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Chapter 5

SCIENCE ADVICE FOR CRITICAL DECISION MAKING

Emma E. Doyle and David M. Johnston

INTRODUCTION

During and after a large-scale disaster, numerous agencies and advisory bodies can be involved in the response and recovery, guiding the critical decisions of emergency managers and other protective service agencies. This is particularly true for extreme natural hazard events, which pose a threat to life, infrastructure, and business, including volcanic eruptions, tsunamis, hurricanes, floods, and severe weather events. For uncertain and unfamiliar events such as these, science agencies, individuals, and collaborative science advisory groups are commonly called on to provide technical advice to emergency managers about the impacts and outcomes. This advice plays an important role in the planning, mitigation, and response, and thus it is vital that it is effectively communicated to aid the decision-making processes.

In this chapter, we briefly review the emergency management structure of New Zealand and how science advice is incorporated into that process, as well as decision-making processes and methods for coping with uncertainty. We then discuss NZ's 2008 national Civil Defense Exercise Ruaumoko, which highlights the importance of training to build a common understanding across the emergency management and science advisory sectors. Finally, we discuss methods that help build resilience via the formation of scientific advisory groups, train-

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Charles C. Thomas Publisher, Springfield, Ill. ISBN 978-0-398-08693-0 (Chap 5, pp 69 - 92)

ing programs, and by increasing knowledge of potential future eruptions and impacts to reduce uncertainty and enhance decision making.

NATURAL HAZARDS AND EMERGENCY MANAGEMENT

NZ's Ministry of Civil Defense and Emergency Management (MCDEM) promotes and manages policies and programs for civil defense and emergency management (MCDEM, 2008b) by concentrating on the four Rs: Reduction, Readiness, Response, and Recovery. Civil defense emergency management planning is a requirement of agencies across the nation, as part of the Civil Defense Emergency Management Act of 2002, which has been utilized in recent natural hazard crises such as the 2004 Manawatu Floods and the Magnitude 7.1 Darfield earthquake, Canterbury, on September 4, 2010 (Wood, Robins, & Hare, 2010). One of the criterions for effective disaster management, defined by Quarantelli (1997), is to "have a well-functioning Emergency Operations Centre (EOC)" (p. 51). NZ's national response to any civil defense emergency or crisis event is led through a central Emergency Operation Centre (EOC) via MCDEM's National Crisis Management Center (NCMC), which liaises with and supports the 16 regional council CDEM groups across NZ. Each of these operates a Group EOC (GEOC), which coordinates and supports the local council and territorial authority CDEM EOCs located in cities, towns, and districts (Lee, 2010). These EOCs are central command and control facilities activated during an event to handle the response of multiple agencies (fire, police, protective agencies, Civil Defense, volunteers, etc.) via a number of key coordination points following the structure of the Coordinated Incident Management System (NZ Fire Services Commission, 1998). This CIMS system was initiated in 1996 by the Fire Services of New Zealand and has its foundation in the Incident Command System developed in Southern California in 1970 and the Australian Inter-service Incident Management System (AIIMS) developed in the 1980s. CIMS is built around four major components (NZ Fire Services Commission, 1998, p 14):

- CONTROL: management of the incident
- PLANNING/INTELLIGENCE: collection and analysis of incident information and planning of response activities

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- OPERATIONS: direction of an agency's resources in combating the incident
- LOGISTICS: provision of facilities, services, and materials required to combat the incident.

External advice from scientific individuals, expert panels, agencies, and Science Advisory Groups (SAGs) or Committees (SACs) is commonly integrated into the Planning and Intelligence function described above, as well as being communicated directly to the Control decision maker.

Science advisory bodies have been called on during many volcanic crises worldwide, and best practice has identified that these advisory groups should be composed of many experts not only to pool expertise but also to combat issues that may arise due to conflict between scientists (Barclay et al., 2008). In NZ, many Science Advisory Groups have been formed over the last five years (see Smith, 2009), including the Central Plateau Volcanic Advisory Group (CPVAG) to advise officials about the Central Volcanoes in the North Island, the Auckland Volcanic Scientific Advisory Group (AVSAG) to advise officials about the volcanic field residing under Auckland City (discussed later), and the Tsunami Expert Panel, which forms in response to a local, regional, or distant, source earthquake and tsunami warning.

The advice provided by these technical and scientific experts is vital for the effective planning, intelligence gathering, and decision making of the emergency personnel and government officials in the protection of life, infrastructure, and welfare. However, to effectively provide advice to emergency managers, it is important to understand decision-making strategies and how this complex information is incorporated.

DECISION MAKING AND UNCERTAINTY

In Quarantelli's (1997) evaluation of the management of community disasters, the sixth criterion for good disaster management is to "permit the proper exercise of decision-making" (p. 46). From management decision-making research, a strategy for decision-making usually incorporates the stages (Flin, 1996, pp. 141–142):

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1. "Identify the problem."
2. "Generate a set of options for solving the problem/choice alternatives."
3. "Evaluate these options concurrently using one of a number of strategies, such as weighting and comparing the relevant features of the options."
4. "Choose and implement the preferred option."

This can be considered to be an "analytic" decision-making process (Saaty, 2008). However, many decisions are made based on intuition, in a faster, almost automatic way (Flin, 1996). These decision-making processes have been studied extensively across a number of subdisciplines, including Classical Decision-Making (CDM), Behavioral Decision Theory (BDT), Judgment and Decision-Making (JDM), Organizational Decision-Making (ODM), and Naturalistic Decision-Making (NDM) (as reviewed in Lipshitz, Klein, Orasanu, & Salas, 2001). Decisions made in naturalistic settings have been characterized as involving (Orasanu & Connolly, 1993, as cited in Zsambok & Klein, 1997, p. 5):

1. "Ill-structured problems (not artificial, well-structured problems)."
2. "Uncertain, dynamic environments (not static, simulated situations)."
3. "Shifting, ill-defined, or competing goals (not clear and stable goals)."
4. "Action/feedback loops (not one-shot decisions)."
5. "Time stress (as opposed to ample time for tasks)."
6. "High stakes (not situations devoid of true consequences for the decision maker)."
7. "Multiple players (as opposed to individual decision making)."
8. "Organizational goals and norms (as opposed to decision making in a vacuum)."

Decision-making processes under these naturalistic conditions (NDM) can be defined as the way people use their experience to make decisions in real-world settings (Crichton & Flin, 2002; Klein, 2008; Zsambok & Klein, 1997). For critical incident management, research

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has identified four key NDM processes (Crego & Spinks, 1997; Crichton & Flin, 2002; Pascual & Henderson, 1997): (1) recognition-primed and intuition led action; (2) a course of action based on written or memorized procedures; (3) analytical comparison of different options for courses of action; and (4) creative designing of a novel course of action, ordered by increasing resource commitment.

The range of naturalistic decision-making models in the literature all consider that decision makers are utilizing and synthesizing prior experience to categorize situations and make decisions, rather than generating and comparing available decision options. The recognition-primed decision-making model of Klein (1998) considers that fireground commanders evaluate options without pattern matching or comparing to other options, instead using mental simulations to imagine the outcome of a decision and repeating until the first workable, rather than the best possible, outcome is found. The RPD model can thus be considered to involve a blend of both intuition and analysis (Klein, 2008). This model has evolved into three basic versions (see reviews in Flin, 1996; Klein, 1998; Lipshitz et al., 2001): (1) a simple match based decision based on the recognition of both a situation and the appropriate course of action; (2) a decision that requires diagnosis and assessment of the situation before a course of action can be implemented, often involving mentally simulating the events leading up to what is observed; and (3) a decision that requires an evaluation of the appropriate course of action often by mental simulation of the outcomes of those actions. Although these three levels may appear analytic, to the decision maker, they feel like a faster intuitive response (Flin, 1996).

A subset of NDM research concerns the study of emergency decision makers, where the particular pressures inherent in NDM are amplified–namely, the uncertainty, the high risk, the time pressure, and the constantly changing conditions. Martin, Flin, and Skriver (1997) identified that the dynamic decision-making processes occurring in these crises can vary considerably depending on the "task condition." In addition, different phases within any one incident may cause different decision-making processes to be adopted, ranging from the intuitive RPD approach through to the fully analytical approach, and the decision strategy may continue to switch as the situation continues to change. Martin et al. (1997) thus outline a framework for deci-

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Cannon-Bowers et al. **Task characteristic**	***Intuition inducing*** *(e.g. RPD)*		***Analysis inducing*** *(e.g. option comparison)*
uncertain, dynamic	uncertain, fast	←→	clear, slow moving
decision structure	ill defined	←→	well defined
multiple goals	shifting/competing	←→	clear/stable
time constraints	high (brief)	←→	(low) long
quantity of	overload	←→	adequate
decision complexity	low	←→	high
multiple feedback loops	effect not yet determined		
risk/stakes	high	←→	variable
multiple players	effect not yet determined		

Figure 5.1. Inducement of intuition and analysis in emergency situations as a function of task characteristics (conditions), after Martin et al. (1997, p. 283).

sion making in emergency situations that illustrates the inducement of an intuition or analysis approach-based on the emergency task "characteristic" outlined in Figure 5.1, suggesting that the emergency decision maker adapts their decision strategy depending on where the current situation characteristics sits on the various scales.

An emergency decision thus involves two distinct steps: (1) a definition of the problem and task characteristic via situation assessment (Endsley, 1997; Martin et al., 1997), and (2) a choice of what to do

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based on the four decision-making strategies (Crichton & Flin, 2002): (1) recognition-primed, (2) written or memorized procedures, (3) analytical, and (4) creative. Situation assessment (SA) addresses the question "What's the problem?" (Crichton & Flin, 2002, p. 209) and requires the correct evaluation of the event characteristics (Cannon-Bowers & Bell, 1997). It is considered by Endsley (1997, pp. 270–271) to have three levels:

- Level 1 SA: Perception of the elements in the environment in time and space.
- Level 2 SA: Comprehension of the current situation (in relation to the goals).
- Level 3 SA: Projection of the future status.

A decision maker may make the correct decision based on his or her perception of the situation, but if his or her situation assessment is incorrect, this may negatively influence his or her decision (Crichton & Flin, 2002). In making a decision, two factors are thus vital for the effective choice of action; the situation assessment and the *ongoing* situational awareness of the individual or team decision makers throughout the crisis (Sarna, 2002), as the different stages of the incident may require a different decision-making strategy and action.

Information Provision and Coping with Uncertainty

Information provision and science advice is a key component of the initial situation assessment and ongoing situation awareness during natural hazard crises. During the recent national CDEM Exercise Tangaroa conducted in NZ to test the response to a national tsunami warning, a threat level advisory map for the coast of New Zealand was provided by the science provider GNS Science and enabled rapid initial situation assessment by emergency managers (personal observations, October 20, 2010). For Exercise Ruaumoko, which tested the all-of-nation response to a volcanic eruption in the Auckland Volcanic Field, NZ (discussed further later; MCDEM, 2008a), ongoing situation assessment and awareness was improved by the information provided by the Auckland Volcanic Scientific Advisory group over a number of days. This ongoing advice allowed the emergency managers to adapt their decisions and responses accordingly as the situation evolved and

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the (theoretical) magma rose to the surface. In both of these exercises, the science advice was a key component of the emergency managers' situation awareness, influencing their action choices and the strategies used to make those decisions. However, as described by Harrald and Jefferson (2007, p. 3) "to provide the meaning component of situational awareness, the recipient of the information must be able to accurately perceive the situation described." Thus, it is not just the provision of the advice that is important, but also that the advice is correctly interpreted and meets the needs of the decision makers.

During a natural hazard crisis, this scientific information and advice may be sought by the emergency managers to address the uncertainty of the unfolding situation. Kuhlthau (1993; as cited in Sonnenwald & Pierce, 2000 p. 463) identified that "uncertainty is a cognitive state which causes anxiety and stress." Thus, any reduction of this uncertainty for emergency managers, via the provision of effective science advice, has the potential to reduce their anxiety and stress. After an extensive literature review of the terms *uncertainty, risk,* and *ambiguity* in decision making, Lipshitz and Strauss (1997, p. 150) define uncertainty in the context of action as "a sense of doubt that blocks or delays action" and identify that it can be "classified according to their issue (i.e., what the decision maker is uncertain about) and source (i.e., what causes this uncertainty)" (p. 151). From an analysis of decision makers' written accounts of dealing with uncertainty, they further identify that sources of uncertainty for action include (1) "incomplete information", (2) "inadequate understanding," and (3) "undifferentiated alternatives" (p. 151). Uncertainty in the context of the issue can relate to the outcome, the situation itself, and the alternative actions available. This uncertainty can occur on the level of the data, the level of the knowledge, and the level of understanding (Klein, 1998). Science advice may thus be subjected to uncertainties in the data due to (Patt & Dessai, 2005, pp. 426–427; van Asselt, 2000, p. 85): (1) the natural stochastic uncertainty, representing the random variability or chaotic nature of the system; and (2) the epistemic uncertainty, due to a lack of knowledge of the physical process.

Many formal and behavioral decision theories identify the R.Q.P. heuristic for coping with uncertainty in decision-making (see review in Lipshitz & Strauss, 1997), which represents the *reduction* of uncertainty by information searching, the *quantifying* of the magnitude of uncertain-

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ty that cannot be reduced, and the *plugging* of the result into a formal decision making scheme that incorporates uncertainty. However, this is limited by the need for multiple experts, the time to evaluate the uncertainties, and the issue that some uncertainties cannot be quantified into a numerical value (Lipshitz & Strauss, 1997). To investigate an alternative, Lipshitz and Strauss (1997) analyzed the written accounts of decisions made with uncertainty and found that the decision makers either:

> - **Reduced the Uncertainty:** collecting additional information, deferring decisions until additional information became available, soliciting advice and following SOPs, and filling in their gaps in factual knowledge through assumption based reasoning
> - **Acknowledged Uncertainty:** taking the uncertainty into account in the selection of an action by incorporating slack into the decisions/actions, improving readiness by generating new alternatives to pre-empt a specific potentially negative outcome, and weighing up the pros and cons of an approach.
> - **Suppressed Uncertainty:** ignoring the uncertainty, relying on intuition, and rationalising and removing the doubts that block action. (p. 153-154, see also Lipshitz et al., 2001)

From this, they proposed their RAWFS (Reduce, Assumption-based reasoning, Weighing pros and cons, Forestalling, Suppressing) heuristic, stating that "how decision makers cope, or ought to cope, with uncertainty is principally determined by the nature or quality of the uncertainty" (Lipshitz & Strauss, 1997, p. 160). One of the key elements of the reduction phase of the RAWFS heuristic is the soliciting of advice and opinions of experts, demonstrating how science advice is not just about providing information for situation assessment but also about providing advice to help decision makers understand, acknowledge, reduce, or suppress the uncertainties in the source and the complex physical systems.

Team Decision Making: Shared Mental Models

Many decisions made in emergency management involve large and complex teams. In the NZ context, there are multiple team levels, from the team that operates within the Emergency Operation Center handling the response to the extended team that includes liaison offi-

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cers from partner agencies. For the distributed decision making inherent in a multiorganizational emergency response such as this, people differ in their profession, expertise, functions, roles, and geographical location (Rogalski & Samurcay, 1993, as cited in Paton & Jackson, 2002), and thus the effective decision making of this distributed group is a function of the completeness of their shared mental model of the response environment in time and space, how their expertise contributes to different parts of the same plan, and their understanding of each others' knowledge, skills, roles, anticipated behavior or needs (Flin, 1996; Paton & Jackson, 2002).

If emergency managers turn to science advisors to solicit further information to guide their situation assessment and cope with uncertainty, then the communication between the science advisors and the emergency management team starts to play a vital role in the effectiveness of the entire decision process. However, it is not just a case of providing the emergency managers with all available science information but about understanding their needs to meet their information requirements. Simply providing as much advice as possible may actually hinder the decision process due to cognitive overload and an overuse of these available resources (Omodei, McLennan, Elliott, Wearing, & Clancy, 2005; Quarantelli, 1997). An on-site science advisor or an off-site expert panel can be considered to be part of the extended and distributed team handling the emergency management response. For a team to make effective decisions, many NDM concepts play a vital role, including team situation awareness, shared problem assessment, team mind, and shared mental models (see review in Lipshitz et al., 2001). To build up an understanding of the decision makers' needs and information requirements, the scientific advisors thus need to develop a shared mental model with the emergency managers. These shared mental models, or common knowledge bases, enable the team members to develop accurate expectations of the performance of themselves and their team mates and allow an effective coordination among team members without the need for extensive overt strategizing (Salas, Stout, & Cannon-Bowers, 1994).

A shared mental model is closely related to team situational awareness (SA), where team members have a specific set of SA elements about which they are concerned, determined by their individual responsibility (see review in Endsley, 1994). The overlap between

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each team member's SA then constitutes most of the interteam coordination (Endsley, 1994). If a team is composed of individuals with different levels of expertise, then the recognition of a situation or pattern will inherently come from an individual, while the interpretation of these recognized patterns is dependent on the conversational process of others in the team (Salas, Rosen, & DiazGranados, 2009). Orasnau (1994; as cited in Lipshitz et al., 2001, p. 341) identified that team SA can be achieved when team members "collect and exchange information earlier and plan farther in advance." Feedback between team members is then vital for the accuracy and refinement of these team member mental models (Salas et al., 1994). In the context of science advice for decision making, this supports the early integration of science information and involvement and a continued dialogue between the decision makers and advisors. By building a shared mental model, a team will have a shared understanding of the task, who is responsible for what, and what each other's information requirements are (Lipshitz et al., 2001).

Effective teams under high time pressure or increased workloads commonly adopt a communication style dominated by implicit supply of information rather than explicit requests, where members provide not only good information but unprompted information (see reviews in Kowalski-Trakofler, Vaught, & Scharf , 2003, p. 282; Paton & Jackson, 2002, p. 117). This implicit information gathering requires a good understanding from all team members of the information required by the main decision makers at critical periods. In addition, as discussed by Paton and Flin (1999, p. 261), if the format of this information does not require extensive additional information processing, while also matching the needs of the decision makers in terms of both content and format, then the stress for the decision maker can be reduced. Stress in a naturalistic setting may not cause poor decisions to be made based on the available information, but rather it can cause problems for information gathering, processing, and working memory (Crichton & Flin, 2002; Klein, 1998). Stress is thus likely to have a greater effect on decision-making styles that require generation and contrasting available options such as an analytical or a creative approach, rather than a recognition-primed or rule-based approach, due to the greater cognitive effort required for those strategies (Crichton & Flin, 2002; Klein, 1998).

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Thus, as discussed by Paton (2003, p. 204), it is particularly important in these situations for the emergency communication from science advisors to involve (1) an anticipation and definition of information needs, (2) organized networks with information providers and recipients, and (3) an established capability to "provide, access, collate, interpret and disseminate information compatible with decision needs and systems." The science communication should tend more toward an implicit supply, through an understanding of the needs and demands on the decision maker, via a good team mental model that incorporates both the decision-making team and the science advisor. More multiorganizational and multidisciplinary planning activities with all team members and advisors will help in the development of similar mental models of the task (see review in Paton & Jackson, 2002), and collaborative exercises and simulations can further facilitate this understanding (Paton & Jackson, 2002). In addition, through the analysis of past events, lessons for successful communication, advice provisions, and distributed decision making can be learnt.

IMPROVING NZ'S RESPONSE CAPABILITY FROM 1995 TO 2007

The response to the eruptions at Ruapehu Volcano, NZ, from 1995 -1996 involved more than 40 agencies and organizations, with GNS Science acting as the major science provider (Johnston, Houghton, Neall, Ronan, & Paton, 2000). Analysis of the organizational response to these eruptions by Paton, Johnston, and Houghton (1998) identified that although 63 percent of the responding agencies reported getting information from GNS Science, limited formalized interorganization networking had been established prior to the event. This resulted in an ad hoc interaction with other agencies. As a result, science advisory processes in NZ have changed considerably since those eruptions. The use of a Science Advisory Group (SAG) representing the volcanological and social science expertise in an integrated emergency response was first fully tested during the recent National CDEM Exercise Ruaumoko. This occurred from November 2007 to March 2008 to test the local, regional, and national arrangements for dealing with the impact of a large natural hazard event on a major population center, and focused on the lead up to a volcanic eruption in the Auckland metropolitan area (MCDEM, 2008a).

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Auckland sits on a "monogenetic" basalt volcanic field where eruptions occur over many different distributed volcanic vents. Over the last 250,000 years, 49 volcanic centers have been identified over the 360 km2 field, with the largest and youngest eruption approximately 600 years ago forming Rangitoto Island (see review in Lindsay et al., 2009). In the lead up to an eruption, felt earthquakes may cause a considerable amount of societal anxiety, as has occurred during seismic periods at other volcanic centres (e.g. Johnston et al., 2002). An eruption is likely to involve damaging earthquakes, explosions, and radially propagating base surges affecting buildings within 2 km of the vent and ash falling up to 10 km away (Lindsay et al., 2009; MCDEM, 2008a). As eruptions can occur anywhere within the Auckland Volcanic Field (AVF) and the location may not be known until magma is very close to the surface, decisions in exercises and any future real event will be typified by a high degree of uncertainty due to the eruption timing, location, severity, hazards, impacts, and consequences.

For Exercise Ruaumoko, the volcanic unrest scenario was developed in secret by a GNS Science volcano seismologist who did not participate in the exercise, and the exercise ended when the eruption started (see reviews in Lindsay et al., 2009; MCDEM, 2008a). Prior to the start of the exercise, the Auckland CDEM Group established and formalized the Auckland Volcanic Scientific Advisory Group (AVSAG), which contained a wide range of scientific expertise from GNS Science, NZ Universities (Auckland, Waikato, and Massey), and the Kestrel Group, as well as members of local and national CDEM (see reviews in MCDEM, 2008a; McDowell, 2008; Smith, 2009). AVSAG was conducted through a tripartite subgroup system (Monitoring, Volcanology, and Social), all of which reported upward to a smaller core SAG. During the days and weeks prior to the theoretical eruption, these subgroups liaised through teleconferences resulting in a coordinated advice provision to the NCMC and the Auckland Group EOC (AGEOC). This allowed for a direct question-and-answer dialogue to occur between the emergency managers and a wide range of science advisors. This dialogue supplemented the routine Scientific Alert Bulletins being produced on at least a daily basis by the GeoNet monitoring arm of GNS Science, and incorporated changes to the Volcanic Alert Levels for the AVF. Consistency between these two advice pathways was ensured by the fact that personnel writing the

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GeoNet bulletins also were in AVSAG. In addition, as the scenario evolved, two on-site science advisors were dispatched from GNS Science to act as liaison officers within the NCMC and AGEOC to provide further advice and act as an information conduit among AVSAG, GeoNet, and the CDEM sector.

Postexercise reviews by MCDEM (2008a) and McDowell (2008) identified that this structure for science advice resulted in the science advice being very well delivered, clear, timely, and valuable. However, McDowell identified that during the most active periods of a volcanic eruption response, having separate subgroups composed of the predominately university-based "volcanology" group and the "monitoring" group of GNS-based scientists was unrealistic, and that the priority is not to have these separate groups but rather "the rapid assessment and decision making in relation to technical data" (McDowell 2008, p. 22). The presence of a science advisor in the Auckland CDEM Group EOC provided a "critical link for instant assessment and decision-making in relation to changing scientific information" (MCDEM, 2008a, p. 26), and other CDEM groups commented in their reviews that "the performance of the science providers has engendered a huge degree of confidence about their capacity and capability" (MCDEM, 2008a, p. 26).

MCDEM's (2008a) review further highlighted that the AVSAG approach's main strength lies in its inclusiveness of a wide range of scientific experts and competency, stating, however, that this inclusivity and "due process" slowed down the advice provision during the most active period. In addition, they identified the potential for a disconnect to occur between the local and national advice provision to the AGEOC and the NCMC, respectively. As highlighted by Cronin (2008), during the exercise, the two separate on-site advisors in these EOCs resulted in a divergence of the science advice as the event escalated, such that differences emerged in the evacuation planning at the local and national levels.

A potential disconnect may occur not only between the science advice to the local and national CDEM groups but also between the local and national science research *response, capability, and processes.* To address some of these limitations and coordinate the scientific advice beyond what is likely to be a limited knowledge pool and resources in a locally impacted area, an advisory group model is being coordinat-

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ed by MCDEM (Smith, 2009), which will evolve to address the need for mobilization of NZ-wide science capability while remaining responsive to local CDEM needs. This model is described by Smith as having: "at its core national hazard monitoring capability and processes (e.g. GeoNet), with involvement of additional capability from universities and other science organisations based on thresholds of response. The intent is that GeoNet (both the technology and the science expertise of GNS Science) be the hub of any science response for earthquake, volcano, tsunami or landslide events" (p. 77).

This model still supports the existence of regions having existing scientific or planning advisory groups with a volcanic and/or earthquake focus, an example of which is the Central Plateau Advisory Group discussed earlier.

Beyond the successful coordination of the scientific response and the provision of science advice both nationally and locally, MCDEM (2008a) identified that communication between the advisors and the CDEM sector was negatively affected by the use of geological terminology, a degree of assumed knowledge, as well as challenges in interpreting scientific data. The scientific uncertainty of an event such as this, particularly with respect to the definition of the evacuation zones, the eruption timing, and impacts, creates a challenging environment for response planning and emergency management decisions. MCDEM (2008a) thus recommend that the frustration experienced by the CDEM sector due to this uncertainty would be reduced by an improved understanding of the AVF hazard, precursory signals, and a further translation of this primary science information to meet the needs of all organizations and limit misinterpretation.

ADVICE TAKING AND COMMUNICATING UNCERTAINTY

Existing research and case study reviews indicate that through collaborative preplanning, exercises, and training, which incorporates science advisory groups and bodies, the response capability and resilience of the entire integrated multiorganizational emergency response can be significantly enhanced. In developing these advice processes, relationships, and procedures, it is also important to consider the research fields concerned with advice taking, and the communication of uncertainty and probabilities.

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Advice taking is considered by Harvey and Fischer (1997, p. 117) to be composed of three main components: "accepting help, improving judgement, and sharing responsibility," with the latter particularly apparent for experienced judges "when the risk associated with error was high." Whether this still applies in an emergency management decision-making context has not yet been investigated; however, the judgment literature has explored many aspects of advice taking and aggregation of opinions that are relevant in the CDEM context. This includes the degree to which people will take and utilize available advice, the role of multiple sources of advice, what happens when experts disagree, or there is conflicting advice, advice confidence, decision accuracy, and differences between advisors and decision makers (Bonaccio & Dalal, 2006; Budescu, Rantilla, Hsiu-Ting, & Tzur, 2003; Harvey & Fischer, 1997; Yaniv & Milyavsky, 2007).

Exercise Ruaumoko highlighted the benefits of science advice being provided by "one trusted source" during a crisis (MCDEM, 2008a), and forming this consensus requires a rationalization and integration of a wide range of potentially conflicting scientific opinions, model outputs, and outcome scenarios. Budescu et al. (2003) investigated the decisions made when a decision maker obtained probabilistic forecasts regarding the occurrence of a target event from a number of distinct, asymmetric advisors, where the asymmetry is due to the amount of information and the quality or accuracy of the advisors' previous forecasts. They found that the decision makers' final estimate can be described "as a weighted average of advisor forecasts, where the weights are sensitive to both [those] sources of asymmetry" (Budescu et al., 2003, p. 178). They identified that if the advisors' opinions were in perfect symmetry, then this was associated with the highest level of information fragmentation and the greatest degree of effort on the part of the decision maker who has to pay attention to all the opinions, reconciling the inconsistencies and disagreements. However, for a more asymmetric distribution of information, they postulate that it is easier for the decision maker to anchor his or her judgment to a smaller subset of the judges, and effort is reduced without sacrificing too much accuracy.

The importance of communicating a consensus opinion is further supported by the investigations of Yaniv and Milyavsky (2007), who found that when there was a wide range of advisor opinions, the deci-

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sion makers revised their opinion in an egocentric manner, giving more weight to confirming opinions closer to their own than the disconfirming advice far from their own. However, this was sensitive to how much the decision maker already knew to begin with, with high-knowledge participants placing greater weight on their own opinion and on advice close to that, while the low-knowledge participants placed greater weight on the advice further from their own as well as utilizing all the advice more.

Due to the highly complex nature of volcanic eruptions, and the still many unknowns in volcano science, precise prediction is not achievable in many situations, and thus forecasts usually involve knowledge of both the dynamical phenomena and the uncertainties involved (Sparks, 2003). Thus, the use of numeric probability statements by scientists is becoming increasingly popular in volcanic crises due to a desire to make objective decisions via quantitative volcanic risk metrics and, ideally, predefined thresholds of probability based on a cost-benefit analysis (see review in Lindsay et al., 2009). In recent volcanic crises, consensus probability distributions have been produced via weighted and anonymous expert elicitation processes, which have then been fed into forecasting systems, such as Bayesian Event Trees (Aspinall & Cooke, 1998; Marzocchi & Woo, 2007). Adopting an approach such as this is highly advantageous for the decision-making process of the scientists, because it clarifies decision thresholds as well as optimizing the decision-making time (Lindsay et al., 2009). In addition, it offers the hindsight ability to clearly explain how a decision was made.

However, Solana, Kilburn, and Rolandi (2008) have also found that authorities at Vesuvius volcano, South Italy, prefer to receive deterministic statements instead of probability statements. Meanwhile, Haynes, Barclay, and Pidgeon (2008, p. 263) found that scientists at Montserrat Volcano Observatory, West Indies, considered using probabilities "to complicate communications as the likelihoods and associated uncertainties were neither well-explained nor understood." However, implicit in any evacuation decision by the authorities is the concern of making an "economically disastrous, unnecessary evacuation" (Tazieff, 1983; as cited in Woo, 2008, p. 88). Thus, authorities and other decision makers *do* commonly want to know the likelihood of potential hazard scenarios, likely casualty numbers, the effectiveness

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of an evacuation, and the uncertainties in the risk assessment (Woo, 2008) via a probabilistic decision theory methodology such as a cost-benefit analysis.

The weighted expert elicitation processes inherent in these volcanological decision aids help scientists to form a consensus and thereby reduce the effort required by emergency managers to "aggregate these opinions and generate a single response" when making a decision (Budescu et al., 2003, p. 178). However, once a collaborative, probabilistic communication is made, the probabilistic statements can commonly be misinterpreted. Research into the public understanding of probabilistic phrases has identified that the framing, directionality, and probabilistic format of these statements can bias people's understanding, affecting their action choices (e.g., Budescu, Broomell, & Por, 2009; Teigen & Brun, 1999). Thus, care must be taken with the presentation and wording of the communicated information, because it can affect the accuracy of the situation assessment made by individuals and teams and thus hinder the first crucial step in a decision-making process.

CONCLUDING REMARKS: BUILDING RESILIENCE THROUGH TRAINING

Relationship building before an event is vital for an effective response, as highlighted during the response to Hurricane Katrina, which Garnett and Kouzmin (2007, pp. 180–181) suggest was hindered by "differences in organizational culture and lack of trust that surfaced before Katrina had even formed." The effective communication across many agencies in a crisis is heavily dependent on this trust, as summarized by Comfort and Cahill (1998; as cited in Garnett & Kouzmin, 2007, p. 181), who state, "In environments of high uncertainty, this quality of interpersonal trust is essential for collective action. Building that trust in a multiorganizational operating environment is a complex process, perhaps the most difficult task in creating an emergency management system."

Group learning in a crisis context is thought to occur along three dimensions: personal, interpersonal, and institutional (Borodzicz & van Haperen, 2002). A number of research studies have investigated effective ways to train for naturalistic decision making (e.g., Cannon-

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Bowers & Bell, 1997) and to enhance decision skills (e.g., Pliske, McCloskey, & Klein, 2001). Methods to train effective teams (e.g., Salas, Cannon-Bowers, & Johnston, 1997) have also been developed as part of research programs, such as TADMUS (Tactical Decision-Making Under Stress) (see review in Flin, 1996). Research has also identified methods to develop effective critical incident and team-based simulations (e.g. Crego & Spinks, 1997), where "in addition to knowledge and skill development, training should address how the disaster context influences performance and well-being" (Paton, Smith, & Violanti, 2000, p. 176). These simulations should also aim to reproduce reality as closely as possible, so decision makers and experts can experience the needs and realities of the advisory process in turbulent conditions (Borodzicz & van Haperen, 2002; Rosenthal & 't Hart, 1989). However, this alleged realism can also be a danger as personnel may believe at the end of an exercise that they know what will happen in a real crisis (Borodzicz & van Haperen, 2002). Evaluation of exercises and events must be carefully conducted to minimize the risk of creating an optimistic bias that overestimates future response preparedness and capability, particularly if a real event has not constituted a major test of the response system (Paton, Johnston, & Houghton, 1998).

In conclusion, the successful integration of science advice into the emergency decision-making process depends on a number of factors: (1) a well-functioning Emergency Operations Center with liaison officers from representative agencies and advisory bodies; (2) an environment and collaborative process that permits the proper exercise of decision making; (3) the experience and ability, or use of external experts, to develop an initial situation assessment and an ongoing situational awareness that permits an effective choice of action and decision style; (4) methods to reduce, acknowledge, or suppress uncertainty via the use of external experts and knowledge building about future potential crises; and (5) the development of relationships and a mutual understanding of each other's knowledge, skills, roles, and needs by both the emergency decision makers and their external advisors, promoting a shift from explicit requests to the implicit supply of science information. Only through an examination of historic case studies and participation in interorganizational simulations and training can these key response factors be developed to enhance future resilience and capability.

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