire and flood science, and its contribution to risk mitigation policy and planning. The project draws on human geography, political science, legal studies and science and technology studies, to investigate how policy makers, practitioners, courts, inquiries and the community differentiate, understand and use scientific knowledge in relation to bushfire and flood risk. It uses qualitative social science methods and case studies to analyse how diverse forms of knowledge are ordered and judged as salient, credible and authoritative, and the pragmatic meaning this holds for emergency management across the prevention, preparedness, response and recovery (PPRR) spectrum.

This RMPP project report surveys the key scientific uncertainties encountered, managed and utilised by practitioners and decision-makers involved in bushfire and flood risk mitigation practices in Australia. Other knowledge practices—professional experience, local knowledge, and Indigenous knowledge—are also very important to bushfire and flood risk mitigation, though these are outside the scope of this report. Scientific uncertainties are those 'known unknowns' and 'unknown unknowns' that emerge from the development and utilisation of scientific knowledge. They are the things we have comparatively limited knowledge about, whether we know it or not, because of limits in available methods, data or models. As this report shows, while bushfire and flood risk mitigation involve their own specificities, and therefore their own specific uncertainties, they also share some common practices and common uncertainties. For example, there are uncertainties that are simply latent in all meteorological and climatological prediction methods, as they rely on imperfect historical data to predict the occurrence of comparatively rare and catastrophic weather events within a changing climate. Risk and risk mitigation are in turn calculated in regards to the transformations of fluid entities including climate, weather, flora, fauna and human populations. Above and beyond these considerations, there are other widespread practical issues, such as the 'data and computational friction' generated by modelling (Edwards, 2010) and the unavoidably fragmented work of data collection and storage.

Borrowing geographer John Handmer's (2008) tripartite analysis of flood risk, we can think of risks as composed of processes of *risk creation, risk mitigation, and residual risk*. Risk creation involves those processes, such as urban planning, through which populations, values and assets are placed in relation to a natural hazard. Risk mitigation involves those processes through which agencies, many of which are responsible for risk creation, attempt to limit vulnerability to that hazard. Residual risk, in this schema, is therefore the processes though which remaining vulnerability is distributed to, and borne by, emergency management, citizens and insurance companies. As such, for the purposes of this report, risk mitigation is defined as the steps taken by people in different levels of government to quantify and minimise the probabilities and consequences of a given hazard. Further elaboration is given in the following sections, though it is important to note that this definition differs from broader definitions of risk mitigation or risk management as, for example, 'the culture, processes and structures that are directed towards effective management of potential opportunities and adverse effects', or the 'sum of measures instituted by people or organisations in order to reduce, control and regulate risks' (Renn, 2008b: 145). This is not to suggest that culture, individuals and organisations are not all highly relevant to risk mitigation, but that a more limited definition of mitigation itself is preferable for reasons of analytical clarity in this report.

BOX 1

Framing risk (adapted from Handmer, 2008):

Risk creation: governments' planning system locates, approves and makes development legal in hazard prone area.

Risk mitigation: scientific studies, engineering works, legal standards and other measured developed and implemented by governments to minimise hazard probabilities and consequences.

Residual risk (or risk transference): the remaining vulnerability to hazard probabilities and consequences borne by non-government actors.

Risk mitigation itself is divisible in three ways, between processes aimed at likelihood reduction, consequence reduction or risk transference (e.g. Ellis et al., 2004). Given that risk transference is, in light of Handmer's analysis, a matter of sharing or distributing responsibility for a risk to non-state actors, risk transference is only marginally included in this analysis. As such, this report focuses on scientific practices related to likelihood reduction and consequence reduction, while indicative research on risk transference strategies such as community awareness, education, and hazard warnings is included without comprising a core of the report's analysis. Approximately 250 academic sources on bushfire and flood risk science were drawn upon in completing this report, including research on hazard modelling, prescribed burning, hydrological engineering, development planning, meteorology, climatology and evacuation planning. The report also incorporates theoretical insights from the fields of risk studies and science and technology studies (STS), as well as indicative research regarding the public understandings of science, risk communication and deliberative planning.

Many different scientific methods and forms of knowledge are used to inform practitioners and decision-makers in risk mitigation in Australia. Examining bushfire and flood risk mitigation in any one region, one may expect to uncover meteorological, climatological, ecological, cartographical, and, in the case of flood, hydrological and hydraulic knowledge at work. This literature review takes a problem-centred approach over a practice-centred approach in order to focus on the uncertainties particular to these hazards while, at the same time, seeking to produce findings that are relevant to risk mitigation generally. Therefore, the author has sought to identify categories of uncertainty through this review that are applicable across hazards. The categories of uncertainty developed in this report—historicist, instrumental, interventionist—will form the basis for further research into the role of scientific knowledge and uncertainties in project case studies. The identification of these categories of uncertainty will also provide greater clarity to researchers, practitioners and decision-makers seeking to identify and communicate scientific uncertainty to both professional and lay audiences.

In the first section of the report, the author presents a framework for understanding scientific knowledge, risk and risk mitigation as complex phenomenon emerging within specific cultural contexts. While, indeed, risk is the product of acts of objective calculation, these calculations and the ways they are measured are produced and interpreted across a heterogeneous network of public and private individuals. The second section examines uncertainties that are universal across the diverse scientific practices used in bushfire and flood risk mitigation. The third section surveys uncertainties that are particular to these specific hazards and examines their expression in two case study areas—the Hawkesbury-Nepean Valley in New South Wales and the Barwon-Otway area of Victoria—to show how these uncertainties might be of greater or lesser concern in a given circumstance. This report then closes with a brief conclusion rearticulating the categorisation of scientific uncertainties in bushfire and flood risk mitigation practices as historicist, instrumental or interventionist.

This report will be of particular use to non-scientists, including those engaged in research and industry roles, in generating an understanding of some of the key causes and consequences of scientific uncertainty in bushfire and flood risk mitigation. Such an understanding is a necessary to any investigation of how individuals and agencies use and understand diverse scientific evidence and other forms of knowledge in their risk mitigation roles. As it is a necessary element of scientific methods, and as such risk mitigation practitioners and researchers alike should seek to 'embrace uncertainty' (Moore et al., 2005).

1: RISK, RISK MITIGATION, AND SCIENTIFIC KNOWLEDGE

In Australia, risk is often defined in industry standards as ‘probability x consequences,’ or the probability of a given event and its consequences in relation to assets and values (Standards Australia, 2009b). While this definition has significant functional utility, it does not make explicit the situated and contingent character of probabilities and consequences, factors which can not only have a determining influence on policy and planning. As sociologist Peter Glasner argues (2000: 134), ‘any discussion of risk is as much about culture, institutions, perceptions, control and activity as it is about how risks are framed by experts’. As such, the sociological literature on risk that has flourished since Douglas and Wildavsky’s Risk and Culture (1982) has tended to speak of ‘risk culture’ or ‘risk society’. A risk society, as described in the work of sociologists such as Ulrich Beck and Anthony Giddens, is a social formation in which vulnerability to, and responsibility for, natural hazards are the object of calculation and calculated distribution across populations. Reviewing this scholarship, Scott Lash (2000) summarises its achievements as having uncovered the ways in which we are all articulated in relation to, on the one hand, uncertainties and vulnerabilities and, on the other, practices of figuring uncertainties and vulnerabilities that are neither simply chosen nor are they naturally allocated. As Beck argues (1992: 23), news media, scientific experts, governments, courts, insurance agencies are all important actors shaping and shaped by dominant definitions of what is and is not a risk, what causes a risk, who is liable for a risk, and so on. Lay publics can—and sometimes do—drive the creation, mitigation and distribution of risk.

To return to Handmer’s tripartite analysis, *risk mitigation* is the name for the many practices through which a hazard and its associated uncertainties are calculated, managed and controlled. It is an intermediary stage between the creation and privatisation of risk—between its formation and the distribution of responsibility to non-state parties—involving decisions about at-risk values and assets and the political, environmental and economic consequences of interventions. In the context of bushfire and flood risk in Australia, mitigation occurs through efforts to predict where and how bushfire and flood events might occur, limiting the likelihood of bushfires and flood events where possible, and minimising the consequences of unavoidable events. The various measures brought to bear are often interrelated as, for instance, a predictive tool such as a flood study is also routinely a crucial component of planning overlays which seek to minimise hazard effects. This brings us to another key point about risk, which is that it is not only addressed in a number of contexts by a number of different private and public agencies, but that it is also captured in specific calculations and calculating devices. Several practical examples are given below to illustrate how scientific knowledge in risk mitigation emerges from material networks.

Like risk, scientific knowledge is shaped—but not determined—by the context in which they emerge. This insight is at the centre of science and technology studies

(STS) and the sociology of scientific knowledge, both of which emphasise the importance of examining how knowledge develops from specific technical apparatuses, archives and institutions (see Bijker et al., 1987; Hackett et al., 2008). Scientific knowledge is in this sense, as sociologist David Turnbull argues, a 'local knowledge practice' employed by specific individuals labouring in collaboration with specific apparatuses in specific institutional locations. To use the language of STS, we come to know a hazard in a given place through an assemblage of agents, including measuring devices (anemometers, thermometers, hygrometers, fuel estimation scales), archives of historical data (rainfall and burn history) and standardised algorithms for synthesising the two. Risk mitigation is, on this account, reliant on the creation of synthetic facts, or what sociologist Bruno Latour calls 'combinable mobiles' (1987: 227), that are comprehensible, translatable and available to new syntheses in other locations. Fire danger measures such as McArthur Forest Fire Danger Index (FFDI), the Canadian Forest Fire Weather Index System, and the United States National Fire Danger Ratings System are examples of such mobiles, devised to represent the many measures of bushfire risk in a single quantum.

This report begins by foregrounding the scholarship of risk studies and STS because it makes clear the conventionalised and contingent character of scientific knowledge and risk mitigation. That is, it makes clear that the devices, archives, algorithms and quanta used to scientifically articulate and understand risk are not incidental. While the use of each may be determined as much by institutional 'lock-in' as by its scientific merit, these objects may also be replaced and refined. Each is an 'epistemic object,' at the same time both functioning 'things-to-be-used' and fluid 'things-in-a-process-of-transformation' (Knorr-Cetina, 2001; see also Sundberg, 2009: 165-177). In addition, this literature illustrates the necessity of attending to how objectified knowledge is shaped by, and responds to, the contingencies of what may be known and achieved in that place and, simultaneously, what those involved contend may be known and achieved in that place. In some instances, a hazard may only be perceived 'downstream', long after its initial occurrence. In other instances, a form of risk mitigation based on available calculations may be mistaken for a surety, leading to drastic increases in the number of assets that are put at risk (Burby, 2006; also Smith, 1998: 232-233; Stevens et al., 2010). Thus, in thinking about risk mitigation we should not lose sight of the 'permeable, changeable, and contestable' boundaries between scientific research, scientific knowledge and the political, economic and social context (van Kerkhoff and Lebel, 2006: 454). Risk mitigation occurs at a complex interface where reception and utilization is a matter of 'who is engaged and which interests are represented' (Petts, 2008; Wynne, 1992). Just as uncertainty can elicit necessary caution, new lines of inquiry and new collaborations, it can equally be exploited for partisan gain.

This brief introduction to the social science fields of risk studies and STS suggests that understanding the forms of scientific knowledge and scientific uncertainties encountered in risk mitigation requires more than insights into the technical parameters of scientific manuals. Risk is socially constructed and socially distributed, and thus it is necessary to acquire both a broad view of knowledge and uncertainties and to examine their articulation in a given context or case. The following sections are devoted to these two tasks.

2: METHODOLOGICAL UNCERTAINTIES

It is important to be clear that all scientific practices are necessarily probabilistic and, therefore, absolute universal reliability is a false standard against which to judge scientific knowledge (see Latour, 1999; Popper, 2014). The nature of scientific inquiry is to produce knowledge or facts verified by their reproducibility, a task that also involves attempts to falsify existing theories and to perfect the data and theories on which these verified and reproducible facts are based. However, while datasets can be expanded, measurements can be made more accurate, algorithms can be adjusted and practices can be synthesised to produce complex understandings of natural systems, scientific practices cannot eliminate the existence of uncertainty—they can only seek to identify, minimise and quantify specific uncertainties. For example, while meteorological modelling and prediction have progressed massively thanks to the development of Numerical Weather Prediction (NWP) and 'Monte Carlo' ensemble prediction techniques—where the probabilities of variations around a central 'control' forecast are tested through multiple simulations (e.g. Cloke and Pappenberger, 2009: 615)—there is a degree of residual uncertainty that is simply endemic to the task of anticipating non-linear dynamical systems such as weather (see Handmer and Dovers, 2007: 26). As Collins and Evans have argued, if we hope to understand scientific fields, we must pay attention to the extent to which their major debates and uncertainties are capable of closure (Collins and Evans, 2002). Whereas some fields contain no major disputes ('normal science') or the potential for closure ('golem science'), others have many disputes and present little prospect for closure (see Box 1).[1]

BOX 2

Typology of scientific fields (Collins and Evans, 2002):

- *Normal science*: fields in which there are no major disputes; methods and theories procedures are as routinised and settled as possible.
- *Golem science*: fields which have the potential become 'normal' but are not yet; debates continue not only within the field but also involve politicians and publics.
- *Historical science*: fields which do not have significant potential to become 'normal', largely because they deal with unique historical trends (e.g. climate) rather than repeatable phenomena.
- *Reflexive historical science*: as above, those these are fields in which human actions and debates shape the object under study (e.g. climate change).

In addition, it is important to understand that the probabilities generated to predict and mitigate natural hazards are, to a significant degree, reliant on historical data. They are, in this sense, *historicist* in that their use implies a determining relation between the past, the present and the future (Hulme, 2010). In predicting and mitigating floods, Lane et al. write (2011: 1784), 'the futures imagined are tied to

---

[1] Sociologists of science have paid significant attention to Collins and Evans's provocative and normative terms. For example, see: Rip A. (2003) Constructing Expertise: in a third wave of Science Studies? *Social Studies of Science*: 419-434, Wynne B. (2003) Seasick on the third wave? Subverting the hegemony of propositionalism: Response to Collins & Evans (2002). *Social Studies of Science* 33: 401-417.

pasts experienced'. This historical data comes in a wide variety of forms—rainfall volumes, stream heights, stream flow velocity, topography, floor heights etc.—and is universally subject to two types of limitation:

- *Measuring:* The first type are limitations owed to the technological and political history of measurement, including gaps in available data due to innovations in measuring apparatuses, variations in data metrics, and variations in the geographical spread of measuring apparatuses. For instance, the coverage of rain and stream gauges across catchments in Australia is highly inconsistent due to historic funding shortfalls and debates between jurisdictions over their respective responsibilities (Wenger et al., 2013). Alternately, there is historic variation in wind speed metrics, meaning archives and practice are not only limited by unreliable measurements but also by the inhomogeneity of units of measurement and, thereby, data homogenisation processes (HEPEX, 2014; Lucas, 2010). In other instances, data are commercially sensitive or their collection and storage is fragmented across parties, creating further 'holes' in the datasets available to private and public agencies predicting and mitigating natural hazards.
- *Climate change:* the second type of limitation in historical data is attributable to the effect of climate change on the widespread presumption that natural systems fluctuate within an unchanging envelope of variability known as 'stationarity'. As Westra et al. (2010) have argued, 'the validity of the historical record… becomes increasingly questionable in directly evaluating flood risk in the light of anthropocentric climate change'. Climate change puts in question both the parameters of this envelope and our ability to know this envelope, meaning that, as climate scientists suggest, 'stationarity is dead' (Milly et al., 2008). Climate change projections of environmental variables could, in turn, be understood as a form of 'historical data' with a dynamic relationship to the past. In this regard, it is important to note that the extent to which climate change is relevant to a given hazard and its mitigation varies widely depending on the temporal parameters of an analysis. That is, the relevance of climate change to understandings of a hazard in a particular area is a product of the anticipated changes and the timespan over which they will occur (see Merz et al., 2010; Lins and Cohn, 2011; Galloway, 2011).

Our ability to predict both the timing and effect of both hazard events and mitigation interventions are also limited by practical considerations relating to technology, reporting, and resourcing. While uncertainties introduced through the use of historical data are significant in bushfire and flood risk mitigation, there is perhaps no greater source of uncertainty than the practical business of data collection and analysis in the present. Several specific examples will be given in the following sections, though some illustrative examples are, for instance, the common use of point-based data to measure dynamic and extremely localised phenomena such as rainfall or the use of data on the presence of particular species as a measure of gross biodiversity. In each case, a combination of measures acts an index for a presence we know exists but cannot yet measure directly. These same issues also reoccur in attempts to plan and understand interventions to reduce consequences and likelihoods, as any intervention produces their own 'explosions of uncertainty' (Dessai et al., 2009) regarding their actual environmental effects and how these effects will be legible. Further, these practitioners must manage what historian Paul Edwards (2010: 83-110) calls the 'data and computational friction' generated by modelling. In practice, any synthesis of data to calculate probabilities and generate scenarios strains against the limitations of available computational resources and reporting requirements. Thus, uncertainties may be introduced to the practical work of risk mitigation to manage computational drag. Measuring apparatuses and resources are finite and we come to 'know' the behaviour of a system within institutional bounds whose finitude may not be obvious.

The final category of general methodological uncertainties are those introduced through the use of standards whose applicability and accuracy are contested. These uncertainties are related to those originating in resource limitations, though they are due less to practical concerns than they are 'cultural' factors such as path dependency (see Wilson, 2012; Berkhout, 2002). Bushfire and flood risk mitigation both offer primary examples of these contested standards. For example:

- *Flood risk:* Most jurisdictions in Australia use the 1% Annual Exceedence Probability (1%AEP) level as the general standard in flood modelling, mapping and development planning (Comrie, 2011: 193). This standard has different names—ARI (Average Recurrence Interval), 'one-hundred year flood', Q100—but, as Wenger et al. explain, it is always 'a statistical estimate of the average period in years between the occurrence of a flood of a given size'; a 100ARI, Q100 or 1%AEP flood event are both events that have a predicted 1:100 likelihood of occurring in any given year. Of course, to speak of averages and probabilities is to invoke the historical data sets from which they are drawn and, thereby, the contention that the given system is sufficiently stationary as to be averaged. The adoption of this standard has been criticised for being insufficiently cautious and 'a very coarse tool' for judging flood risk (Wisner et al., 2004: 201-242), since the difference between a predicted 1%AEP and Probable Maximum Flood (PMF)—the theoretically largest flood resulting from a combination of the most severe meteorological and hydrologic conditions that could conceivably occur—may be considerable (Smith et al., 1996: 51; Bewsher and Maddocks, 2003). At the same time, 1%AEP predictions are often misinterpreted as corresponding to a flood event that should occur solely every hundred years rather than every hundred years on average over time (see McKay, 1984; Kidson and Richards, 2005; Bell and Tobin, 2007).
- *Bushfire risk:* the dominant standard measure of bushfire risk in Australia is McArthur FFDI. Developed in the 1960s by CSIRO scientist A.G. McArthur and others (see Pyne, 1991: 338-361), FFDI combines temperature, relative humidity, wind speed and an estimate of fuel conditions to produce a number predicting the intensity of a hypothetical fire (Lucas, 2010). Like 1%AEP, FFDI is a tool of translation based upon historical data, and McArthur used condition records for 13 January 1939 or 'Black Friday' in Victoria to

> represent the maximum of 100 FFDI (Adams and Attiwill, 2011: 28). While many consider its simplicity and translatability to be real benefits (San-Miguel-Ayanz et al., 2003), others have drawn attention to its unproven assumptions, its insensitivity to ecological variation, its high sensitivity to changes in wind speed, and its inability to incorporate several significant environmental factors that influence fire behaviour such as fuel type and topography (Dowdy et al., 2009). Like 1%AEP, this scientific standard is an answer to the question of required model complexity (see Apel et al., 2009). The fact that FFDI is not simply central to risk mitigation activities, such as total fire bans, but also how the public understand fire risk and the dangers of climate change (e.g. Hughes and Steffen, 2013), indicates that it is sufficiently accurate for many. We should nonetheless be mindful of the fact that operational utility may inadvertently mask the uncertainties and suppositions underpinning it.

All scientific knowledge in risk mitigation is conditioned by its probabilistic and historicist methods. It is 'limited' by these factors in the sense that they represent the specific character, and therefore specific strengths, of expert disciplines such as meteorology, climatology, hydrology, fire ecology, hydraulic engineering, and so on. At the same time, these practices are—in pure research and applied contexts alike—conditioned by practical limitations of available technology, reporting requirements, and present and past resourcing. They also function within the parameters of contested but institutionalised standard measures, formula and processes. In sum, we might say that scientific knowledge within risk mitigation takes the form of cycles of abductive reasoning—cycles in which logical inferences from available data and available knowledge are made to produce functioning hypotheses in light of known uncertainties, only to be revised as data, knowledge and knowledge about uncertainties continue to change (Thagard and Shelley, 1997). As such, known unknowns are a necessary and necessarily changeable part of bushfire and flood risk mitigation practice.

3: KNOWING THE HAZARD: FLOOD AND BUSHFIRE

3.1: FLOOD

In Australia, floods cost on average $377 million annually, making them the nation's most expensive natural hazard (Wenger et al., 2013: 65). Major floods in southeastern and northern Australia over the past decade have demonstrated this fact, most recently through the December 2010-January 2011 floods in southeast Queensland, which were responsible for 38 fatalities, approximately $2.38 billion in damages, and an estimated $30 billion in lost revenue. Also in January 2011, western and central Victoria experienced 'one of the worst flood events in its history', in the words of one forecaster, leading to 2 fatalities and approximately $2 billion in damages (Turnbull, 2011). Four years earlier, in June 2007, flooding in the Hunter and Central Coast regions of New South Wales led to 10 fatalities and insured losses of $1.17 billion, while two years before this, in June 2005, flooding in northeast New South Wales and southeast Queensland led to another 3 fatalities. North Australia is also subject to flooding, and in 1998 Katherine and Daly River were inundated during Tropical Cyclone Les, leading to 3 deaths, 30 casualties and an estimated $200 million in damages. This is only a partial list of the floods in the past two decades that have caused loss of life in Australia, and does not include the many floods which have caused significant damage to property and infrastructure. Thus, given the frequency and disastrous effects of these events it is understandable that a significant amount of effort has been put towards understanding floods, quantifying the risks they pose and mitigating those risks.

Floods come in many varieties, including river (fluvial) floods, flash floods, urban floods, pluvial floods, sewer floods, coastal floods and glacial lake outburst floods. This report focuses on river flooding, the dominant hazard in Australia, which occurs where a main river channel is unable to carry the amount of water being supplied to it over a short period of time from precipitation. Such floods are therefore a function of precipitation (rainfall and runoff), channel geometry and floodplain topography, meaning that scientific inquiry into flood behaviour and flood mitigation are largely devoted to measuring and managing one or more of these three dimensions.

In Australia, the task of understanding floods is fundamentally conditioned by the fact that the continent has the most variable river flow patterns in the world, in part due to the influence of the El Niño Southern Oscillation and its ability to produce both extreme aridity and extreme rainfall in the same site (White, 2000); the world's driest inhabited continent also has the greatest annual rainfall and runoff variability. More generally, as Schaake et al. state (2007), there are 'tremendous uncertainties' that must be managed in assessing flood occurrence and behaviour and in mitigating flood risk anywhere. Predictions of flood occurrence, for example, involve a combination of methods whose relative accuracy is uncertain, including written accounts, gauge readings and paleoflood hydrology, which, in turn, involves radiocarbon or optically stimulated luminescence dating of sediments to estimate flood history over the past 100-10,000 years (Benito et al., 2004). Rather than avoid these uncertainties, some have called upon flood scientists and practitioners to 'embrace uncertainty' in flood science, adopting a risk-based understanding of flood science practices (Moore et al., 2005). This amounts to being clear about the extent to which understanding floods involves the use of strategic practices based on strategic knowledge; what can be done in the present situation based on what can be known with the present tools. As the determining effects of a given context mean the 'embrace' of uncertainties will be dependent of local political, economic and environmental factors, this paper will later assess a specific flood risk landscape. Nonetheless, it is worthwhile to first summarise some widespread issues in understanding this hazard and its mitigation.

A primary obstacle to understanding floods scientifically is the rarity of major floods within any given region, despite their seeming ubiquity across countries such as Australia. This leads to a broad set of issues related to how we might not only predict, for example, what height a 1%AEP flood might reach but also how such an extreme flood might behave. As Cloke and Pappenberger state (2009: 616), several uncertainties follow from the inherent rarity of floods:

- *Validating forecasts*: first, any attempt to evaluate meteorological forecasts for hydrological applications, and thus to validate flood forecasts, is fundamentally limited by the low frequency of extreme floods. It is difficult to test the correspondence between a rare phenomenon and its projection in a given floodplain without recent historical exemplars.
- *Many influences*: second, land use, soil character (permeability, soil moisture content and its vertical distribution), ground water, channel and riverbed characteristics, riverine vegetation and river management in floodplains all influence flood behaviour. But because none of these aspects are static over time, any comparison between the present and a historic flood event is potentially tenuous. Dams, roads, land clearance, erosion, pre-burst rainfall, and many other factors influence how floodwaters travel beyond the riverbank (see also Wenger et al., 2013: 44). Equally, whether a flood occurs in winter or summer, or after bushfire or landslip, can have a significant effect on its behaviour (Kemp and Wright, 2008).
- *Data redundancy*: third, the bulk of historical data available on a catchment's behaviour may be able to produce predictions of mean and median river flow, for instance, however such syntheses provide no major insights into flood discharges; floodwaters describe a nonlinear flow once they exceed the riverbank which is, again, difficult to model without an abundance of historical examples. The location of flood discharge is a product of the timing and magnitude of flows, which are individual to each event (Cloke and Pappenberger, 2009: 617).
- *Data paucity*: fourth, in cases where there are historical exemplars, measurements of river height, velocity or rate of rise may not be recorded or comprehensive, particularly as major flood events can sometimes exceed measuring devices and destroy measuring infrastructure.

This is not to suggest that refined predictions of flood occurrence and behaviour are not possible, but that they must necessarily manage these uncertainties. One prevalent way of doing this is through a flood study which, as Wenger et al. state, analyses different statistically probable rainfall scenarios and the stream flows expected to result from them in a particular catchment area (hydrology studies), as well as identifying flood behaviour in terms of flow rate, velocity, depth and extent (hydraulic studies). Further, they incorporate 'historical flood data, surveys, vegetation cover, land use, topography, riverbed mapping, sediment movement behaviour and data from weather stations… [taking] account of numerous different variables, such as when and where rain falls in the catchment, the soil saturation level and dam levels, tides, predicted rain and even the effect of different dam operation strategies'. The correlate to such a flood study is a flood map, which visually represents how one or more flood events will likely be distributed across the catchment. In Australia, these syntheses are the responsibility of a catchment authority[2] which are, in turn, reliant on centralised funding, subject to government pressure and often reliant on out-dated data (Barry, 2008). Recent floods in Victoria and Queensland have helped establish that there is 'a wholly inadequate level of flood mapping' in these regions (QFCI, 2012: 62). In Victoria, for example, a 1%AEP event has been mapped in 80 per cent of floodplains and incorporated into planning schemes in 56 per cent of cases (Comrie, 2011: 194-195), while only 37 per cent of Queensland's planning scheme contain any flood-related mapping, less than a quarter of which meet current guidelines (Wenger et al., 2013: 20-25). It is important to note, also, that such flood information is often not publically available even where it exists (Box et al., 2012). As such, it is perhaps unsurprising that the Insurance Council of Australia has developed its own commercial-in-confidence National Flood Information Database (NFID) to store flood studies and other flood information (Van Den Honert and McAneney, 2011: 1169).

Flood studies have many public and private applications but are foremost created as a basis for mitigation interventions. Globally, the major forms of mitigation interventions are engineering works such as dams, levees, detention basins (or 'dry dams'), flood walls, land clearance, dredging, backflow prevention and evacuation infrastructure, and legal strictures such as land use planning and building codes (Fordham, 1999; Vojinović and Abbott, 2012: 459-474). Such interventions, as noted above, contain their own complex 'explosions of uncertainty' (Dessai et al., 2009) in that each comes with its own distinct set of effects and consequences that cannot be wholly anticipated in advance. The construction of dams and levees, for example, often produces a 'safe development paradox', or what geographer Gilbert White (1945) described as the 'levee effect' (see also Parker, 1995; Pielke, 1999; Smith, 1998: 232-234; Burby, 2006; Atkins, 2009). Governments, developers and others often mistake engineering works for protection, subsequently reducing

---

[2] The names for these authorities vary across Australia: Catchment Management Authorities in Victoria; Local Land Services in New South Wales; Catchment Councils in Western Australia; Natural Resource Management Boards in South Australia and Queensland. Tasmania, ACT and the Northern Territory do not presently have equivalent sets of bodies.

development controls and placing more development in a ‘safe’ floodplain. Dams and levees can, in addition, badly affect ecosystems that rely on periodic flooding. As Lane et al. summarise (2011: 1787), such interventions alter ‘the spatial distribution of risk’ to both humans and non-humans in ways that effect risk creation and residual risk. The effect of planning interventions is equally difficult to anticipate, as such regulations can involve static assumptions about changing hazards (Godden and Kung, 2011) and sit within complex political-economic contexts in which regulations may be waived or not applied. In Queensland, for instance, it is essentially optional to consider flood maps in many development assessments, whereas in Victoria it is only compulsory if flood mapping exists in a given area (Wenger et al., 2013: 20-21).

There are other uncertainties to be managed in predicting and mitigating flood hazards, though they are each fall within the categories already identified in this report. What has not yet been noted is the importance in flood mitigation of understanding at-risk assets, typically divided into the built environment and human population, though environmental values are increasingly being included. For the former, this may extend not simply to itineraries of cultural heritage, transport infrastructure, utilities and critical assets (electricity, sewerage, etc.), private properties and their respective elevations, but also their capacities and vulnerabilities in a probable flood event. The design of both flood preparation and response is informed, for example, by not only modelling the level at which point a roadway becomes inundated, and the likelihood of this inundation, but also the carrying capacity of the road and its role in evacuation (Cova and Church, 1997; Shekhar et al., 2012; Pillac et al., 2013). How many vehicles can travel over a given evacuation route in an hour? What is the sum of functioning vehicles amongst a population? How many will need emergency assistance? How can we calculate for human error? These variables and others, and their requisite uncertainties, are synthesised in order to assess evacuation planning and whether an evacuation can occur between forecasters being sufficiently certain about a coming event and that event’s occurrence.

Equally, understanding at-risk populations is not only a matter of complex demographic calculations, but also significant sociological and psychological judgements regarding risk preparedness and behaviour. Over a decade ago, Handmer suggested that ‘advice on how flood water will actually affect people, and on appropriate action, is often minimalist or missing’ (2000: 6). Since this time a large body of research has emerged suggesting that the greatest uncertainties are not in providing warnings to populations but in making communities and emergency management agencies responsive to these warnings. In Australia, Keys and Cawood conclude (2009), the flaws are chiefly ‘cultural rather than technical’. This report is not positioned to detail the immense body of work that has been devoted to this topic, though it should be noted that multiple methods and evidence bases are utilised in considering effective and efficacious warnings, including experimental psychological and sociological studies to test correlations between risk communication, risk perception and preparedness (e.g. Bell and Tobin, 2007; Gigerenzer, 2003; Griffin et al., 2008; Terpstra et al., 2009; Visschers et al., 2009; Baan and Klijn, 2004; Kellens et al., 2013), case studies of community responses to actual flood events (e.g. Pfister, 2002; Opper et al., 2006; Gissing et al., 2010), and the broader literature on collaborative planning and community engagement (see Hajer and Wagenaar, 2003; Renn, 2008a; Healey, 2006; Head, 2007).

Anticipating flood hazards and designing and implementing forms of flood risk mitigation are, as the above suggests, a complex and interdisciplinary business. As noted at the beginning of this section, others have suggested that flood science should 'embrace uncertainty' by adopting a risk-based understanding of its practices. Summarising those uncertainties addressed above, we might suggest that such an embrace in any one context would include consideration of: the forecasting confidence of meteorological data; the availability of hydrological data from past flood events and their use in test modelling; the existence of comprehensive flood studies and their relative availability to public and private users; the necessary unpredictability of interventions including both engineering works and legal strictures, their application and the forms of knowledge that underwrite them; the fallibilities and redundancies of the built environment; and, the heterogeneity of the given population. This report will now address these uncertainties in relation to a specific case study—the Hawkesbury-Nepean Valley—showing how the historical, economic and political particularities of a floodplain shape how we might know and manage a flood hazard.

3.2: CASE STUDY: FLOOD RISK IN THE HAWKESBURY-NEPEAN VALLEY

The Hawkesbury-Nepean Valley is an area comprised of the catchment of the Nepean and Hawkesbury rivers in Greater Western Sydney, New South Wales. While the first post-settler flood is recorded as occurring in 1795, geological analysis indicates that the area has been witness to significant flooding over thousands of years (Bewsher et al., 2013: 5; Johnson, 2000). Following several devastating floods, Governor Macquarie ordered in December 1810 that development should not take place on the low-lying floodplains, establishing the towns of Richmond, Windsor, Pitt Town, Wilberforce and Castlereagh on what he believed to be flood proof sites. But Macquarie's planning was based on a very limited flood record and in 1867 many of these towns were completely overwhelmed by floodwaters. Twelve people were killed in the largest recorded flood, the Hawkesbury River reaching a height calculated as having a 1:200 to 1:300 chance of occurring in any given year. Since this time there have been over twenty 'major' floods in the valley in which infrastructure has been inundated and communities isolated. As Bewsher et al. note (2013: 2), there are many buildings with significant flood exposure in the valley, a risk that is not evenly distributed between different areas. The suburbs of McGraths Hill and South Windsor are, in particular, vulnerable to inundation in 2%AEP flood events. An estimated 73,000 people live in areas prone to flooding in the valley (DPI, 2014: 5).

Geographically, there are three significant factors to note about the floodplain.

- The first is the presence of the 142 metre high Warragamba Dam. Built between 1948 and 1960 to secure a potable water supply for Sydney city, the dam impounds several rivers north of the Warragamba's confluence with the Nepean River to create one of the largest reservoirs for urban water supply in the world, Lake Burragorang, within the Blue Mountains National Park. After various reviews between the 1960s and 1980s revealed that the dam's original spillway was built to withstand a flood less than half the size of the modelled PMF (Deen et al., 1989), the dam wall was strengthened and raised by 5 metres in the late 1980s, while a larger auxiliary spillways was built between 1999 and 2009. While the dam was not built to mitigate flood risk, it both reduces the amount of water normally entering into the Valley system (Warner, 2014) and creates a capacity to add significant amounts of flood water to the Hawkesbury-Nepean system, whether through dam failure or to prevent the 'topping' of the dam wall.
- Secondly, the topography of the floodplain itself presents a very low profile that is conducive to a ponding or 'bathtub effect'. Below the Warragamba Dam, the Penrith floodplain flows into Castlereagh Gorge which then opens into the Richmond-Windsor floodplain before narrowing again into Sackville Gorge. In a flood event, the two gorges act as 'choke' points, delaying the outflow of floodwaters and raising flood levels within the floodplains.
- Third, the floodplain includes the existence of 'islands' or sites which are encircled by floodwaters in major flood events. McGraths Hill, for example, would become an isolated island in 5%AEP flood event and would be inundated in a 1%AEP flood event. This means that, in the latter event, McGraths Hill would first be isolated and then inundated.

In the words of one 2006 State government report, the Valley 'has been described as exhibiting a combination of the worst characteristics of riverine flooding (depth and extent), and the worst characteristics of flash flooding (rapid rise of floodwaters and limited warning time)' (Hawkesbury-Nepean Floodplain Management Steering Committee, 2006: 11).

The risk equation of probabilities and consequences is presently shifting in the Hawkesbury-Nepean Valley. Between the 1986 and 2006 Censuses, the total number of persons in the floodplain increased by 17,000 and dwellings increased by 7,700 (HCC, 2012a: 137). This level of growth, while remarkable, will be dwarfed if recent planning decisions by State government agencies are realised.

- In 2007, the New South Wales Department of Planning's Northwest Subregional Strategy set a target of 5,000 extra dwellings within the Hawkesbury LGA by 2031. Proposals to meet this target include Bligh Park Stage 2 (North Bligh Park) and Pitt Town, each involving the creation of approximately 800 lots (HCC, 2012a: 137). Much of Bligh Park Stage 2 (North Bligh Park) is beneath the 1%AEP flood level.
- 2,500 new dwellings scheduled for Vineyard, on the eastern edge of the floodplain, as part of the North-West Growth Centre of 60,000 extra dwellings.

- A target of 25,000 new dwellings was set for Penrith in the same period, including the Penrith Lakes development of 5,000 new dwellings in flood prone land adjacent to the Nepean River.

As might be expected, the different agencies involved in actualising these plans each have their own preferences in regards to the magnitude and distribution of new development and, therefore, in the magnitude and distribution of risk mitigation and residual risk. At the same time, preliminary surveys suggest that despite the high flood risk of the area, 'severe flooding is perceived as a remote event which is easily dismissed or denied' by residents (Gillespie et al., 2002: 28). One 2008 survey suggested that 70 per cent of residents were unaware they lived in a flood prone area (Becker et al., 2008). These indicators are unlikely to improve as more people without major flood experience move into this high risk floodplain. At the same time, the effects of climate change are predicted to alter the probability of major flood events occurring. For instance, as Bewsher Consulting (2012a: 18) have shown, a flood event with a 1:100 probability of occurring in any given year would have a 1:80 probability were annual rainfall to increase by 5 per cent. Geographer Robin Warner (2014: 374) states that precipitation in the Valley's catchment could change by +7 to –13 per cent by 2030 and by +20 to –40 per cent by 2070. Such climactic scenarios present a very broad spectrum of flood scenarios.

The statuses of other aspects of the flood risk equation in the Hawkesbury-Nepean floodplain are less clear. Several sections of the floodplain's evacuation routes—such as the M4 (Western Motorway), State Highway 44 (Great Western Highway) and the M7 (Westlink)—are prone to inundation in major flood events, potentially leading to the isolation of communities (Molino Stewart, 2012; Pillac et al., 2013). As such, one significant aspect of flood risk mitigation in the floodplain is evacuation planning (Opper et al., 2010; HCC, 2012a: 82-90). As elsewhere, the envelope within which evacuation must occur is determined by forecast certainty, and in the Valley the Bureau of Meteorology can predict flood events approximately 9 hours in advance with 95 per cent certainty (HCC, 2012a: D1-3). Subsequently, Opper et al. have attempted to calculate the number of buildings with and without vehicles to be evacuated, the number of buildings with containing vulnerable people, as well as introducing several suppositions as proxies for predicted human behaviour. For example, they suggest that traffic can flow at approximately 600 vehicles per lane per hour, but that a 'traffic safety factor' of 1-2 hours should be introduced to such calculations to account for delays due to accidents. Other proxies include a warning time (number of house to be warned, multiplied by 5 minutes per house and divided by the number of warning teams), a 1 hour 'warning lag factor' (the delay between warning delivery and being prepared for evacuation) and a 1 hour 'warning acceptance factor' (the delay between a warning and its subjective acceptance), all of which attempt to incorporate the manifold uncertainties of 'the human factor'. Such evacuation timelines, in turn, reveal the importance and influence of evacuation infrastructure. As such, the widening and raising of evacuation routes is currently the subject of a multi-agency review which is inquiring into the feasibility of multiple risk mitigation measures, including dredging waterways, excavating the gorges and raising the height of Warragamba Dam.

While some hold that it is better to focus upon non-structural forms of mitigation, such as planning reform (Smith et al., 1996; Bewsher et al., 2013), the major reviews of flood risk in the valley that have occurred since 1980 have been devoted to weighing the benefits of major infrastructural intervention, particularly the raising of the Warragamba Dam wall or 'crest' (e.g. Gutteridge, 1980; HNFMAC, 1997; HCC, 2012a; DPI, 2014). In 1995, a government assessment of a $300 million proposal to raise the dam wall suggested the reduction in predicted flood damages justified the cost, though the newly-elected Carr state government vetoed the proposal on the basis of environmental concerns and appended a $111 million auxiliary spillway to the dam instead. The initial report of the current review suggests that raising the dam wall is the 'most effective option for… mitigating regional downstream flooding' with estimated costs of 'between a half and one billion dollars' (DPI, 2014: 27). But such engineering works will not eliminate flood risk, particularly given the hydrological role of the Nepean and Grose Rivers, or the need for accurate emergency flood prediction.

As already indicated, development planning is a significant factor in regional flood risk, in part due to New South Wales' chequered history regarding flood mapping and its disclosure to the public. As Handmer states (1985; also Box et al., 2013), government flood policy in New South Wales underwent a series of reversals between 1977 and 1984, beginning with a commitment to remove subsidies for those developing in flood prone land and to map floodplains. The state government subsequently retreated from flood mapping, while the federal *Environmental Planning and Assessment (EPA) Act 1979* and two 1982 legal decisions made clear that local governments were responsible for taking flood risk into account in development planning decisions and, therefore, legally liable for the consequences. In New South Wales, pressure from the Liberal Party in 1983 and 1984 regarding the effect of flood mapping on property values led the Wran administration (1976-1986) to abolish 1%AEP as a planning standard and to make its own flood maps unavailable. As a recent state government report states, today there is 'no strategic governance framework for coordinating data collection' and no single source of information on flood risk (DPI, 2014: 17-19). At the same time, the Hawkesbury Local Environment Plan 1989 prohibits buildings beneath a modelled 10%AEP level while permitting them above the 1%AEP level, treating proposals within the intervening zone on a case-by-case basis. This approach to development planning is both insufficiently cautious and insufficiently strategic (see HCC, 2012g).

This section has sought to give a broad view of the forms of knowledge, uncertainties and major political, social and geographic factors shaping flood risk and flood risk mitigation in the Valley today. There are other factors to consider to gain a holistic sense of flood risk in the Hawkesbury-Nepean Valley—including community education, community preparedness, and warning systems of specific communities—though these are categorised as risk transference for the purposes of this report. It is apparent that the dominant concerns in flood risk mitigation today are the role of Warragamba Dam and flood prediction in relation to development and evacuation planning. This indicates that further qualitative research into this case study should begin by engaging with practitioners involved in these concerns and inquiring into the key uncertainties surveyed here, including the influence of Warragamba Dam in flood behaviour, the parameters of flood planning levels, the role of climate change in flood prediction parameters, and the calculation of human populations.

BOX 3

Major issues in flood risk distribution and flood risk mitigation in the Hawkesbury-Nepean Valley:

- Warragamba Dam, which was built using now-dated flood estimates; the 'bathtub' effect of two gorges; multiple 'islands' that are isolated and/or inundated in major floods.
- Both municipal and state government committed to creating more housing within floodplain.
- Evacuation infrastructure prone to inundation; evacuation planning manages meteorological and human behaviour uncertainties.
- History of government fixation on engineering solutions to flood risk and limited availability of flood mapping.
- Use of 'one-hundred-year flood' in mitigation disputed, as Probable Maximum Flood significantly higher.

3.3: BUSHFIRE

The loss of life and property to bushfire has long been an abiding concern to rural and remote residents, particularly in the large eucalypt forests of Australia's south and southeast and the grasslands of northern Australia's tropical savannah. The 'Universal Australian,' to quote Pyne (1991), the eucalypt is 'a fire creature' as it produces abundant fuel loads in the form of bark—as well as volatile organic compounds—and is unusually dependent on regular wildfire for regeneration (Adams and Attiwill, 2011: 27-38). Every day of the week now implicitly commemorates a catastrophic fire in the south and southeast, including Black Thursday in 1851, Black Monday in 1865, Red Tuesday in 1898, Black Sunday in 1926, Black Friday in 1939, Black Tuesday in 1967, Ash Wednesday in 1983, and Black Saturday in 2009. Black Saturday fires led to 173 fatalities and the burning of 450,000 hectares in Victoria, while Ash Wednesday fires led to 47 fatalities in Victoria and 28 fatalities in South Australia. Other major fires have also claimed properties and thousands of hectares, such as the 2003 Canberra bushfire, which left over 490 people injured and 4 fatalities. This history gives some indication as to why bushfire is a major concern for governments and emergency service agencies, amongst others, a concern that is growing as more individuals choose to live in the rural and peri-urban fringe, fire seasons begin earlier and fire weather becomes more severe (Hughes and Steffen, 2013). Thus, major efforts have been devoted in the past to attempting to measure and mitigate this risk, particularly in areas with large eucalypt coverage.

The scientific knowledge applied in bushfire risk mitigation is subject to uncertainties parallel to those encountered in flood risk mitigation, particularly in regards to the modelling and prediction of the hazard. Fire behaviour might be regarded as a 'golem science', to use Collins and Evans' term, in that the field is both relatively settled while remaining a source of continuing mysteries and continuing discovery (e.g. McRae et al., 2013). Thus, while the physics of fire behaviour are comparatively well understood, the behaviour of actual bushfires remains difficult to anticipate due to the extreme localisation of fire dynamics and their responsiveness to variability in three factors that are difficult to measure: fuel load, fuel type and wind speed (see Cruz et al., 2012a). While a region may have an archetypical weather pattern—and therefore archetypical dynamics regarding fire spread—it is not always possible to accurately model a particular fire's behaviour in advance at the level of, for instance, the distribution of firebrands by ambient winds or convection columns (known as 'spotting') (Pastor et al., 2003: 145-147; Saeedian et al., 2010). As is discussed further in the case study, while fire intensity and fire damage can be modelled from given ignition points under given weather conditions, ignition points themselves are more difficult to predict. A related point is that—as in flood prediction—attempts to model future fires are typically validated through comparing model outputs and empirical data from an historical fire event. Such models are, to a varying degree, reliant upon sometimes limited data regarding past 'worst case' events that are, by definition, relatively rare. The data unpinning these aspects in any model must be the object of scrutiny if we are to understand the levels of speculation and 'model tuning' that are operating within a prediction and mitigation scheme. Tuning occurs where coefficients, equations or other aspects underpinning a model are adjusted without a scientific justification to produce closer agreement between predictions with observations (Sundberg, 2009: 170).

As noted earlier, interventions to mitigate bushfire risk such as prescribed burning, building codes, fire prevention works, or new planning laws are themselves complex 'explosions of uncertainty'. Risk of house ignition can occur through a variety of vectors, including through embers or burning debris carried by the wind, heat radiation, direct flame contact, or wind damage allowing the entry of embers and burning debris. The effects of restrictive building and planning codes on lowering vulnerability to these forms of ignition are, in particular, difficult to either anticipate or measure in Australia because they are a novelty (see Groenhart et al., 2012). Between 2009 and 2011 two major reforms occurred in Victoria, the first being the implementation of a new building standard prescribing mandatory construction requirements for new buildings in bushfire prone areas (Standards Australia, 2009a), the second being the creation of a planning overlay (Bushfire Management Overlay) prescribing other requirements relating to access, water supply, and proximity to vegetation (Chang-Richards et al., 2013). It is too early to report on the effect of these mitigation strategies, particularly as they relate solely to new developments. Nonetheless, there is a significant body of research examining the effect of fuel treatments (such as slashing), building materials and building design on house losses in the wildland-urban interface (Ramsay and Rudolph, 2003; Ramsay et al., 1996; Leonard and McArthur, 1999; Ager et al., 2010; Mell et al., 2010; Leonard et al., 2009). The micro-dynamics of actual bushfires, variability in housing stock and the ability for management activity during a bushfire to effect house loss all present major difficulties in attempting to scientifically verify the effect of these forms of mitigation on house loss.

In Australia, prescribed burning is the dominant form of risk mitigation, presenting a long history as an 'Australian strategy' bolstered periodically by government responses to catastrophic fires (Pyne, 1991: 338-363). Between January and March 1961, for instance, a series of massive bushfires burned through southwest Western Australia, largely destroying the towns of Dwellingup and Karridale and significantly damaging others. A Royal Commission led by G.J. Rodger subsequently called for a renewed focus on research into fire behaviour and fuel abatement, following which the State's Forests Department initiated an intensive program of fuel-reduction burning on state lands, averaging about 300,000 hectares between 1961 and 1990. Prescribed burning programs have been adopted in all other states, most generally treating 2 per cent of Crown lands in a given year (Adams and Attiwill, 2011: 75-76). A significant amount of research produced on fuel-reduction burning suggests that as the average area burnt for fuel reduction increases the average area burnt by bushfires decreases (Sneeuwjagt, 2008; Boer et al., 2009). In other words, the supposition is that reducing fuels decreases the intensity and rate of spread of subsequent bushfires, though the efficacy of these treatments in reducing losses is dependent on other factors such as the geographic pattern of burns and the proximity of treated areas to at-risk assets (Bradstock et al., 2012c; Gill and Stephens, 2009).

To be clear, prescribed burning sometimes refers to any controlled application of low intensity or high intensity fire, including for the purposes of reducing fine fuels, modifying or renewing habitats for specific species, or regenerating forests after timber harvesting, though the dominant meaning in Australia is in relation to fuel reduction. A specific prescribed burning program is examined in the following case study, but it is useful for the purposes of this review to briefly note some of the most significant uncertainties in the science and practice of prescribed burning for risk mitigation (see McCarthy and Tolhurst, 2001; Boer et al., 2009; Bradstock et al., 2012a).

- *Quantifying additionality*: first, quantifying the benefit of prescribed burning is a difficult task as it relies on calculations of the probabilities and consequences of two abstractions. Put differently, the benefit (or 'additionality') of prescribed burning is a product of the calculable difference in terms of fire intensity, loss of human life and property, and/or economic impact between a modelled control scenario and a treated environment. As indicated in the second section, such models are the product of a variety of uncertainties relating to the depth and strength of historical data on vegetation, previous fires, population, and so on.

- *Validating predictions*: second, the ability of prescribed burns to meaningfully reduce the intensity of fires in extreme weather conditions remains open to academic debate (Bradstock et al., 2012a: 66-67; see also Keeley and Zedler, 2009). As in flood, there are significant issues relating to the validation of predictions given that the effectiveness of a prescribed burning program is best demonstrated only after an extremely rare hazard event.
- *Translation processes*: third, the translation of strategic modelling into a prescribed burning program involves another set of uncertainties relating to operational implementation, highlighting again how implementation is equally as complex as research. For instance, it may not be possible to burn given units of land due to weather conditions, isolation or, conversely, their proximity to human life and property. Another operational uncertainty relates to the collection of data after a prescribed burn, as the validation predicted fuel reduction is subsequently fed back into the next round of predictive modelling.
- *Intervention effects*: fourth, as Clode and Elgar note (2014: 1193), there remain 'significant concerns about the health, safety, and ecological impact of broad-scale prescribed burning' (see also Clarke, 2008). In order to estimate the ecological impact of prescribed burning, for example, ecologists have attempted to map landscapes in terms of vegetation classes and their minimum and maximum tolerance for intervals between fires ('tolerable fire interval' or TFI, see Burrows, 2008). Such envelopes are nonetheless estimates and, as such, there is a risk that their lower limits will be treated as unproblematic guides for policy planning. Prescribed burning is a mitigation tool supported by a body of scientific research, but practitioners and decision-makers must remain alert to its assumptions and uncertainties.

This report will now address these uncertainties in relation to a specific case study—the Barwon-Otway area—showing how the historical, economic and political particularities of this place shape how we might know and manage a bushfire hazard, and how science is engaged in that work.

3.4: CASE STUDY: FIRE RISK IN THE BARWON-OTWAY AREA

The Barwon-Otway area is the eastern subsection of the Barwon South West district of southwestern Victoria, on the rolling coast east of Melbourne. The area includes three municipal councils, comprising the entirety of Surf Coast Shire and sections of Colac Otway Shire and Corangamite Shire. At the 2011 Census, the area's population was approximately 290,000 people, most living in the city of Geelong and its surrounds; Surf Coast Shire and Colac-Otway Shire have fulltime resident populations of approximately 25,000 and 20,000 respectively (ABS 2011). The largest towns are Torquay and Colac, which each make up approximately 4 per cent of the region's population, and Camperdown and Anglesea, which each make up approximately 1 per cent of the region's population (DEPI, 2014). Many of these towns are growing quickly, and between 2005 and 2011 Torquay's population grew by 48 per cent. The area also features townships of 200-300 people—such as Forrest, Fairhaven, Wye River and Kennett River—that are either wholly or largely surrounded by eucalypt forest and possess limited or very limited evacuation infrastructure. Presently, the demographic future of the area is being assessed through the Barwon South West Regional Strategic Plan 2012–2015, though an early report suggests the region's population will grow by at least a third between 2012 and 2022 (see Regional Development Australia, 2013). Notably, a comparatively high number of properties in the Surf Coast Shire are holiday homes. This is demonstrated by the fact that, first, approximately 17 per cent of residential properties in Surf Coast Shire are owners' second homes and, second, censes indicate that 60-70 per cent of residential properties in coastal towns such as Anglesea and Lorne are unoccupied in winter (see ABS 2011 and Frost, 2003). Such high numbers of seasonal residents can present obstacles to bushfire risk education and mitigation (Bright and Burtz, 2006).

Economically, the Barwon-Otway area has two main industries—tourism and dairy production—which are loosely divided geographically between the northwest and southeast. The fact that Barwon South West is Australia's largest dairy production region (Regional Development Australia, 2013) is only apparent in the Barwon-Otway area near Colac and its surrounds. To the south and southeast, Colac is separated from the coast by the forested Otway Ranges.[3] The major draw cards for the estimated seven million visitors who come to Barwon-Otway area annually are:

- The 103,000-hectare Great Otway National Park, and other large tracts of State Forest such as the Anglesea Heath.
- The Twelve Apostles, distinctive limestone stacks near Port Campbell.
- The Great Ocean Road, a coastal road which winds along the coast from Torquay through to Warnambool built between 1919 and 1932 to commemorate the soldiers who fought in World War I (see Kerr, 2013).

As such, bushfire risk is highest during the summer months, not only because this is the period during which conditions for catastrophic bushfires are at their worst, but also because this is the time during which a large number of short-term domestic and international visitors rapidly come to the region to enjoy the weather, beaches and bush land. This influx of an at-risk population with little awareness of bushfire risk potentially affects bushfire risk mitigation strategies. It is reasonable to suppose that, in a area which relies heavily on the tourist season and the preservation of wilderness values, some sectors of the community will not necessarily support the closing of roads during extreme bushfire risk conditions or the charred grasslands, smoke and access restrictions that are a requisite part of prescribed burning.

---

[3] The Great Otway National Park was established in June 2005 on the basis of Otway National Park, four existing State Parks and other Crown lands.

The Barwon-Otway area, like other comparable sites in Australia's southeast, is a high bushfire risk area because it is at risk of bushfires that are low probability but extremely high consequence. The particularly elevated level of bushfire risk in this area is a combination of three factors:

- First, the area's forests exhibit an abundance of old-growth eucalypts (particularly mountain ash (*E. regnans*)) and their litter in large contiguous areas of flammable heath and forest. This fuel, under the right conditions, is capable of creating a catastrophic crown fire with abundant spotting.
- Second, the extensive wildland urban interface of coastland towns such as Lorne, Anglesea, Aireys Inlet, Wye River and Fairhaven, where resident and tourist populations are in close proximity to forested areas.
- Third, the typical regional weather pattern produces strong dry northwesterly winds followed by a southwesterly 'cool change' moving in from the sea later in the day.

These three factors combined are capable of creating intense firestorms that do much of their damage in the space of a day, first burning in a narrow southerly direction through contiguous forest to create what, following a perpendicular 'cool change', can turn into a wide fire front threatening a large number of lives and structures along the coastline (e.g. Cruz et al., 2012b). Several of the catastrophic post-settlement fires to affect the Barwon-Otway area followed this pattern, such as the Ash Wednesday fire in February 1983, a firestorm that started in Dean's Marsh and burnt through 41,000 hectares between Lorne and Anglesea, destroying 782 buildings and killing 3 people (Bardsley et al., 1983; Mills, 2005). Other major post-settlement fires include the January 1914 and January 1919 fires, and Black Friday fire of January 1939 which claimed one family near Barongarook.

As noted earlier, the dominant mitigation strategy in southeastern Australia is prescribed burning, which is used to decrease the prospective intensity of bushfires to limit their damage and aid fire suppression. During the Victorian Bushfires Royal Commission into the Black Saturday fires (see 2009), many experts identified the high fuel loads and lack of prescribed burning in the Yarra Valley and Central Gippsland as key contributors to the fires' intensity, as well as identifying the role of infrastructural deficits, planning laws and fire safety advice in the high number of fatalities (VBRC, 2010; see also ENRC, 2008). Thus, a major Royal Commission recommendation, subsequently adopted by the Victorian government, was to treat at least 5 per cent—and up to 8 per cent—of public land per year with prescribed burning. However, the adoption of prescribed burning in Victoria is conditioned by factors other than its scientific basis. First, because state agencies hold legal responsibility for public lands, they necessarily have considerably more discretion over their treatment than private lands. Prescribed burning requires significant preparation works—such as the bulldozing of 'fuel breaks'—which could effect financial, ecological and social utility for landholder's when conducted on private lands. A number of other considerations must still be taken into account by agencies conducting burns, including protected species, smoke hazard (both to the public and agriculture), and appropriate weather conditions. Second, other public land mitigation strategies, such as vegetation thinning, have significantly higher infrastructure and labour costs. Third, while a significant amount of vegetation, and therefore bushfire risk, resides on private land, transaction costs for implementing bushfire risk mitigation on private land are higher. This includes, for instance, the costs to government involved in issuing fire prevention notices to landholders requiring works to fire hazards and negotiating permission and land access for works.[4] Fourth, there are both political and economic obstacles to implementing other mitigation strategies on public and private land, often because they inflict costs on stakeholders. These include compulsorily acquiring high-risk properties, creating more restrictive building and planning codes, or compelling electricity companies to move ignition hazards, all of which were recommended by the Victorian Bushfires Royal Commission and have faced significant opposition (see McLennan et al., 2014; Rhodes, 2012).

The contiguity of forested public lands makes the Barwon-Otway area both high risk and conducive to the dominant mitigation method. Nonetheless, planning and implementing prescribed burning is extremely complex, not only in its production of scientific knowledge but also in their application and translation for community stakeholders. Some of the most highly treatable public lands in the Barwon-Otway area are the foothill forests and heathlands between Anglesea and Lorne, areas where the effects of prescribed burning—smoke, restricted access, potential for uncontrolled bushfires—sometimes clash with the values and expectations of residents and visitors. In some circumstances, those planning and executing burns have to work against community perceptions of prescribed burning as ineffective or unsafe. In November 1994, two houses in Moggs Creek, a small community south of Aireys Inlet, were destroyed when a prescribed burn jumped containment lines (see Tippet, 1994; Faulkner, 1994; Schauble, 1994). Such incidents can have long-term effects on community trust (see Winter et al., 2004; Lijeblad et al., 2009). Meanwhile, less populated areas such as the rainforest in the west of the region are significantly harder to treat, due to the moisture of the fuels outside bushfire season. Also, while prescribed burning is a scientifically informed practice, it is not a solution to bushfire risk. As DEPI has stated, modelling suggests that residual risk has a theoretical minimum of 10 per cent in the Barwon-Otway area, meaning that were all public lands to be treated simultaneously—which is not legally or practically possible—the risk to built assets would still be 10 per cent of the baseline rather than zero. State action is not a complete answer.

Parallel to the Victorian government's renewed focus on prescribed burning, over the past decade the state agency responsible for public lands, the Department of Environment and Primary Industries (DEPI)[5], has piloted the use of ensemble forecasting software to inform prescribed burning strategies. In 2005, the Department began the Future Fire Management Project with researchers supported by the Bushfire Cooperative Research Centre (see Bushfire CRC, 2013) and partners in Parks Victoria and other agencies, focusing on the two pilot study areas: the

---

[4] Under the *Country Fire Authority Act 1958* (Vic) s. 42.

[5] Previously the Department of Sustainability and Environment, and recently renamed the Department of Environment, Land, Water & Planning

Barwon-Otway area and the Central Highlands. The aim of this project was to evaluate the outcomes of different fuel management regimes in terms of reducing risk to life and property, biodiversity, timber and water quality and yield impacts, using PHOENIX RapidFire, a program able to 'both visualise and quantify the potential effect of fuel reduction activities on bushfire risk across both public and private land' (Ackland et al., 2014; see also Duff et al., 2013; Tolhurst et al., 2014). In short, data relating to topography, weather, fuel load (vegetation mapping and fire history), asset locations, and ignition locations are loaded into the modelling software to generate predictions of fire spread and intensity for hypothetical fires lit under 'worst case scenario' weather conditions. Using ignitions across a 5 kilometre grid, it models single-day single-ignition fires under multiple fuel treatment scenarios to, in turn, demonstrate the potential efficacy of a burning program. The core of this approach is 'residual risk', understood as the remaining risk to built assets—used as a proxy for other losses—after prescribed burning treatment when measured against a purely theoretical control in which no fires occur whatsoever (State of Victoria, 2013: 1-7). It is estimated that increased and more strategic planned burning after 2007 has lowered residual risk in the Barwon-Otway area from nearly 80 per cent to approximately 60 per cent. Importantly, this risk-based approach differs for the '5 per cent' activity-based target otherwise used by the Victorian government to measure mitigation.

A high risk area with comparatively treatable fuels, the Barwon-Otway area is a good site to test the efficacy of prescribed burning in mitigating risk to multiple values and assets. Amongst its benefits, the state's forecasting program is able to make synthetic abstractions visible and material, simulating a catastrophic event the like of which has not occurred in the region for over 30 years and is thus outside many residents' experience. It is also founded on Geographical Information System (GIS) technology, meaning that spatially dynamic entities and spatially static entities can be incorporated into the forecasts as topographical 'layers'. Data on the addresses of vulnerable people—that is people with limited abilities to defend their home from bushfire—can be used to show how they might be affected under different scenarios, while historical data on lightning strike locations can be mined to predict likely future ignition points. Another layer, presently being developed for incorporation within the system, attempts to measure biodiversity in order to better incorporate such values into decision-making. The landscape is thus divided up into spatial units and each unit, using collated data on species populations, is assigned a Geometric Mean Abundance of Species value (see Kelly et al., 2014). As in the use of address point data as a proxy for human life and property, here a synthetic abstraction is made to stand in for elusive real world flora and fauna. The innovative approaches are now being expanded across the State's seven bushfire 'catchments' through the Victorian Bushfire Risk Profiles initiative, though it is important for anyone assessing such mitigation efforts to remain clear about the simulations in play and their innate, and sometimes obscure, uncertainties. On the one hand, limitations in species population data, or uncertain correlations between the presence of one (measured) species with another (unmeasured) species, can impose significant confidence limits on any corresponding risk calculation. On the other hand, it is possible that emergent measures of risk may reveal that current programs focused on reducing risk to human life and property are harming assets and values such as biodiversity.

BOX 4

Major issues in bushfire risk distribution and bushfire risk mitigation in the Barwon-Otway area:

- Significant numbers of growing coastal townships; high numbers of seasonal residents and high number of seasonal visitors during bushfire season.
- Contiguous flammable heath and forestlands; extensive wildland-urban interface; prevailing weather pattern capable of catastrophic fire event.
- Dominant mitigation strategy is fuel reduction burning to reduce risk to life and property; other mitigation strategies more costly and politically contentious; some parties oppose burning.
- New innovative approached used to plan and quantify mitigation; significant uncertainties surrounding impact of prescribed burning on flora and fauna; similar uncertainties likely to emerge from measuring risks to other assets and values.

This section has sought to give a broad view of the knowledge practices and major political, social and geographic factors shaping bushfire risk and bushfire risk mitigation in the Barwon-Otway area. There are other factors to consider in trying to gain a holistic sense of bushfire risk in the region—demography, community preparedness, warning systems and so on—though these are categorised as risk transference for the purposes of this report. Nonetheless, it is apparent that the dominant concerns in bushfire risk today are the reduction of fuel on public and private lands. This indicates that further qualitative research into this case study should begin by engaging with practitioners involved in these concerns and inquiring into key uncertainties surveyed here, including the verification of PHOENIX RapidFire, the ability of PHOENIX RapidFire model spatially dynamic assets and processes of translation that occur between modelling and operations. Further research should also examine the apparent lack of attention paid in available literature to evacuation planning as a bushfire risk mitigation strategy in the Barwon-Otway area.

4: CONCLUSION

The first section of this report presented a framework for understanding risk and risk mitigation as complex phenomenon emerging within specific contexts and 'local knowledge practices'. How we understand a risk, and the relative responsibilities of different parties to mitigate that risk, is a product of social, economic, and political factors that include the development and local availability of measuring apparatus, archives, and synthesisers. Having now reviewed a wide array of literature covering the scientific practices and scientific uncertainties in bushfire and flood risk mitigation, it is useful to re-categorise the forms of uncertainty encountered in this review. It is anticipated that these categories will prove useful to future research within the Scientific Diversity and Scientific Uncertainty in Risk Mitigation Policy and Planning project, as well as helping guide other social science researchers and qualitative research projects engaging with the complex practices of risk mitigation professionals. The discrete categorisation of uncertainties may also be useful to risk mitigation professionals themselves in informing their own attempts to explain risk and justify mitigation practices both to other risk mitigation professionals and to the public.

The following are the three categories of scientific uncertainties drawn from this report:

1. **Historicist uncertainties**: those uncertainties which emerge from the reliance of scientific knowledge on archives of historical data. These include: uncertainties that stem from variations in metrics and the gaps in data collection; uncertainties due to the impossibility of certain types and volumes of data; uncertainties the variability in the availability of data; and uncertainties due to the variability in the syntheses of data between different parties. If, returning to Lane et al., 'the futures imagined are tied to pasts experienced,' then historicist uncertainties are those owed to the limited availability of the past in the present.
2. **Instrumental uncertainties**: those uncertainties which emerge from the limitations of a given apparatus, heuristic or theory. As this report shows, different scientific theories and tools may be used in risk mitigation for a number of overlapping reasons. The use of a technique or apparatus may be justified by: its superior operational efficiency; its being within the limits of available resources; its having been adopted as an industry standards; or, its being the leading application of existing validated research findings. Each such 'instrument' will be a 'local knowledge practice' with inherent uncertainties owing to its parameters, design and development.
3. **Interventionist uncertainties**: those uncertainties which emerge from a given mitigation intervention, meaning the uncertainties involved in predicting and/or calculating the effect of an intervention. Arguably, a vast number of activities might be thought of as interventions, though this report is solely focused on those that are undertaken intentionally by governments to reduce a hazard's probabilities and/or consequences. Relevant

interventions include strategic planning exercises, legal reforms, policy changes, and engineering works, amongst others, all of which attempt to manage a risk, often by geographically and/or temporally redistributing it. All such interventions are 'explosions of uncertainty' with effects that, first, can and should be scientifically quantified in advance and, second, nonetheless cannot be wholly predicted by scientific methods.

A summary table is provided at the end of this report (see Table 1).

It is worth noting the existence of another category of uncertainties that are correlated to scientific knowledge but are not themselves scientific, and are therefore excluded from this categorisation. Translation uncertainties are those uncertainties which emerge from the translation of scientific knowledge into practice by individuals, institutions and agencies. This report has, for example, only touched briefly on the many difficulties of translating or transferring risk—as it is made legible to and by risk professionals—into action by residents within an at-risk site. To revisit the standardised definition of risk, it is important to understand that risk fluctuates because both probabilities and consequences are fluid. Community preparedness (e.g. McGee and Russell, 2003; Molino and Huybrechs, 2004) and public understanding of science (e.g. Sturgis and Allum, 2004; Lezaun and Soneryd, 2007) rise and fall, and may vary widely within and between demographics. The effectiveness of attempts to translate forms of scientific knowledge between audiences and contexts each depend on multiple local factors, some, such as political allegiances and trust in government agencies, being outside the control of any one party. Any mitigation intervention that relies significantly on public action encounters uncertainties stemming from the given local social, political and economic context. As such, translation uncertainties are very important to risk mitigation practice and will necessarily be a key element in the RMPP project's engagement with risk mitigation professionals in its three case studies. These uncertainties are, nonetheless, not scientific and are therefore outside the scope of this report.

This report's categorisation of uncertainties encountered and managed by bushfire and flood risk mitigation professionals will facilitate the methods of this project, including ensuring that the research is engaged with industry practice and policy priorities, as well as being useful to other people and institutions more broadly:

- First, the categorisation of uncertainties developed will be useful to this project and other social science research projects engaging with the complex and technical practices of risk mitigation professionals. Framing these uncertainties categorically as well as technically will prove useful to analysing the management of uncertainty across and between case studies.
- Second, it is anticipated that risk professionals will express differing opinions about the different uncertainties in mitigation practice in terms of their relative influence, changeability, volatility, and so on. Increased knowledge about the importance of different categories of uncertainties to mitigation practice will facilitate management of these uncertainties, for

example, in terms of resourcing and design of risk mitigation training, communications and education.

- Third, this categorisation of diverse forms of scientific knowledge and their uncertainties supports the capacity of risk mitigation professionals to explain risk and justify mitigation practices both to other risk mitigation professionals and to the public. Being able to describe a scientific uncertainty is a vital aspect of internal and external risk communication and, as such, these categories will prove useful in communicating the origins and character of an uncertainty.
- Fourth, this report will be of particular use to non-scientists, including those engaged in research and industry roles, in generating an understanding of some of the key causes and consequences of scientific uncertainty in bushfire and flood risk mitigation. Such an understanding is necessary to any investigation of how individuals and agencies use and understand diverse scientific evidence and other forms of knowledge in their risk mitigation roles.

This report's review of the literature relating to scientific uncertainty in bushfire and flood risk mitigation illustrates that there are a multitude of 'known unknowns' that must be encountered and managed by practitioners and decision-makers if they hope to effectively manage these risks. Social science research methods are well positioned to investigate how these uncertainties are understood and managed by risk mitigation practitioners across multiple practices, agencies and sites.

TABLE 1: Uncertainty Categories for Scientific Knowledges Used in Bushfire and Flood Risk Mitigation[6]

Uncertainty type	Key forms	Elaboration
Historicist – uncertainty arising out of reliance on historical data, due to assumed determining relationship between the past, the present and the future	Gaps and inconsistencies in historical datasets on relevant environmental variables	Gaps can arise out of: innovations in measuring apparatuses; variations in data metrics; variations in the geographical spread of measuring apparatuses; unreliable measurements; commercially sensitive data collections; fragmented storage; and, funding constraints.
	Relative rarity, uniqueness and force of a given hazard event	Lack of historical exemplars is a barrier to prediction. Catchment data sets that are based on mean and medium river flow have limited insights into flood discharges. Measuring apparatuses can be destroyed during hazard event. Relative randomness of bushfire ignition points, and fire behaviour unique to fire-terrain and fire-atmosphere interactions.
	Assumption that natural systems fluctuate within an envelope of variability known as 'stationarity'	Climate change requires recognition of both temporal and spatial variability into the future, the parameters of which are uncertain.
Instrumental – uncertainty arising out of limitations of a given apparatus, heuristic or theory[7]	Difficulty of capturing hazard behaviours in simulators, largely due to uncertainties surrounding behavioural algorithms	E.g.: the complexity of feedback mechanisms between fire and atmosphere; the assumptions of mass and momentum conservation in hydrology and hydraulics, though catchment responses to rainfall are necessarily non-linear. Difficulties with behavioural algorithms include historicist uncertainties, such as data limits. Data synthesis strains against computational resources and reporting requirements.
	Limits to modelling of at-risk assets and values	Spatially static entities (e.g. property, infrastructure) can be incorporated into topographical modelling; but spatially dynamic entities (e.g. human life, flora and fauna) are either excluded or rendered through static proxies.
	Contested methodological standards	E.g. '100-year flood'. Standards do not include all available data but remain in use because of resource limitations, institutional preferences and literacies. These also iteratively influence the framing of scientific methods and projects.
Interventionist – predictive calculations about the effect of mitigation interventions	Quantifying intervention additionality	Mitigation benefits have their own historicist and instrumental uncertainties, and are influenced by non-scientific aspects such as policy priorities, social values, and political context.
	Reflexivity, with respect to parameters and primary, secondary and emergent consequences of interventions	Uncertain effects of interventions on at-risk values, e.g.: 'safe development paradox' or 'levee effect'; and, the ecological effects of prescribed burning and dams and levees. Uncertainty surrounding implementation of interventions. These unintended consequences should be considered calculable and non-calculable uncertainties.

---

[6] Developed for the purposes of the 'Scientific Diversity, Scientific Uncertainty and Risk Mitigation Policy and Planning' project by Timothy Neale and Jessica K. Weir.

[7] Note that bushfire risk is typically figured on likelihood of conducive conditions not on likelihood of occurrence. Flood risk is usually calculated in two ways: the likelihood of occurrence of rain-driven flood events; and, the spatial modelling of flood behaviour.

REFERENCES:

Ackland A, Blackett A, Norris J, et al. (2014) Development of the Victorian Bushfire Risk Profiles and the concept of residual risk. *AFAC 2014.* Wellington, NZ.

Adams MA and Attiwill PM. (2011) *Burning issues: sustainability and management of Australia's southern forests,* Collingwood, Vic.: CSIRO Pub. in association with Bushfire CRC.

Ager AA, Vaillant NM and Finney MA. (2010) A comparison of landscape fuel treatment strategies to mitigate wildland fire risk in the urban interface and preserve old forest structure. *Forest Ecology and Management* 259: 1556-1570.

Apel H, Aronica G, Kreibich H, et al. (2009) Flood risk analyses: how detailed do we need to be? *Natural Hazards* 49: 79-98.

Atkins B. (2009) The Launceston flood policies: levees and beyond. *Australian Journal of Emergency Management* 24: 32-37.

Baan P and Klijn F. (2004) Flood risk perception and implications for flood risk management in the Netherlands. *International Journal of River Basin Management* 2: 113-122.

Bardsley KL, Fraser AS and Heathcote RL. (1983) The Second Ash Wednesday: 16 February 1983. *Australian Geographical Studies* 21: 129-141.

Barry M. (2008) Total flood warning systems. *Australian Journal of Emergency Management* 23: 21-29.

Beck U. (1992) *Risk society: towards a new modernity,* London: Sage.

Becker J, Johnston D, Coomer M, et al. (2008) Flood risk perceptions, education and warning in four communities in the Hawkesbury- Nepean Valley, New South Wales, Australia – results of a questionnaire survey, February 2006. *GNS Science Report 2008/02.*

Bell HM and Tobin GA. (2007) Efficient and effective? The 100-year flood in the communication and perception of flood risk. *Environmental Hazards* 7: 302-311.

Benito G, Lang M, Barriendos M, et al. (2004) Use of systematic, palaeoflood and historical data for the improvement of flood risk estimation: review of scientific methods. *Natural Hazards* 31: 623-643.

Berkhout F. (2002) Technological regimes, path dependency and the environment. *Global Environmental Change* 12: 1-4.

Bewsher D, Grech P and Yeo S. (2013) Hawkesbury's Flood Risk Management Plan: 15 years in the making. *Floodplain Management Association National Conference.* Tweed Heads, NSW.

Bewsher D and Maddocks J. (2003) Do We Need to Consider Floods Rarer Than 1% AEP? *Healthy Floodplains Wealthy Future: Victorian Flood Management Conference.* Horsham.

Bijker WE, Hughes TP and Pinch TJ. (1987) *The social construction of technological systems: new directions in the sociology and history of technology,* Cambridge, Mass.: MIT Press.

Boer MM, Sadler RJ, Wittkuhn RS, et al. (2009) Long-term impacts of prescribed burning on regional extent and incidence of wildfires: evidence from 50 years of active fire management in SW Australian forests. *Forest Ecology and Management* 259: 132-142.

Box P, Thomalla F and Van Den Honert R. (2013) Flood risk in Australia: whose responsibility is it, anyway. *Water* 5: 1580-1597.

Box P, Thomalla F, Van Den Honert R, et al. (2012) How can residents know their flood risk? A review of online flood information availability in Australia. *Australian Planner* 49: 339-348.

Bradstock RA, Cary GJ, Davies I, et al. (2012a) Wildfires, fuel treatment and risk mitigation in Australian eucalypt forests: Insights from landscape-scale simulation. *Journal of Environmental Management* 105: 66-75.

Bradstock RA, Williams RJ and Gill AM. (2012c) Future fire regimes of Australian ecosystems: new perspectives on enduring questions of management. In: Bradstock R, Gill AM and Williams RJ (eds) *Flammable Australia: fire regimes, biodiversity and ecosystems in a changing world.* Collingwood, Vic: CSIRO Publishing, 307-324.

Bright AD and Burtz RT. (2006) Firewise activities of full-time versus seasonal residents in the wildland-urban interface. *Journal of Forestry* 104: 307-315.

Burby RJ. (2006) Hurricane Katrina and the paradoxes of government disaster policy: bringing about wise governmental decisions for hazardous areas. *Annals of the American Academy of Political and Social Science* 604: 171-191.

Burrows N. (2008) Linking fire ecology and fire management in south-west Australian forest landscapes. *Forest Ecology and Management* 255: 2394–2406.

Bushfire CRC. (2013) *Enhancement of fire behaviour models.* Available at: http://www.bushfirecrc.com/projects/2-2/enhancement-fire-behaviour-models.

Chang-Richards Y, Wilkinson S, Potangaroa R, et al. (2013) Resource challenges for housing reconstruction: A longitudinal study of the Australian bushfires. *Disaster Prevention and Management* 22: 172-181.

Clarke MF. (2008) Catering for the needs of fauna in fire management: science or just wishful thinking? *Wildlife Research* 35: 385-394.

Clode D and Elgar M. (2014) Fighting fire with fire: does a policy of broad-scale prescribed burning improve community safety? *Society and Natural Resources* 27: 1192-1199.

Cloke HL and Pappenberger F. (2009) Ensemble flood forecasting: a review. *Journal of Hydrology* 375: 613-626.

Collins HM and Evans R. (2002) The third wave of Science Studies: studies of expertise and experience. *Social Studies of Science* 32: 235-296.

Comrie N. (2011) Review of the 2010–11 flood warnings and response. Melbourne, Vic: Victorian Government.

Cova T and Church R. (1997) Modelling community evacuation vulnerability using GIS. *International Journal of Geographical Information Science* 11: 763-784.

Cruz MG, McCaw WL, Anderson WR, et al. (2012a) Fire behaviour modelling in semi-arid mallee-heath shrublands of southern Australia. *Environmental Modelling and Software* 40: 21-34.

Cruz MG, Sullivan AL, Gould JS, et al. (2012b) Anatomy of a catastrophic wildfire: The Black Saturday Kilmore East fire in Victoria, Australia. *Forest Ecology and Management* 284: 269-285.

Deen AR, Craig RW and Carr R. (1989) Warragamba Dam probable maximum flood. *Hydrology and Water Resources Symposium 1989: Comparisons in Austral Hydrology.* Christchurch, NZ: Institution of Engineers, Australia, 382-385.

DEPI. (2014) *Barwon Otway bushfire risk landscape.* Available at: http://www.depi.vic.gov.au/fire-and-emergencies/managing-risk-and-learning-about-managing-fire/managing-bushfire-risk/barwon-otway-bushfire-risk-landscape.

Dessai S, Hulme M, Lempert R, et al. (2009) Co we need better predictions to adapt to a changing climate? *Eos, Transactions American Geophysical Union* 90: 111-112.

Douglas M and Wildavsky A. (1982) *Risk and culture: an essay on the selection of technical and environmental dangers,* Berkeley: University of California Press.

Dowdy AJ, Mills GA, Finkele K, et al. (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.* Canberra: Centre for Australian Weather and Climate Research.

DPI. (2014) Hawkesbury-Nepean Valley Flood Management Review: stage one report. Sydney: Department of Primary Industries (NSW).

Duff TJ, Chong DM and Tolhurst KG. (2013) Quantifying spatio-temporal differences between fire shapes: Estimating fire travel paths for the improvement of dynamic spread models. *Environmental Modelling and Software* 46: 33-43.

Edwards PN. (2010) *A vast machine: computer models, climate data, and the politics of global warming,* Cambridge, Mass.: MIT Press.

Ellis S, Kanowski P and Whelan RJ. (2004) *National inquiry on bushfire mitigation and management,* Canberra: Commonwealth of Australia.

ENRC. (2008) Inquiry into the impact of public land management practices on bushfires in Victoria: report of the Environment and Natural Resources Committee on the Inquiry into the Impact of public land management practices on bushfires in Victoria. *Parliamentary paper 2006-10 no. 116.* Melbourne, Vic.

Faulkner J. (1994) We're Sorry: Fire Chief. *The Age.*

Fordham M. (1999) Participatory planning for flood mitigation: models and approaches. *Australian Journal of Emergency Management* 13: 27-34.

Frost W. (2003) *A hidden giant: second homes and coastal tourism in south-eastern Australia*: Monash University Faculty of Business and Economics.

Galloway GE. (2011) If stationarity is dead, what do we do now? *Journal of the American Water Resources Association* 47: 563–570.

Gigerenzer G. (2003) *Reckoning with risk: learning to live with uncertainty,* London: Penguin.

Gill AM and Stephens SL. (2009) Scientific and social challenges for the management of fire-prone wildland-urban interfaces. *Environmental Research Letters* 4: 1-10.

Gillespie C, Grech P and Bewsher D. (2002) Reconciling Development with Flood Risks: The Hawkesbury-Nepean Dilemma. *Australian Journal of Emergency Management*: 27-32.

Gissing A, Keys C and Opper S. (2010) Towards resilience against flood risks. *Australian Journal of Emergency Management* 25: 39-45.

Glasner P. (2000) Reporting risks, problematising public participation and the human genome project. In: Allan S, Adam B and Carter C (eds) *Environmental Risks and the Media.* London: Routledge, 130–141.

Godden L and Kung A. (2011) Water law and planning frameworks under climate change variability: systemic and adaptive management of flood risk. *Water Resource Management* 25: 4051-4068.

Griffin RJ, Yang Z, ter Huurne E, et al. (2008) After the flood: anger, attribution, and the seeking of information. *Science Communication* 29: 285-315.

Groenhart L, March A and Holland M. (2012) Shifting Victoria's emphasis in land-use planning for bushfire: towards a place-based approach. *Australian Journal of Emergency Management, The* 27: 33.

Gutteridge HD. (1980) *The Hawkesbury Valley: summary report,* Sydney: N.S.W. Coastal Rivers Flood Plain Management Studies Steering Committee.

Hackett EJ, Amsterdamska O, Lynch M, et al. (2008) *The Handbook of Science and Technology Studies,* Cambridge, Mass.: MIT Press.

Hajer MA and Wagenaar H. (2003) Deliberative policy analysis: understanding governance in the network society. Cambridge, UK: Cambridge University Press.

Handmer J. (1985) Flood policy reversal in New South Wales, Australia. *Disasters* 9: 279-285.

Handmer J. (2000) Are flood warnings futile? Risk communication in emergencies. *The Australasian Journal of Disaster and Trauma Studies* 2.

Handmer J. (2008) Risk creation, bearing and sharing on Australian floodplains. *International Journal of Water Resources Development* 24: 527-540.

Handmer J and Dovers S. (2007) *The handbook of disaster and emergency policies and institutions,* London: Earthscan.

Hawkesbury-Nepean Floodplain Management Steering Committee. (2006) *Managing flood risk through planning opportunities: guidance on land use planning in flood prone areas,* Parramatta, NSW: NSW Government.

HCC. (2012a) Hawkesbury Floodplain Risk Management Study & Plan: Main Report. Epping, NSW: Hawkesbury City Council Floodplain Risk Management Advisory Committee.

HCC. (2012g) *Hawkesbury Floodplain Risk Management Study & Plan: Planning Issues*: Hawkesbury City Council Floodplain Risk Management Advisory Committee.

Head BW. (2007) Community engagement: participation on whose terms? *Australian Journal of Political Science* 42: 441-454.

Healey P. (2006) *Collaborative planning: shaping places in fragmented societies,* New York: Palgrave Macmillan.

HEPEX. (2014) Good practices in forecast uncertainty assessment and communication. (accessed 7 August).

HNFMAC. (1997) *Achieving a Hawkesbury-Nepean floodplain management strategy: a report,* Windsor, N.S.W.: Hawkesbury-Nepean Flood Management Advisory Committee.

Hughes L and Steffen W. (2013) *Be prepared: climate change and the Australian bushfire threat,* Canberra: Climate Council of Australia.

Hulme M. (2010) Cosmopolitan climates: hybridity, foresight and meaning. *Theory, Culture & Society* 27: 267-276.

Johnson AG. (2000) Fine resolution palaeoecology confirms anthropogenic impact during the late holocene in the Lower Hawkesbury Valley, NSW. *Australian Geographer* 31: 209-235.

Keeley JE and Zedler PH. (2009) Large, high intensity fire events in southern California shrublands: debunking the fine-grained age-patch model. *Ecological Applications* 19: 69-94.

Kellens W, Terpstra T and De Maeyer P. (2013) Perception and communication of flood risks: a systematic review of empirical research. *Risk Analysis* 33: 24-49.

Kelly LT, Bennett AF, Clarke MF, et al. (2014) Optimal fire histories for biodiversity conservation. *Conservation Biology* 29: 473–481.

Kemp DJ and Wright CJ. (2008) The causes and effects of uncertainty in flood estimation: expect the unexpected. *Water Down Under.* Modbury, SA: Engineers Australia, 620-628.

Kerr R. (2013) The Great Ocean Road: Landscape, memory and emotion. *Agora* 48: 38.

Keys C and Cawood M. (2009) Identifying and reducing inadequacies in flood warning processes: an Australian perspective. *Journal of Flood Risk Management* 2: 190–197.

Kidson R and Richards KS. (2005) Flood frequency analysis: assumptions and alternatives. *Progress in Physical Geography* 29: 392-410.

Knorr-Cetina K. (2001) Objectual practice. In: Savigny Ev, Schatzki TR and Knorr-Cetina K (eds) *The Practice Turn in Contemporary Theory.* New York: Routledge.

Lane SN, Landstrom C and Whatmore SJ. (2011) Imagining flood futures: risk assessment and management in practice. *Philosophical Transactions of the Royal Society A: Mathematical, Physical and Engineering Sciences* 369: 1784-1806.

Lash S. (2000) Risk culture. In: Adam B, Beck U and Loon Jv (eds) *The Risk Society and Beyond: critical issues for social theory.* London: SAGE, 47-62.

Latour B. (1987) *Science in action: how to follow scientists and engineers through society,* Cambridge, Mass.: Harvard University Press.

Latour B. (1999) *Pandora's hope: essays on the reality of science studies,* Cambridge, Mass.: Harvard University Press.

Leonard J, Blanchi R, Lipkin F, et al. (2009) *Building and land-use planning research after the 7th February Victorian bushfires: preliminary findings*: CSIRO and Bushfires CRC, Final Report USP2008/018–CAF122-2-12.(Melbourne).

Leonard J and McArthur NA. (1999) A history of research into building performance in Australian bushfires. *Proceedings of the Bushfire 99 Conference*: 219-225.

Lezaun J and Soneryd L. (2007) Consulting citizens: technologies of elicitation and the mobility of publics. *Public Understanding of Science* 16: 279-297.

Lijeblad A, Borrie WT and Watson AE. (2009) Determinants of trust for public lands: fire and fuels management on the bitterroot national forest. *Environmental Management* 43: 571-584.

Lins HF and Cohn TA. (2011) Stationarity: wanted dead or alive? *Journal of the American Water Resources Association* 47: 475-480.

Lucas C. (2010) On developing a historical fire weather data-set for Australia. *Australian Meteorological and Oceanographic Journal* 60: 1-14.

McCarthy GJ and Tolhurst KG. (2001) Effectiveness of broadscale fuel reduction burning in assisting with wildfire control in parks and forests in Victoria. *Fire Management Research Report No. 51.* Vic: Department of Natural Resources and Environment.

McGee TK and Russell S. (2003) 'It's just a natural way of life…': an investigation of wildfire preparedness in rural Australia. *Global Environmental Change Part B: Environmental Hazards* 5: 1-12.

McKay JM. (1984) Community response to hazard information. *Disasters* 8: 118-123.

McLennan B, Weir J, Eburn M, et al. (2014) Negotiating risk and responsibility through law, policy and planning. *Australian Journal of Emergency Management* 29: 22-29.

McRae R, Sharples J, Wilkes S, et al. (2013) An Australian pyro-tornadogenesis event. *Natural Hazards* 65: 1801-1811.

Mell WE, Manzello SL, Maranghides A, et al. (2010) The wildland–urban interface fire problem: current approaches and research needs. *International Journal of Wildland Fire* 19: 238-251.

Merz B, Hall J, Disse M, et al. (2010) Fluvial flood risk management in a changing world. *Natural Hazards and Earth System Sciences* 10: 509-527.

Mills GA. (2005) A re-examination of the synoptic and mesoscale meteorology of Ash Wednesday 1983. *Australian Meteorological Magazine* 54: 35-55.

Milly PCD, Betancourt J, Falkenmark M, et al. (2008) Stationarity is dead: whither water management? *science* 319: 573-574.

Molino S and Huybrechs J. (2004) Do education strategies sink and communities swim? Evaluation of the Woronora preparedness strategy five years on. *Australian Journal of Emergency Management* 19: 33-34.

Molino Stewart. (2012) Hawkesbury-Nepean flood damages assessment: final report. Parramatta, NSW: Infrastructure NSW.

Moore RJ, Bell VA and Jones DA. (2005) Forecasting for flood warning. *Comptes Rendus Geoscience* 337: 203-217.

Opper S, Cinque P and Davies B. (2010) Timeline modelling of flood evacuation operations. *Procedia Engineering* 3: 175–187.

Opper S, Gissing A, Molino S, et al. (2006) To flee or not to flee: an evaluation of warning and evacuation effectiveness. *Floodplain Management Authorities Conference.* Lismore, NSW.

Parker DJ. (1995) Floodplain development policy in England and Wales. *Applied Geography.*

Pastor E, Zárate L, Planas E, et al. (2003) Mathematical models and calculation systems for the study of wildland fire behaviour. *Progress in Energy and Combustion Science* 29: 139-153.

Petts J. (2008) Public engagement to build trust: false hopes? *Journal of Risk Research* 11: 821-835.

Pfister N. (2002) Community response to flood warnings: the case of an evacuation fromGrafton, March 2001. *Australian Journal of Emergency Management* 17: 1324-1540.

Pielke RA. (1999) Nine fallacies of floods. *Climatic Change* 42: 413-438.

Pillac V, Van Henetenryck P and Even C. (2013) A conflict-based path-generation heuristic for evacuation planning. *Technical Report VRL-7393.* Melbourne, Vic: NICTA.

Popper K. (2014) *The logic of scientific discovery,* Hoboken, NY: Taylor and Francis.

Pyne SJ. (1991) *Burning bush: a fire history of Australia,* New York, N.Y.: Holt.

QFCI. (2012) *Queensland Floods Commission of Inquiry: final report,* Brisbane.

Ramsay C and Rudolph L. (2003) *Landscape and building design for bushfire areas,* Collingwood: CSIRO Publishing.

Ramsay GC, McArthur NA and Dowling VP. (1996) Building in a fire-prone environment: research on building survival in two major bushfires. *Proceedings of the Linnean Society of NSW* 116: 133–139.

Regional Development Australia. (2013) Barwon South West Regional Strategic Plan 2012–2015. Regional Development Australia.

Renn O. (2008a) *Risk governance: coping with uncertainty in a complex world,* London: Earthscan.

Renn O. (2008b) White paper on risk governance: towards an integrative approach. Geneva, Switzerland: International Risk Governance Council.

Rhodes A. (2012) Finding a way forward: policy response to the 2009 Victorian bushfires. *Human Dimensions of Wildland Fire Conference.* Seattle, Washington: International Association of Wildland Fire.

Rip A. (2003) Constructing Expertise: in a third wave of Science Studies? *Social Studies of Science*: 419-434.

Saeedian P, Moran B, Tolhurst K, et al. (2010) Prediction of high-risk areas in wildland fires. *2010 5th International Conference on Information & Automation for Sustainability (ICIAFs)*: 399-404.

San-Miguel-Ayanz J, Carlson JD, Alexander ME, et al. (2003) Current methods to assess fire danger potential. In: Chuvieco E (ed) *Wildland fire danger estimation and mapping: the role of remote sensing data.* Singapore: World Scientific Publishing, 21-61.

Schaake JC, Hamill TM, Buizza R, et al. (2007) HEPEX: the hydrological ensemble prediction experiment. *Bulletin of the American Meteorological Society* 88: 1541-1547.

Schauble J. (1994) Fire Chiefs Warn Of Need For Vigilance. *Sunday Age.*

Shekhar S, Yang K, Gunturi VV, et al. (2012) Experiences with evacuation route planning algorithms. *International Journal of Geographical Information Science* 26: 2253-2265.

Smith DI. (1998) *Water in Australia: resources and management,* Melbourne: Oxford University Press.

Smith DI, Handmer J, Williams B, et al. (1996) Non-destructive measures in australian urban floodplain management: barriers and recommendations. *Australian Journal of Emergency Management* 11: 51-56.

Sneeuwjagt R. (2008) *Prescribed burning: how effective is it in the control of large forest fires.*

Standards Australia. (2009a) *AS 3959-2009: Construction of buildings in bushfire-prone areas.*

Standards Australia. (2009b) *AS/NZS ISO 31000:2009: Risk management: principles and guidelines,* Sydney, NSW: Standards Australia.

State of Victoria. (2013) *Victorian Bushfire Risk Profiles: A foundational framework for strategic bushfire risk assessment,* Melbourne, Vic: Department of Environment and Primary Industries.

Stevens MR, Song Y and Berke PR. (2010) New Urbanist developments in flood-prone areas: safe development, or safe development paradox? *Natural Hazards* 53: 605-629.

Sturgis P and Allum N. (2004) Science in society: re-evaluating the deficit model of public attitudes. *Public Understanding of Science* 13: 55-74.

Sundberg M. (2009) The everyday world of simulation modeling: the development of parameterizations in meteorology. *Science, Technology, & Human Values* 34: 162-181.

Terpstra T, Lindell MK and Gutteling JM. (2009) Does communicating (flood) risk affect (flood) risk perceptions? Results of a quasi-experimental study. *Risk Analysis* 29: 1141-1155.

Thagard P and Shelley C. (1997) Abductive reasoning: logic, visual thinking, and coherence. *Logic and Scientific Methods* 259: 413-427.

Tippet G. (1994) Residents Blamed For Burn-off Spreading. *Sunday Age.*

Tolhurst KG, Duff TJ and Chong DM. (2014) Using fire simulations to assess house vulnerability at the urban interface. *Fire Note* 126.

Turnbull J. (2011) More Victorian towns to be evacuated. *The Age.*

Van Den Honert R and McAneney J. (2011) The 2011 Brisbane floods: causes, impacts and implications. *Water* 3: 1149-1173.

van Kerkhoff L and Lebel L. (2006) Linking knowledge and action for sustainable development. *Annual Review of Environment and Resources* 31: 445-477.

VBRC. (2009) *Victorian Bushfires Royal Commission: Interim Report*: Parliament of Victoria.

VBRC. (2010) *Victorian Bushfires Royal Commission: Final Report*: Parliament of Victoria.

Visschers VHM, Meertens RM, Passchier WWF, et al. (2009) Probability information in risk communication: a review of the research literature. *Risk Analysis* 29: 267-287.

Vojinović Z and Abbott MB. (2012) *Flood risk and social justice: From quantitative to qualitative flood risk assessment and mitigation,* London: IWA Publishing.

Warner RF. (2014) Environmental flows in two highly regulated rivers: the Hawkesbury Nepean in Australia and the Durance in France. *Water and Environment Journal* 28: 365-381.

Wenger C, Hussey K and Pittock J. (2013) Living with floods: key lessons from Australia and abroad. Gold Coast, Qld: National Climate Change Adaptation Research Facility.

Westra S, Varley I, Sharma A, et al. (2010) Addressing climatic non-stationarity in the assessment of flood risk. *Australian Journal of Water Resources* 14: 1-16.

White G. (1945) *Human adjustment to floods,* Chicago, IL: University of Chicago.

White ME. (2000) *Running down: water in a changing land,* East Roseville, N.S.W.: Kangaroo Press.

Wilson GA. (2012) *Community resilience and environmental transitions,* Abingdon, Oxon: Routledge.

Winter G, Vogt C and McCaffrey S. (2004) Examining social trust in fuels management strategies. *Journal of Forestry* 102: 8-15.

Wisner B, Blaikie P, Cannon T, et al. (2004) *At risk: natural hazards, people's vulnerability, and disasters,* London: Routledge.

Wynne B. (1992) Public understanding of science research: new horizons or hall of mirrors? *Public Understanding of Science* 1: 37-43.

Wynne B. (2003) Seasick on the third wave? Subverting the hegemony of propositionalism: Response to Collins & Evans (2002). *Social Studies of Science* 33: 401-417.