The Provision and Utility of Science and Uncertainty to Decision-Makers: Earth Science Case Studies

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1 Abstract

This paper investigates how scientific information and expertise was provided to decision-makers for consideration in situations involving risk and uncertainty. Seven case studies from the earth sciences were used as a medium for this exposition: *(1)* the 2010-2011 Canterbury earthquake sequence in New Zealand, *(2)* agricultural farming system development in North West Queensland, *(3)* operational flood models, *(4)* natural disaster risk assessment for Tasmania, *(5)* deep sea mining in New Zealand, *(6)* 3-D modelling of geological resource deposits, and *(7)* land-based pollutant loads to Australia's Great Barrier Reef. Case studies are lead-authored by a diverse range of scientists, based either in universities, industry, or government science agencies, with diverse roles, experiences, and perspectives on the events discussed. The context and mechanisms by which scientific information was obtained, presented to decision-makers, and utilized in decision-making is presented. Sources of scientific uncertainties and how they were communicated to and considered in decision-making processes are discussed. Decisions enacted in each case study are considered in terms of whether they were scientifically informed, aligned with prevailing scientific evidence, considered scientific uncertainty, were informed by models, and were (or were not) precautionary in nature. The roles of other relevant inputs (e.g., political, socioeconomic considerations) in decision-making are also described. Here we demonstrate that scientific evidence may enter decision-making processes through diverse pathways, ranging from direct solicitations by decision-makers to independent requests from stake-holders following media coverage of relevant research. If immediately relevant scientific data cannot be provided with sufficient expediency to meet the demands of decision-makers, decision-makers may (i) seek expert scientific advice and judgement (to assist with decision-making under conditions of high epistemic uncertainty), (ii) delay decision-making (until sufficient evidence is obtained), and / or (iii) provide opportunities for adjustment of decisions as additional information becomes available. If the likelihood of occurrence of potentially adverse future risks is perceived by decision-makers to exceed acceptable thresholds and/or be highly uncertain, precautionary decisions with adaptive capacity may be favoured, even if some scientific evidence suggests lower levels of risk. The efficacy with which relevant scientific data, models, and uncertainties contribute to decision-making may relate to factors including the expediency with which this information can be obtained, the perceived strength and relevance of the information presented, the extent to which relevant experts have participated and collaborated in scientific communications to decision-makers and stake-holders, and the perceived risks to decision-makers of favouring earth science information above other, potentially conflicting, scientific and non-scientific inputs. This paper provides detailed Australian and New Zealand case studies showcasing how science actions and provision pathways contribute to decision-making processes. We outline key learnings from these case studies and encourage more empirical evidence through documented examples to help guide decision-making practices in the future.

Keywords: earth science, environmental science, decision-making, policy, natural disasters, risk, uncertainty

2 Introduction

Earth science has much to offer decision-makers in situations involving risk and uncertainty. Risks may result from the exposure of vulnerable elements to earth science hazards and/or other forms of risk inherent to decision-making with uncertain outcomes. Risks discussed in this paper include human fatality, physical, social or psychological injury, damage to property and infrastructure, economic loss (or non-maximization of potential profit), environmentally adverse effects such as pollution and habitat loss, and risks to decision-makers (e.g., political and/or job security risks, including those that might amplify in complex ways throughout the decision-making process). These risks are further described and analysed using decision trees in a companion paper (Quigley et al., Minerva, in review).

All science, and thus all scientifically-informed decision-making, is inherently uncertain (Fischoff and Davis, 2014). Uncertainty may arise from incomplete scientific knowledge (i.e., epistemic uncertainty), intrinsic variability in the system(s) or processes under consideration (i.e., aleatoric uncertainty), vagueness, ambiguity and under-specificity in communications between science providers, decision-makers, and affected parties (i.e., linguistic uncertainties), and ambiguity or controversy about how decision-makers quantify, compare, and value social goals, objectives, and trade-offs in decision-making processes (i.e., value uncertainties) (Regan et al., 2002; Ascough II et al., 2008; Morgan and Henrion, 1990; Finkel, 1990). Decision-makers tasked with developing and implementing policy, issuing evacuations in emergency situations, deciding whether to approve mining consents, or selecting amongst distinct approaches for resource extraction, may all draw on earth science inputs to assist in characterising and reducing various forms of uncertainty. Decision-makers may be individuals or collectives that are operating in their own self-interest or on behalf of others. Decision-makers may ask the earth science community to provide forecasts of the occurrence, magnitude, and likely impacts of natural and human-induced environmental phenomena, ranging from earthquakes, to floods, to land-use practises, to climate change (e.g., Sarewitz and Pielke Jr., 1999; Pielke Jr. and Conant, 2003). Some risks may be reduced through mitigation against and/or avoidance of potential hazards.

Governments around the world spend billions of dollars each year on obtaining relevant earth science that might assist in decision-making. However, many issues are complex with highly uncertain outcomes, and may be strongly influenced by inputs that reside outside of the immediate earth science domain, such as cost-benefit analyses, political considerations, and other socioeconomic factors. Enacted decisions may not align with prevailing science and because these issues are often informed by scientific, socioeconomic, and/or political models of the future, the potential outcomes of enacted decisions are not known with certainty.

This contribution is presented in response to the *Recommendations from the 2016 Theo Murphy High Flyers Think Tank: An interdisciplinary approach to living in a risky world* (2017). The event brought together a group of Australian- and New Zealand-based, early- and mid-career researchers form a broad range of disciplines across science, social science and the humanities (including the authors of this paper), who were tasked with developing recommendations for scientists, the public and decision-makers regarding how to understand, communicate, and assess risk in conditions of uncertainty, ignorance and partial knowledge (Colyvan et al. 2017). In many earth science disciplines, the scientific contributions to decision-makers aim to describe and communicate uncertainty by quantifying the probability of risks occurring if a decision is taken related to a specific action that would create exposure to a hazard. Among the diverse expertise represented in the Think Tank, we found there was an overarching lack of awareness and an absence of critical assessment of the utility of the provision of science in decision-making under conditions of high uncertainty and risk. This lack of appraisal by scientists on the utility of their evidence-based contributions creates an obstacle that prohibits science providers from understanding of how their science was used (or not) by decision-makers.

Our findings led to the creation of two key recommendations (Colyvan et al. 2017): 1) Develop a better understanding of how uncertainty affects decision-making, and 2) Facilitate improved communication of risk and uncertainty between scientists, decision-makers and the general public. To address the first recommendation, we suggested that more empirical evidence is needed on how scientific uncertainties contribute to the decision-making process. To achieve this, we have called for contributions from scientists and decision-makers that describe how scientific uncertainty of all forms is considered within the decision-making scenarios, interdisciplinary research priority should be placed on understanding how decision-makers, media, and public respond to uncertainty in the dissemination of scientific research, including the trustworthiness of science, scientists and communicators, and lastly, that decision-makers are provided with training to recognise the conventions and inherent frailties of their scientific advisors. The second recommendation may be achieved by creating a set of guidelines for reporting risk and uncertainty, methods for communicating the need or value in supplying more information to decision-makers, standardised pathways for direct and open communication between science experts and decision-makers, and communication training for scientists to communicate scientific uncertainties to the media and public. This paper represents a partial response to Recommendation 1, drawing together contributions from members of the workshop that describe their experiences on how scientific uncertainty has contributed to the decision-making process. To generalise these experiences, contributions from a broader international audience are required.

Due to the high level of complexity and variance in the general field of earth science and decision-making, we adopt a case-study approach aimed at establishing a body of empirical evidence on how scientific uncertainties contribute to the decision-making process (Recommendation 1 above). This descriptive research approach provides a means to document successful and unsuccessful strategies in science provision to, and utility by, decision-makers. Our work builds upon lessons learned from prior analyses of case studies (e.g., Gluckman, 2004; Pielke Jr. and Conant, 2003) including (1) science provides only one of many relevant components in the process of decision-making, (2) predictions drawn from science inputs should not be conflated with policy, and (3) many scientific products are difficult to evaluate and easy to misuse; scientific inputs may have varying levels of accuracy, sophistication, and experience that are not always well described and considered in decision-making (Pielke 2003). The importance of using statistical approaches and quantitative risk evaluation approaches in decision-making has been extensively described (e.g., Clark, 2005; Linkov et al. 2014).

Here, we provide case-studies that highlight how variable and complex decision-making processes often are, including how science and associated uncertainties were provided to and used by decision-makers, and how enacted decisions aligned or did not align with the science and uncertainties provided. Each study presents the context and mechanisms by which scientific information was obtained, presented to decision-makers, and utilized in decision-making. Sources of scientific uncertainties, and how they were communicated to and considered in decision-making processes are also discussed. Decisions enacted in each case study are considered in terms of whether they (i) were scientifically informed, (ii) aligned with prevailing scientific evidence, (iii) considered scientific uncertainty, (iv) were informed by models, and (v) were (or were not) precautionary in nature. The importance of other relevant inputs (e.g., political, socioeconomic considerations) in decision-making is also briefly described. This paper provides explicit accounts of science utility in diverse forms of decision-making that may be beneficial towards improving communal knowledge of both scientists and decision-makers operating in this highly complex environment.

3 Case study 1: Geoscience communications to decision makers during the 2010-2011 Canterbury earthquake sequence in New Zealand (Author: MQ)

3.1 Overview

The 2010 – 2011 Canterbury earthquake sequence (CES) occurred proximal to and beneath New Zealand's South Island city of Christchurch (2013 census pop. 366,000) (Fig.1). The CES is New Zealand's most fatal (185 fatalities) and most expensive natural disaster to date. Rebuild costs (2012 estimate) are approximately NZ$20 Billion (US$15 billion) excluding disruption costs (10% of GDP) and insured losses are estimated at around NZ$30 billion (US$25 billion) (Parker and Steenkamp 2012).

The CES began with the magnitude (Mw) 7.1 Darfield earthquake in September 2010 and was followed by strong damaging aftershocks in February 2011 (including the fatal Mw 6.2 Christchurch earthquake), June 2011, and December 2011, and more than 400 $M_L \geq 4.0$ earthquakes between September 2010 and September 2012 (Quigley et al. 2016). A national state of emergency was declared following both the 2010 Darfield and 2011 February Christchurch earthquakes. The protracted nature of the sequence including repeated episodes of land and infrastructural damage (Berryman 2012; Hughes et al. 2015), and the fatalities, injuries, and severe social and professional disruptions caused adverse economic and mental health impacts throughout the affected region (Fergusson et al. 2014; Spittlehouse et al. 2014). Communication of a large and diverse amount of geoscientific (geological, seismological, geospatial), engineering, economic, and sociological information to a variety of decision-makers was undertaken during the response and recovery phases of the CES (Becker et al. 2015; Berryman 2012; Wein et al. 2016). In this contribution we address only the geoscientific communications to decision-makers that are known to MQ and / or accessible in the public domain. A complete description of all science communications for this prolonged, multi-phased, and complex disaster is well beyond the scope of this contribution.

Geoscience communications were conducted by individuals and collectives from government-funded Crown Research Institutes ("CRIs", e.g., GNS Science, National Institute of Water and Atmospheric Research), universities, and industry. Communication methods included publications of scientific research (Cubrinovski et al. 2010; Gerstenberger et al. 2011; Quigley et al. 2010; Villamor et al. 2012), commentary on science websites[1] (Quigley and Forte 2017), solicited interviews across all forms of media, communications on social media (Bruns and Burgess 2012; Gledhill et al. 2010), public presentations to large audiences of diverse decision makers[2], publicly-released government white papers[3], and private and public communications with specific decision-makers (e.g., informal communications, email exchanges, and presentations to decision-making entities such as the New Zealand Ministry of Civil Defence & Emergency Management (MCDEM); Urban Search and Rescue; Canterbury Earthquake Recovery Authority (CERA); Christchurch City Council (CCC); Royal Commission panels, independent hearings panels, insurance providers, banks).

[1] www.geonet.org ; www.drquigs.com

[2] http://www.stuff.co.nz/the-press/news/christchurch-earthquake-2011/5248119/Free-public-quake-lectures ; http://www.stuff.co.nz/the-press/news/christchurch-earthquake-2011/canterbury-earthquake-2010/4255970/Thirst-for-quake-info-at-lecture

[3] https://royalsociety.org.nz/assets/documents/Information-paperThe-Canterbury-Earthquakes.pdf

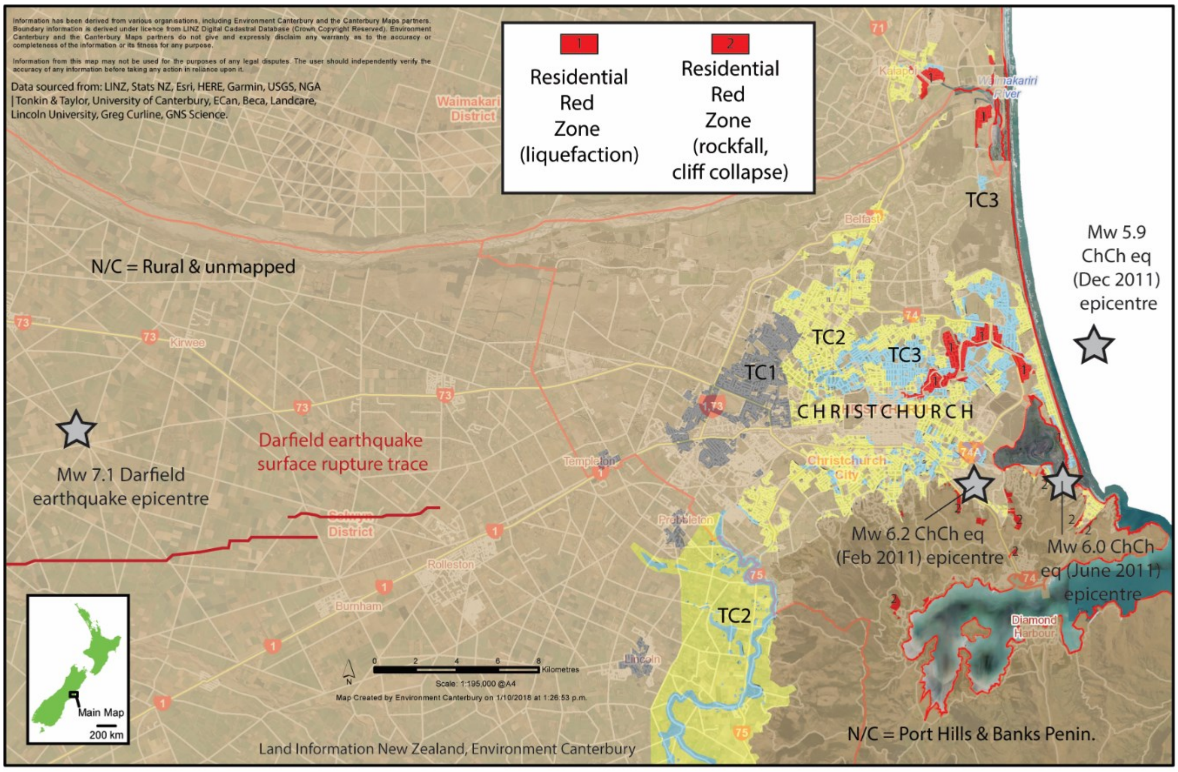

Figure 1: Location of the major earthquakes comprising the 2010-2011 Canterbury earthquake sequence (stars) and location of residential red-zones in Christchurch (red). Small numbers in red zones denote residential red zones for liquefaction (1) and rockfall, debris avalanches, and cliff collapses (2). Definitions of technical categories (TC1-3) are provided at https://www.ccc.govt.nz/consents-and-licences/land-and-zoning/technical-categories-map/. Map produced using Canterbury Maps (https://canterburymaps.govt.nz/).

Immediately following the Darfield earthquake, scientific information was communicated to some types of decision-makers directly impacted by fault rupture (farmers with damaged paddocks, wells, infrastructure, houses), via a science presentation to Federated Farmers of New Zealand by a CRI scientist (P. Villamor, GNS Science) and a university scientist (MQ). Print versions of preliminary fault rupture maps and website links to digital maps and other information were disseminated to interested parties during the meeting and via email afterwards. Personal science communications from GNS Science and university scientists to land and property owners often took place at the site of impact during ongoing science investigations. Other means of communication included print and digital media interviews and on-line publication of peer reviewed research reports and articles. Topics of geoscience communications included (but were not limited to) individual earthquake seismological characteristics (e.g., epicentral location, magnitude, shaking intensity), immediate earthquake environmental impacts (e.g., fault ruptures, liquefaction, subsidence, rockfall, land deformation), immediate earthquake infrastructure impacts (e.g., building damage, subsidence, and relationships to geology), forecasts of future earthquakes (e.g., locations, magnitudes, rates, daily to decadal probabilities of occurrence), forecasts of future earthquake impacts and risks to environments and infrastructure, earthquake triggering mechanisms (natural and anthropogenic), earthquake prediction, and ongoing and planned future studies of earthquakes.

Some decision-makers sought information directly from science providers and some obtained information from other sectors, including the media or other decision-making entities (Becker et al. 2015). Aspects such as whether the decision required urgent action (e.g., immediate evacuations from buildings and other areas of high life safety risk), or could be delayed until further scientific and other inputs became available (e.g., revisions to land-use plans and building codes), may have influenced where the decision-maker sourced the information (Becker et al. 2015). Decisions that needed to be made and that could be informed by geoscience information included whether to continue to reside in and/or utilize damaged buildings, whether to rebuild new infrastructure within hazard zones or relocate new infrastructure outside of these zones (Van Dissen et al. 2015), and what remediation techniques might be most effective in reducing hazards and risks. The large volume and diversity of CES decisions and decision-makers resulted in large variance in which science providers were consulted, the methods by which the science was solicited, provided to, and considered against other inputs by decision makers, and the ultimate decisions chosen. An inclusive summary of all CES-related decisions is outside the scope of this article. Rather, we present a diverse suite of decision-making processes that include documented communications between scientists and decision makers and / or contain undocumented aspects that are known to MQ.

3.2 Governmental policy decisions on land use in areas subjected to liquefaction hazards

The NZ Government responded to the Darfield earthquake by appointing a Minister for Canterbury Earthquake Recovery (Hon. G. Brownlee) on 7 September 2010. The Canterbury Earthquake Response and Recovery Act 2010 was introduced on 14 September 2010 and came into force on 15 September 2010. Following the February 2011 earthquake, Canterbury Earthquake Recovery Authority (CERA) was established as a new Government Department (29 March 2011). The 2010 Act was replaced by the Canterbury Earthquake Recovery Act 2011 on 18 April 2011. Extensive details on the 2011 Earthquake Recovery Act[4] and related cases in the NZ Supreme court[5] and High Court[6] are available on-line.

From April 2011, officials from the national insurer against natural hazards (The NZ Earthquake Commission: EQC), CERA and the NZ Treasury began assessing the impact of land and property damage in the greater Christchurch area and identifying the worst affected areas. Tonkin & Taylor (an international firm of environmental and engineering consultants) was commissioned by the government to assess the land damage caused by the 2010 and 2011 earthquakes. In identifying the land damage, Tonkin & Taylor (T&T) collected their own extensive observations and geotechnical data and obtained further data from sources

[4] http://legislation.govt.nz/act/public/2011/0012/latest/DLM3653522.html
[5] https://www.courtsofnz.govt.nz/cases/quake-outcasts-and-fowler-v-minister-for-canterbury-earthquake-recovery/@@images/fileDecision
[6] http://www.stuff.co.nz/national/83446819/High-Court-denies-uninsured-Quake-Outcasts-appeal

such as Land Information New Zealand, land data from local councils, engineering teams, private surveyors, CRI and university scientists, and other engineering resources. CRI and university scientists, and industry groups participated in data collection, commonly in a co-ordinated collaborative manner. Many of these science research efforts were organized through the New Zealand Natural Hazards Research Platform (NHRP), established in 2009 to foster networking across disciplines, organizations, and sectors in order to pursue the policy goal of "*a New Zealand society that is more resilient to natural hazards*"[7] (NHRP 2009, p. 5). A review of the performance of the NHRP throughout the CES is provided by (Beaven et al. 2016). Property data was also collected from EQC and private insurers. Open access to some scientific information was provided to the general public throughout the CES, in reports from CCC, GNS Science, Tonkin & Taylor, NHRP, EQC and other entities, in reports across all media streams, and from research publications made available through science websites.

The most extensive forms of land and property damage that required a series of decision-making processes at levels ranging from governmental policy to personal decisions by individuals concerned the effects of liquefaction and mass movements on the city of Christchurch. Multiple episodes of liquefaction (i.e., the process where transient shear stresses exerted on soils during strong ground shaking in earthquakes increases pore fluid pressures, reduces soil strength and stiffness, and causes ground deformations and surface ejections of liquefied material and ground water) resulted in extensive and repeated land and infrastructure damage in Christchurch during the CES (Cubrinovski et al. 2010; Hughes et al. 2015; Quigley et al. 2013). Liquefaction affected ~51,000 residential properties and severely damaged ~15,000 residential houses in the Christchurch region. Mass movements included collapse of cliffs (and associated cliff-top recession and cliff-bottom burial by debris) and the detachment of subsequent downslope transport of individual rocks (rockfall and boulder roll) into urban areas (Massey et al. 2014). Mass movements caused five fatalities and damaged approximately 200 houses.

After a major liquefaction-inducing earthquake on 13 June 2011, the New Zealand Cabinet authorised a committee of senior Ministers to make decisions on land damage and remediation issues. On 22 June 2011, the decision-making criteria were recorded in a confidential memorandum for Cabinet ("the Brownlee paper")[8,9] signed by the Hon. G. Brownlee (signature dated 24 June 2011). The decisions were announced to the public by the then Prime Minister Hon. John Key and G. Brownlee on 23 June 2011. The Cabinet committee categorised greater Christchurch into four zones (red, white, green, orange) according to the extent of land damage and the timeliness and economics of remediation[8]. In

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[7]https://www.naturalhazards.org.nz/content/download/9099/49062/file/Hazards_Platform_Partnership_Agreement.pdf

[8] https://ceraarchive.dpmc.govt.nz/sites/default/files/Documents/memorandum-for-cabinet-land-damage-june-2011_0.pdf

detail, for liquefaction-affected properties, the decision framework essentially reduced to an equation with economic inputs (Fig. 2):

The EQC contribution to the land remediation + *The betterment cost (i.e. perimeter treatment and/or additional raising of the land)* + *Infrastructure removal and replacement costs*	
If the cost of the above exceeds the value of the relevant land the area is reclassified as a Red Zone	*If the cost of the above is less than the value of the relevant land then the area is reclassified as a Green Zone, but may require some land repair work*

Figure 2: The equation that underpinned residential red zone decision-making in Christchurch for liquefaction-affected properties. If the estimated cost of reinstating the land to its pre-earthquake condition, up to a maximum value capped by the estimated value of the land ("EQC contribution"), plus the estimated cost of raising the land to an elevation such as to consent with the CCC building code ("betterment cost - raising of land"), plus the estimated cost of mitigating against lateral-spreading effects that could occur in future earthquakes ("betterment cost - perimeter treatment"), plus the estimated cost of removing and replacing damaged infrastructure (e.g., roads, sewerage, potable water, power infrastructure), exceeded the value of the land (the 2007 capital value of entire property minus improvements), then the area was red-zoned. 'Red-zone boundary maps' were constructed by engineering experts but were effectively contour maps based on economic inputs.

The Cabinet committee decided that there would be an offer to purchase insured residential properties in the red zones, which were characterised by the Committee as areas where "*rebuilding may not occur in the short-to-medium term*". Owners of insured properties in the red zones were given two options: (a) purchase by the Crown of their entire property at 100 per cent of the most recent (2007) rating valuation for the properties (land and improvements), with all insurance claims against EQC and private insurers to be assigned to the Crown; or (b) purchase by the Crown of the land only, at 100 per cent of the 2007 rating valuation for the land only component of their properties, with the owner assigning all insurance claims against the EQC for the land to the Crown, but retaining the benefit of all insurance claims relating to improvements. Property owners were initially given a 9-month period to decide whether to accept the offer. Orange zones represented properties were more research was required to enable decision-making. Some orange zones were eventually zoned red. Some white zones (areas in the rockfall hazard areas that required more information before decision-making was enacted) were also ultimately zoned red. A total of 8,060 residential houses in greater Christchurch were eventually zoned red. Of these, 7,346 were in areas affected by liquefaction and 714 were in areas affected by mass movements. In carrying out the zoning decisions and offers, the Crown did not engage in public or cross-parliamentary consultations. The final date for accepting the Crown offer was 10 December 2015. At that time owners of 7,720 properties in the residential red zone had accepted the offer. The final settlement date for these properties was 26 February 2016. Some affected property owners that have not accepted the offer remain engaged in legal action against the Crown[9].

Scientific inputs are stated to have influenced policy development and decision-making in the Brownlee paper[8]. These include data on the extent and severity of the land damage caused by the earthquakes, particularly where it affected properties over a wide area, and the risk of additional damage to the land and buildings from further aftershocks. For example, the paper[8] states "*The ground accelerations recorded from this earthquake [Feb 2011 Christchurch earthquake] are among some of the highest recorded anywhere in the world. Damage from the recent 13 June 2011 5.6 and 6.3 magnitude earthquakes has added to the damage. The seismic factor has recently been increased for Christchurch from 0.22 to 0.3, and after the large aftershocks on Monday 13 June, work is being undertaken to consider if it should be further revised upwards. In any case, there is a reasonable chance of continued large aftershocks and this must be factored into recovery. After the aftershocks on Monday 13 June GNS has indicated the chance of a quake of magnitude between 6 and 6.9 in the region over the coming year being around 34 per cent. If no significant aftershocks or triggering events occur in the next month that likelihood will fall to around 17%.*"[8] A detailed report authored by GNS Science and university scientists on probabilistic assessments of future liquefaction potential for Christchurch was commissioned by Tonkin and Taylor (Gerstenberger et al. 2011). The report concluded that "*liquefaction probabilities for the next 50 years are high for the most severely affected suburbs of the city, and are well in excess of the probabilities associated with the ground-shaking design levels defined in the New Zealand structural design standard NZS1170…*"(Gerstenberger et al. 2011). The Brownlee paper[8] stated that, "*The strength-depth profiles under some parts of Christchurch indicate typically up to 10 metres of 'liquefiable' material. Although some ground settlement may occur, the large reservoir of liquefiable material and these examples suggest that similar characteristics of ground shaking are likely to result in similar amounts of liquefaction in the future*"[8]. The Brownlee paper referenced the Canterbury earthquakes white paper[3] as the source of this information, although the statement was probably more directly informed by geotechnical data and reports from Tonkin and Taylor and the results of the Gerstenberger et al. (2011) paper.

Ultimately, for areas of Christchurch affected by liquefaction, the exact role of each science provision to land zone policy is challenging to determine. It is likely that the observations of recurrent liquefaction and land damage, and the assessments suggesting a relatively high probability of future occurrence, may have influenced governmental decision-makers to recognize the need to develop a land policy in the first place. However, the red-zone equation as stated in the Brownlee paper does not explicitly account for these science and engineering inputs. Instead, the most prominently featured motivation for policy decisions appears to have

[9] https://www.courtsofnz.govt.nz/cases/quake-outcasts-and-fowler-v-minister-for-canterbury-earthquake-recovery/@@images/fileDecision

been "*the urgent need to provide a reasonable degree of certainty to residents in these areas in order to support the recovery process. Speeding up the process of decision-making is crucial for recovery and in order to give confidence to residents, businesses, insurers and investors. This is particularly the case in the worst affected suburbs, where the most severe damage has repeatedly occurred*."[8]

In this context, the sources of epistemic scientific uncertainty (e.g., will future liquefaction-triggering earthquakes occur in the short-to-medium term and what will their characteristics be?), engineering uncertainty (e.g., what exact designs for residential properties and lateral-spreading perimeters would be most effective in terms of mitigating against future liquefaction-triggering earthquakes?), and economic uncertainty (e.g., what are the precise fiscal values of the three components of the economic equation in Figure 2 and what fiscal uncertainty resides within each?) are likely to have been overridden by the decision-makers' (G. Brownlee, CERA, and other key central Government agents) desire to make expedient decisions that could be (at least coarsely) justified by economic, scientific, and engineering criteria, even if parameters sourced from the latter two criteria were not directly used to define boundaries on the red-zone maps (Fig.1). While the incrementation of some decision-making (e.g., 'orange zones') frustrated both decision-makers and affected land owners, this enabled more science and engineering information to be obtained in marginal cases where reduction of epistemic uncertainty was viewed to be valuable. An Independent Hearings process also enabled affected parties to challenge decisions if evidence of sufficient strength to was able to be acquired and presented.

3.3 Risk-based land decisions and independent hearings pertaining to residential properties subjected to rockfall hazards

Immediately following the 22 February 2011 Canterbury earthquakes, people were evacuated from over 200 homes affected by rockfall and cliff collapse, as preliminary observations of precariously fractured rockfall source areas, cliff-top cracks and relatively high estimated probabilities of future strong earthquakes were considered to pose imminent life-safety risks (see Massey et al. (2014) and references therein). In response to the recognition of the threat of future rockfall events, and CCC and NZ Government's priority to give the affected people a timely decision over the future of their properties, the CCC (with additional funding from the NZHRP) commissioned investigations to quantify the rockfalls triggered by the earthquake sequence and to determine the risk posed by future rockfall (e.g., see Massey et al. (2014) and references therein). Massey et al. (2014) adapted the Australian Geomechanics Society framework for landslide risk management (Australian Geomechanics Society 2007) to estimate the annual individual fatality risk (AIFR) for about 1,450 properties in the Port Hills:

$$AIFR = P(H) \times P(S{:}H) \times P(T{:}S) \times V(D{:}T) \qquad (1)$$

where P(H) is the annual probability of a rockfall-initiating event; P(S:H) is the probability of a person, if present, being in the path of one or more boulders at a given location; P(T:S) is the probability that a person is present at that location when the event occurs; V(D:T) is the probability of a person being killed if present and in the path of one or more boulders (i.e., vulnerability). Earth science inputs to P(H) and P (S:H) included seismicity forecasts (incorporating both national seismic hazard models and aftershock-based, regional forecast models to estimate the temporal probability of future strong earthquakes) (Gerstenberger et al. 2011; Stirling et al. 2012), coupled seismic and geologic observations (to quantify the relationship between ground motion parameters such as PGA and peak ground velocities with the occurrence or non-occurrence of rockfall), geospatial analyses using LiDAR data (to map boulder locations, rockfall source-slope angles and heights, and boulder travel distances), and field studies (to measure boulder dimensions). Non-seismic rockfall triggers were also considered but found to be a minimal short-term contributor to rockfall production when compared to seismic triggering (Massey et al. 2014). Rockfall risk maps (i.e. AIFR contour maps for the residential areas of the Port Hills) were generated for different future time intervals, starting from the elevated first 1-year rate of seismicity (starting 1 January 2012) (Massey et al. 2014).

Given a suite of epistemic uncertainties in model parameters, including probability-density distributions of the earthquake ground motions that caused past rockfalls and could cause future rockfalls (due to lack of instrumentation on source slopes for past events and lack of knowledge of the future state of the rock mass in future events), Massey et al. (2014) estimated an order of magnitude (higher or lower) uncertainty range in AIFR estimates presented on the risk maps. A discussion of uncertainties is presented in Massey et al. (2014). Addressing these uncertainties was not a priority in reducing the long-term safety risk in the immediate aftermath of the earthquakes.

Within this context, in 2011, Mr. Brownlee stated that, *"…the decisions that need to be made here are very, very dependent upon research about the condition of the land in Christchurch…"*[10]. In 2012, he told the Christchurch Press that *"…I'd love to be able to fix all of that [earthquake land issues] for people immediately, [but] we've got to get the science and engineering right on how to progress…"*[11]. In 2013, he told the Christchurch Press that *"We know from the extensive ground-truthing and area-wide modelling that the risk of rock roll in this part of the Port Hills is high; hence the need to zone the land red…"*[12].

[10] https://www.courtsofnz.govt.nz/cases/quake-outcasts-and-fowler-v-minister-for-canterbury-earthquake-recovery/@@images/fileDecision
[11] http://www.stuff.co.nz/the-press/news/christchurch-earthquake-2011/7656654/Brownlee-fed-up-with-moaning-residents
[12] http://www.stuff.co.nz/the-press/news/christchurch-earthquake-2011/8220906/I-told-you-so-says-Brownlee-on-rockfall

The changes to land use designations described above required development of a new Christchurch City Replacement District Plan, which provided a process for the review of the previous district plans and preparation of a comprehensive replacement district plan for the Christchurch district. The proposed framework for the plan included a Statement of Expectations outlined by both the Minister for Canterbury Earthquake Recovery and Minister for the Environment. One stated expectation was that the plan would "*avoid or mitigate natural hazards*"[13]. The proposed plan was prepared by CCC in consultation with CRI, university, and industry scientists and engineers[14] and notified in three stages in 2014 and 2015. It was formally acknowledged by the CCC and the Crown that the proposed plan "*is based on complex technical modelling and outputs*" that rely on "*geotechnical and scientific background research*" and that the "*most effective approach*" for "*refining the issues*" that could arise from submitters wishing to challenge decisions within the plan was "*for relevant experts to enter into technical caucusing on the modelling approach and methodology*" prior to "*evidence exchange*" in hearings[15]. Caucusing involved CRI, university and industry scientists and engineers acting on behalf of the CCC and The Crown, and university and industry scientists that were invited to participate in caucusing due to their likely future involvement in hearings as expert witnesses acting on behalf of submitters.

Concurrent with the CCC commissioned research, independent researchers began to study the prehistoric record of rockfalls at a specific site in the Port Hills using a variety of mapping and dating methods (Borella et al. 2016a; Borella et al. 2016b; Mackey and Quigley 2014). This research was neither funded by, nor undertaken for the purposes of, contributing to land policy decision making. Two key conclusions arose from this work; (1) the penultimate (pre-CES) major rockfall event(s) at this site occurred sometime in the middle Holocene (ca. 3-8 ka), with a possible predecessor event at ca. 12-14 ka, interpreted to suggest recurrence intervals of several 1000s of years for rockfall-triggering seismic ground motions (Borella et al. 2016a; Mackey and Quigley 2014), and (2) that finite rockfall travel distances in the pre-CES Holocene events were reduced due to the presence of native vegetation on the currently deforested slopes, which reduced boulder travel velocities through collisions and impedance (Borella et al. 2016b). The results of this research were not available at the time of land-zoning decision-making, but became available via media coverage shortly thereafter, and were considered of relevance by some affected property owners that were challenging zoning decisions through the Independent Hearings Committee process.

MQ was invited to participate in the Independent Hearings Committee process by a submitter wanting to challenge aspects of the CCC rockfall risk decision on her property after the

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[13] http://proposeddistrictplan1.ccc.govt.nz/
[14] http://proposeddistrictplan1.ccc.govt.nz/
[15] http://www.chchplan.ihp.govt.nz/wp-content/uploads/2015/03/310_495-CCC-and-Crown-Joint-Memorandum-re-Preparations-for-Hearing-of-Natural-Hazards-8-12-14.pdf

submitter read a newspaper article published in the Christchurch Press[16] that discussed the authors recently published research on prehistoric rockfall frequencies at a nearby location (Mackey and Quigley 2014). The submitter told MQ that "*Your new research MUST be incorporated in their general model and CERA's submission seems to indicate that they would support it…*". Mackey and Quigley (2014) was ultimately submitted into evidence by the submitter and subsequently considered in the hearings[17]. Another submission group also consulted MQ for advice relating to their claims in rockfall affected coastal holiday properties upon learning of his research through the media.

In caucusing, the experts discussed the research methods and scientific evidence relevant to the proposed plan and prepared a joint statement. The joint statement acknowledged that "*the risk-based modelling approach undertaken by GNS Science acknowledges key uncertainties and is an appropriate method for assessing risk…*" but that "*the area-wide mapping and modelling is not always sufficient to determine risk on a site-specific basis*" and so "*the opportunity to undertake individual site assessment must be provided for in the plan…*"[18]. A separate signed document by three experts (including MQ) stated that "*future earthquakes have the potential to cause additional rockfall and cliff collapse*" and that "*published, peer-reviewed geologic data do not exclude the possibility of future rockfall triggering events from the ongoing sequence or other seismic events. Available site-specific geologic data suggest that clusters of severe rockfall events may be separated by hiatuses spanning 1000s of years but further analysis from additional sites is required to test this hypothesis. The seismicity model was developed by an international expert panel using international best practice and has undergone peer review. Given the recent and modelled earthquake clustering activity and the large uncertainties on predicted ground-motion for an individual earthquake, we agree that the level of conservatism is appropriate*"[19]. Full transcripts from the panel hearings and decisions are available[20].

In the context of rockfall risk, the results of Mackey and Quigley (2014) and other relevant scientific evidence (Borella et al. 2016b) and bearings on the CCC district plan were discussed. MQ delivered a statement, was cross-examined by council acting on behalf of CCC and the Crown, re-examined by the submitter, and asked questions by the decision-making panel. In response to questions from the cross-examiner, MQ stated that "…*there are limitations to any dataset and uncertainties and I think that we have completely adopted that*

[16] http://www.stuff.co.nz/national/10574099/Alpine-Fault-unlikely-to-trigger-Port-Hills-rockfall
[17] http://www.chchplan.ihp.govt.nz/wp-content/uploads/2015/03/IHP_Natural-Hazards-PART_180315.pdf
[18] http://www.chchplan.ihp.govt.nz/wp-content/uploads/2015/03/Technical-expert-witness-caucusing-report-Natural-Hazards-full-signed.pdf)
[19] http://www.chchplan.ihp.govt.nz/wp-content/uploads/2015/03/Technical-expert-witness-caucusing-report-Natural-Hazards-full-signed.pdf
[20] http://www.chchplan.ihp.govt.nz/hearings/

statistical model, and I think that that statistical model needs to be also informed by geology, whilst acknowledging the uncertainties therein….", and "*…site specific investigations need to be better informed by geology…*". He stated that "*…we cannot dismiss the possibility outright of future strong earthquakes, and even though we find very little evidence for that from a geologic perspective we cannot completely discount that possibility. [However] if someone uses statistical seismology to say that there is a six percent chance of a magnitude six earthquake somewhere over a broad region in the next year, an important question to ask is if that event actually happens are they correct or are they incorrect in that statement. What I am finding is there is a tension between source-based geological approaches, where I am forced into somewhat of a binary position, where I have to either say there are active faults in the area close enough to cause rock fall, or there are not, therefore I can be right or I can be wrong. Whereas from a strictly probabilistic approach using overall low bulk probabilities, like say for instance six percent, I think that you, at some level you are correct irrespective of the outcome, although I know more sophisticated analysis can be done to validate those claims and test those claims….*" MQ concluded that "*...my professional opinion is that we are very unlikely to experience any future earthquakes in the short to medium and possibly even to the long term that generate peak ground velocities and peak ground accelerations analogous to those experienced in the February and June earthquakes [that caused severe rockfall] in the Port Hills Region*" but that "*I cannot completely dismiss that possibility, and it would be unprofessional of me to say we are out of the woods and there is no possibility of anything similar to those going forward....*".

Under direct questioning from the panel, MQ was asked, "*given that notwithstanding that this District Plan has a 10-year life, some of the decisions made during that 10 year period will endure for a long period of time, for example, if you build structures in certain locations, they are not going to be taken away after 10 years. Given that, do you think it is wise from a scientific point of view to exercise a degree of caution when delineating where hazards may or may not occur, and how we manage them?*" to which he replied, "*I absolutely do agree with that statement, yes*". MQ was asked, "*So a regime that allowed lines to be adjusted as better information became available, provided that we set the lines conservatively in the first place, that would be a good outcome from your point of view?*" to which he replied, "*Yes…from a strictly geological point of view conservativism is a great thing...*". MQ stated to the panel that "*there is very little in science in general that can be said with 100 percent certainty*" to which a panel member replied, "*I understand that and that is really the point. We are dealing with probabilities on one hand, whereas on the other hand, we and the Council have the responsibility of trying to protect peoples' lives. So doing nothing until further work is carried out would not seem to be an option then…*". Regarding the scientific evidence presented that regenerating the region with native forest could reduce the travel distances of future rockfalls, the panel asked MQ, "*if you wanted to protect from that hazard now with vegetation, it is going to be quite a few years before the trees are substantial enough to be of any value?*" to which he replied, "*That is completely correct. There will be a* *lag time for the trees to grow to the point where they are actually able to effectively mitigate that hazard, yes.*" He was asked, "*…have you given any thought of the level of regulation that would be needed to prevent the cutting down of trees, to prevent fires in trees, all of those sorts of things?*" to which he replied, "*that is a… valid question ..I have no easy answer to that…*".

Ultimately, the decision-making panel decided that they were "*quite satisfied that the evidence of Dr Quigley is not a basis for taking a less cautious approach*". They stated that "*Dr Quigley's evidence was of assistance to the Panel*" and they "*urge[d] that Dr Quigley and his team's work continue to further the current level of understanding*" but noted that "*Dr Quigley accepted a cautionary approach was appropriate*". In some cases, Panel-directed mediations between the CCC and particular submitters (often with input from experts) resulted in agreement that properties could be released in part, or completely, from particular natural hazard areas; in other cases, the panel did not support the removal or relaxation of hazard area controls from properties as sought by submitters. In the case of the submitter that called MQ as an expert witness, the panel stated that "*…Dr Quigley was supportive of a regime that would allow hazard lines to be adjusted when better information becomes available…*" and after further site-specific investigations and consultation with the CCC expert witness, that "*…relief should be granted to the extent that the hazard lines are moved as specified…*".

In this sense, relevant but initially unsolicited research ultimately entered into formal considerations on land use planning, through submission of research papers as evidence to the hearings panel, via an indirect, stake-holder-driven pathway. On balance, the strength of this evidence was ultimately not considered sufficiently relevant to change the magnitude or position of AIFR contours, nor to invalidate the CCCs precautionary approach towards minimizing AIFR to Christchurch residents.

3.4 Individual decisions pertaining to earthquake risks

When considering whether to accept the red zone offer and which option to accept, affected individuals consulted a diverse range of sources (e.g., lawyers, banks, the media, CERA, surveyors, insurance companies, etc.)[21]. Detailed accounts including surveys of people who chose to accept red zone offers[22] and decline red zone offers[23] have been published by CERA and the New Zealand Human Rights Commission, respectively. For those who decided to accept the Crown's red zone offer to relocate, property affordability (47%) and relocating into an area that had little physical damage (34%) and was perceived to be safe from natural

[21] http://www.eqrecoverylearning.org/assets/downloads/2016-02-01-rec3020-cera-residential-red-zone-survey-report.pdf
[22] http://www.eqrecoverylearning.org/assets/downloads/2016-02-01-rec3020-cera-residential-red-zone-survey-report.pdf
[23] https://www.hrc.co.nz/red-zones-report/

disasters (29%) were the most highly cited reasons for relocating. In contrast, when asked why the owners initially chose their (now red-zoned) properties, convenience to the natural environment (56%) was the most highly cited reason, while only 6% cited safety from natural disasters as a priority[24]. Given that the perception of safety from natural disasters relies in part on publicly-communicated scientific information relating to natural disasters, we suggest that geoscience played a role in informing decision-making in this context.

Some individuals and collectives chose to dispute the liquefaction and mass movement hazard maps, and/or corresponding risk classifications estimated for their properties, and/or policy decisions related to the above. The reasons for disputing these classifications included challengers' perceptions that characterisation of hazards at their site was inadequate or inaccurate (e.g., inadequate or inaccurate documentation of CES rockfalls, floods, land movement, and/or liquefaction effects), modelling of exposure to future hazards was inadequate or inaccurate (e.g., under- or over-estimated exposure to falling rocks and/or cliff collapse), modelling of future life safety and property risks was inadequate or inaccurate (e.g., inaccurate inputs into calculations of building occupancy rates), and/or consideration of other inputs was inadequate (e.g., social considerations, community health considerations, insurance considerations, human rights considerations). It is beyond the scope of this article to address each of these in detail. However, the most cited reasons for remaining in red zone properties (financial, attachment to property, attachment to neighbourhood) are not informed by geoscience information. Some individuals (19% of surveyed) indicated that they believed their property to be 'safe' on the basis of their personal perceptions of risk, risk mitigations, and independently obtained geoscience data[25]. The utilization of science evidence in this instance is difficult to assess, as some of the individuals undoubtedly consider their independent observations, risk assessments, and mitigation approaches to be equally if not more scientific than the science evidence available to the New Zealand government and CCC in the land use decision-making.

A large number of other decisions regarding personal safety and risk were made throughout the CES. These include decisions related to safety in homes and workplaces, such as fixing televisions and bookshelves to walls, stocking emergency supplies, and avoiding areas with higher perceived risks. Given the well-reported scientific consensus that the probability of strong earthquakes in the region was higher than average, decision-makers that opted for additional safety measures in these instances are viewed as scientifically informed and precautionary. In response to scientifically unjustified but highly publicized earthquake predictions in the region following the 22 February 2011 Christchurch earthquake[26], some residents evacuated the city on the date at which a large earthquake was proposed by a non-

[24] http://www.eqrecoverylearning.org/assets/downloads/2016-02-01-rec3020-cera-residential-red-zone-survey-report.pdf
[25] https://www.hrc.co.nz/red-zones-report/
[26] https://www.nbr.co.nz/article/scientists-side-campbell-moon-man-quake-prediction-dispute-ck-87208

scientist based on lunar cycles. Several trusted scientists discussed the scientifically unjustified nature of this earthquake prediction through a variety of different media channels. The decision to evacuate the city can be perceived as precautionary, but not scientifically informed.

3.5 Summary

This case study summarizes communications between scientists and decision-makers, including those responsible for policy decisions, and those who made other types of decisions, in relation to the 2010-2011 Canterbury earthquake sequence in New Zealand. The involvement of science evidence, and scientists themselves, in policy deliberations occurred through a diverse range of channels. More traditional channels of delivering science advice to policy makers, such as delivery of scientific research (e.g., maps, reports, research articles) to end users in response to solicitation from these users, were complemented by commentary on science websites, media communications, public presentations, government white papers, and private and public communications with specific decision-makers. Scientific research occasionally entered policy deliberations in unexpected ways, including at the bequest of individuals who became aware of the research through the popular media, and who wanted to see it considered by decision-makers.

The primary two hazards that affected property owners in Christchurch were either related to liquefaction (which posed urban infrastructure risks and personal health risks) and rockfall / cliff collapse (which posed fatality risks, in addition to urban infrastructure risks). A large volume of scientific and engineering information was available to decision-makers (government agencies), who sought to make economically sensible, expedient, pragmatic, and defensible decisions with an overall goal of reducing risks to, and promoting recovery of, the people, economy and infrastructure of Christchurch. It is unclear at the time of writing, and may never be known, exactly how each form of available earth and engineering science information underpinned the red-zone decision-making for liquefaction-affected areas. In the Brownlee paper, the justification of need for expedient land zone policy making and decision-making, to give certainty to Christchurch residents, explicitly mentions knowledge derived from science and engineering provisions. On the other hand, the economic equation used to define red zone areas does not mention how any science and engineering provisions were specifically utilized. Any uncertainty relating to the economic parameters in these inputs, and possibly any of the science and engineering data, is not clearly reflected in the red or green zone decisions. It is possible that the intermediate stage (orange zone) reflects aspects of these uncertainties in a somewhat opaque way. In contrast, the land zone decisions ultimately enacted for the initially-declared white zone (rockfall and cliff collapse areas) were made quite differently; the science utility in constructing these maps is quite clearly defined, and both solicited and initially unsolicited science was considered in subsequent Independent Hearings processes. One of the biggest challenges in this example is to unpick how different forms of uncertainty, for example, statistical uncertainty in earthquake forecasts versus epistemic uncertainty in the paleoseismic data, ultimately influenced decision-makers. In the example presented herein, it appears that uncertainties collectively were used to justify a precautionary approach that could be adapted as more relevant scientific information became available.

Decisions enacted in this case study (i) were scientifically informed, although the extent to which science was actually used in some cases is more explicitly evident than others, (ii) aligned with prevailing scientific evidence, although the extent to which this was because prevailing science at the time of decision-making (or obtained after) supported a decision that was actually enacted using different criteria remains a possibility for the liquefaction scenario example, (iii) considered some scientific uncertainty in at least one case, although the treatment of some uncertainties was more rigorous than others, and uncertainty was used to justify a precautionary approach, (iv) were informed by models (of a variety of types, but most ubiquitously, models of future earthquake occurrence), (v) were incremental, where further scientific and engineering analysis was considered to be required to increase the robustness of decision-making, although it appears that at least in some cases, the incremental nature of this process was driven by the science providers rather than decision-makers, and (v) were precautionary in nature. In the case of rockfall land-zoning, precautionary decisions were informed by both science directly solicited for zoning purposes and independently collected by other parties, evaluated by independent hearings panels, and allowed for adaptive capacity as more scientific information was obtained. These aspects are viewed as positive attributes of that decision-making process. The multi-institutional, diverse, collaborative, pre-prepared, and sustained effort of science providers to communicate science to both decision-makers and stake-holders is, in our opinion, one of the strongest reasons why the CES provides excellent examples of effective science communication for decision-making.

4 Case study 2: Communicating uncertainty to farmers at the forefront of developing irrigated broad acre agricultural farming systems in North West Queensland (Author: KP)

4.1 Overview

North West Queensland represents a new frontier for broad acre crop production. Currently, this region is almost exclusively used for extensive grazing of beef cattle but has over 10 million ha of soils suitable for cropping. The major Flinders and Gilbert river systems have potentially 425 GL of water that could be sustainably extracted for irrigation purposes[27].

[27] https://publications.csiro.au/rpr/pub?pid=csiro:EP1313098

Developing broad acre cropping industries in this region is a priority for the Australian and Queensland governments[28]. To facilitate the development, the Queensland Government is releasing water to land holders and graziers for use in large scale agricultural activities. While this is eagerly welcomed by the local community, the availability of irrigation water is only one key element for successful agricultural production.

Farming systems are extremely complex with interactions between the components of soil/land, plants, animals, management and the farm business along with ever present variations in weather and climate leading to considerable uncertainty. Due to these complexity and uncertainty, the inherent knowledge and learned experience needed for successful farm management takes considerable time and effort to develop. In the already established agricultural regions of Australia, farmers have collectively developed this knowledge over the past 150 years, as evidenced by a 1.8 times improvement in crop yields compared to what was achieved soon after European settlement (Fischer 2009). In these regions, new entrants to the agricultural industries can learn from established farmers with greater levels of experience. However, as broad acre crop production is new to North West Queensland, such opportunities are not available to those graziers and land holders that wish to transition to irrigated broad acre cropping. Consequently, for these farmers there is considerable risk and uncertainty as they develop their cropping systems. The lack of definition surrounding risks involved in crop production leads to uncertainty in decision making and limits the availability of finance and capital to develop enterprises further and fully capture the agricultural opportunities that north Queensland presents. Clearly, developing learned experiences over 150 years is not a viable option for this region so an alternative approach must be sought.

4.2 Agricultural systems modelling and simulation to understand the risks within cropping systems and develop learned experience

Biophysical modelling of farming systems as a research discipline was established in the 1950s (Jones J.W. 2016). The models combine physical and biological principles in a mechanistic way to represent components of a farming system (e.g. crop growth, soil water dynamics). As computation power has increased, the models have become increasingly detailed and complex, addressing more aspects of the system simultaneously (e.g. crop and soil processes). These advances mean models can now be used to explore and make sense of the complex interactions between farming-system components and the environment the system operates within (Holzworth et al. 2014). Whilst these models are often considered research tools, their mechanistic basis means they are also ideally suited to building farmers learned experience rapidly when such experience is not readily available (e.g. in North West Queensland). In North West Queensland, a key issue for farmers is the potential sowing dates

[28] https://www.industry.gov.au/data-and-publications/our-north-our-future-white-paper-on-developing-northern-australia

and irrigation water requirements for their planned cropping program. Figure 3 gives example model results for a chickpea crop grown at Richmond in North West Queensland. The model analysis was undertaken in response to an enquiry by a farmer who was growing chickpeas for the first time and wanted to know if they would have enough water stored on farm in dams to grow the crop successfully, and would he be prepared for the crops sowing window. The enquiry was first made to an industry development officer tasked by the state with assisting new farmers in this region, and the development officer subsequently engaged an academically employed agricultural scientist to assist.

Experimentation in more southern growing areas (New South Wales), along with learned farmer experience in southern Australia, suggests that early sowing is key to growing a successful chickpea crop (Jenkins and Brill 2012). However, there is no field experimental data or learned experience for North West Queensland around this issue. Consequently the biophysical farming systems model APSIM (Holzworth et al. 2014) was used by the agricultural scientist to represent four different crop management scenarios using a locally relevant soil description from the APSoil database (Dalgliesh et al. 2012), and a 115 year daily weather record[29] (Jeffrey et al. 2001) for the location of interest. The modelling results, presented as a probability of exceedance plot in Figure 3, show that earlier sowing of chickpeas improved crop yields, and irrigation increased yields. The modelling showed that in relative terms, irrigation was key to consistently high (>2 t/ha) chickpea yields and the positive impact of irrigation on crop yield was considerably greater compared to the impact from sowing date. Further, irrigation all but ensures the crops achieve a high yield, irrespective of the sowing date. The results were communicated to the farmer as a series of probabilities derived from Figure 3, and the farmer was able to identify that irrigation water availability, rather than sowing date, was the key driver for achieving a high yield. He consequently shifted his management focus to irrigation practices that ensured adequate water was available for irrigation of the chickpea crop, rather than working towards an early sowing date. The crop was sown later than what would be considered optimal in more southern production regions, however, ample irrigation water was available in farm storage to ensure the crop could be fully irrigated.

[29] www.longpaddock.qld.gov.au/silo/

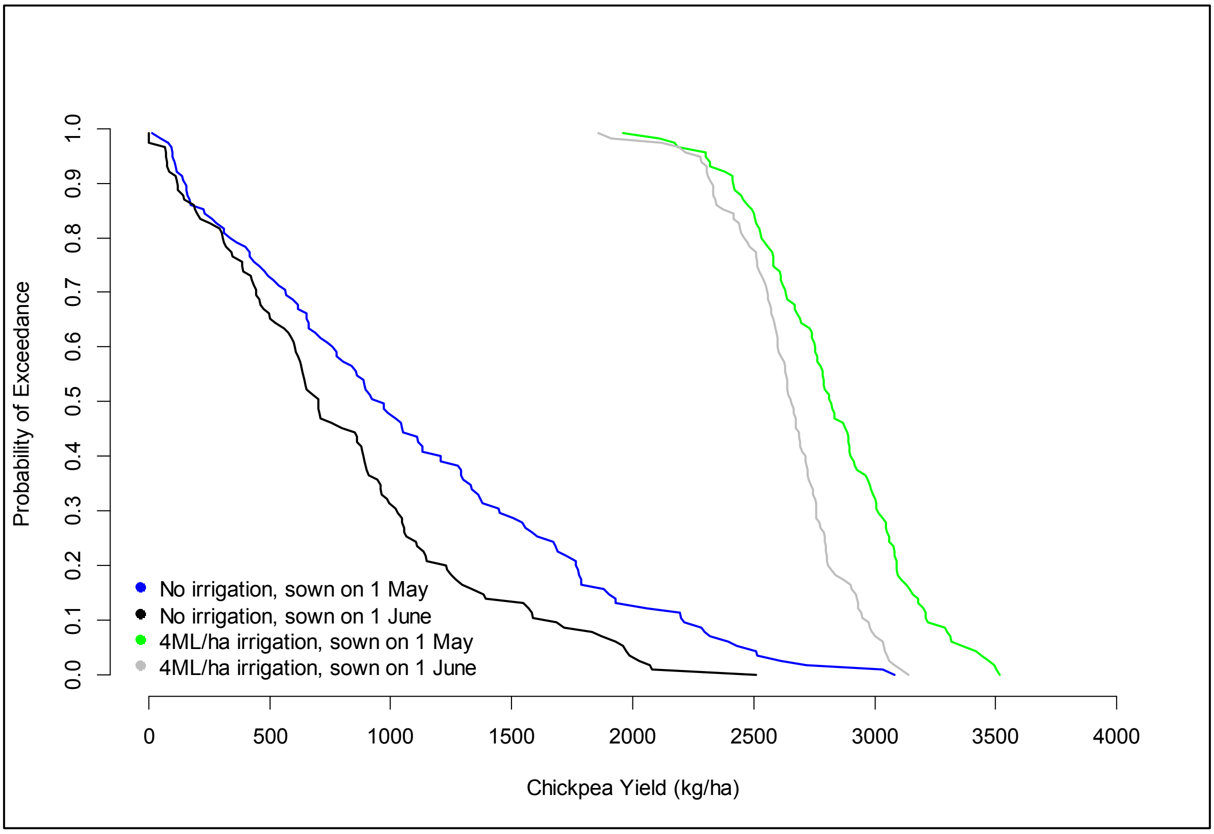

Figure 3: A probability of exceedance plot for the yield of Chickpeas grown at Richmond in north west Queensland when sown on either May 1 or June 1 and receiving either no irrigation or 4ML/ha of irrigation. These results were generated from the APSIM model using a 115 year daily weather record.

4.3 Conveying risks and uncertainty, from one on one to mass communication

The above example involved direct communications between a farmer, agricultural systems modellers and an industry development officer, to define the scope of the modelling analysis and then interpret and present the results in the form of probabilities that informed the decision making. Whilst this strategy was effective in conveying the risks and uncertainties in on-farm decision making, it has limited reach relative to the 150,000 farm businesses in Australia. To gain broad reach, tools and apps[30] are being developed by both public and private sector agricultural scientists and farm advisors, which will enable farmers to undertake the analysis directly from a limited number of inputs and simple interfaces and explore the data themselves using graphical presentations. In particular, the tools and apps aim to provide farmers with understanding of the risks and uncertainties of a particular farm management decision. The tools and apps are not a new concept, with such aims being a key focus of agricultural systems modellers since the discipline was established that underpin them, are iterative in their development and build on each other. For example the tools and apps on www.armonline.com.au build on the very successful ‘Whopper Cropper’ software package (Cox et al. 2004).

[30] www.armonline.com.au

Figure 4 shows an analysis of three different possible nitrogen fertiliser application rates (no fertiliser, 50 kgN/ha and 100 kgN/ha) for a sorghum crop grown at Emerald in central Queensland using the *Crop*ARM app[31]. It highlights that, whilst there is a likely benefit to increasing the rate of nitrogen applied, there is also a chance that there will be little to no benefit in any given year. The multiple methods of graphically presenting this finding, as demonstrated in Figure 4, enables users to customise how risk is conveyed to suit their decision-making requirements and how they best perceive uncertainties. Users are also able to tailor the analysis to the specific seasonal conditions (e.g. dry/drought seasons or wet seasons) via medium-term weather forecasts (Stone et al. 1996) and a gross margin calculator.

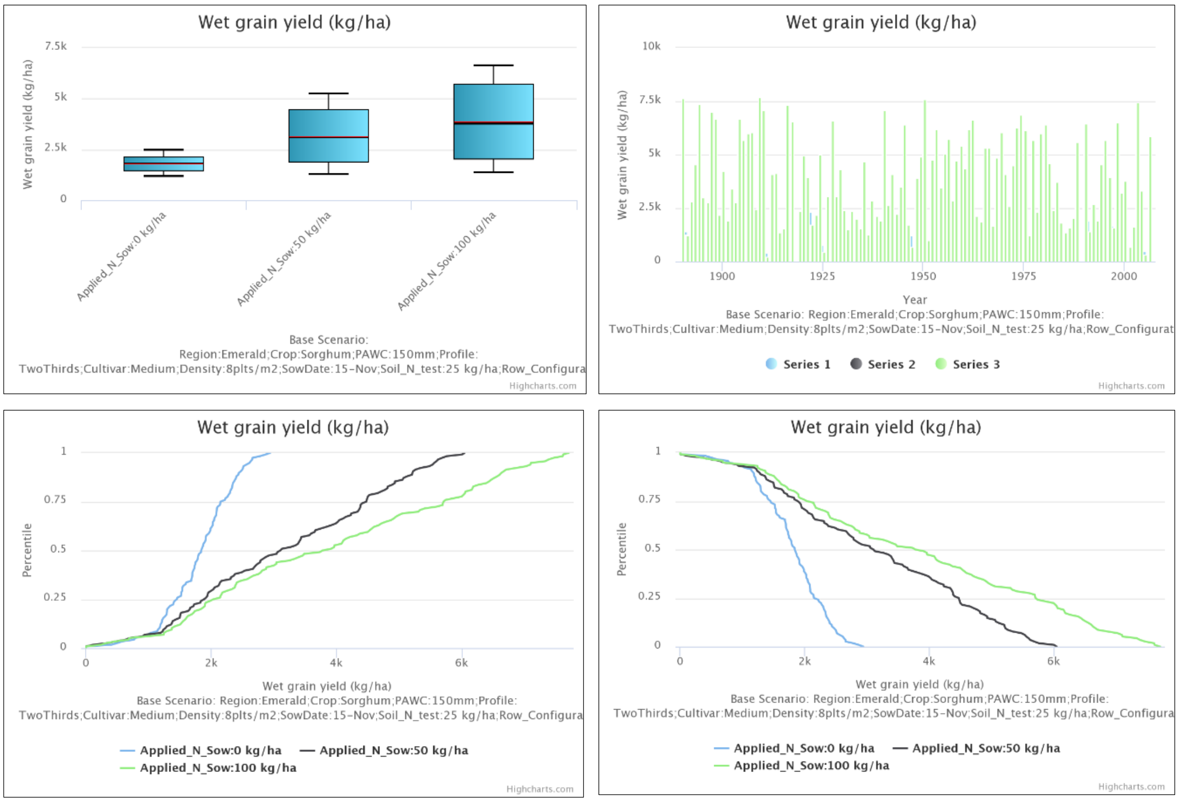

Fig.4: Different presentations of the same analysis undertaken by the *Crop*ARM app that is available through the armonline.com.au suite of tools. The specific analysis is of a sorghum crop grown at Emerald in central Queensland under three different nitrogen fertiliser strategies.

The results presented in Figure 4 are likely to result in farmers applying higher amounts of nitrogen fertiliser, as there is no negative impact on yield (in this analysis). Agricultural economic theory suggests that in the face of uncertainty in climate and soil fertility the slight over application of fertilisers to facilitate higher yields in favourable seasons is the best profit maximisation strategy (Babcock 1992). In areas where the over application of fertiliser can contribute to offsite environmental damage, the presentation of yield probabilities in isolation can lead to actions that contradict broader industry, government and community expectations.

31 www.armonline.com.au

In these cases, conveying specific information regarding the environmental risk of nutrient loss is the best way to influence farming practices. SafeGuage for nutrients is one such application that does this (Moody et al. 2013). It was originally developed for Queensland sugar cane growers and is now extended for use by dairy farmers and crop growers in high rainfall regions (Barlow et al. 2016; Thayalakumaran et al. 2015). The SafeGuage tool presents results as a set of unitless discrete risk profiles, rather than a series of continuous probabilities (Figure 5). Uncertainty is not directly acknowledged in this tool, as it is minimised through the use of very specific scenarios that require a high level of user inputs and engagement.

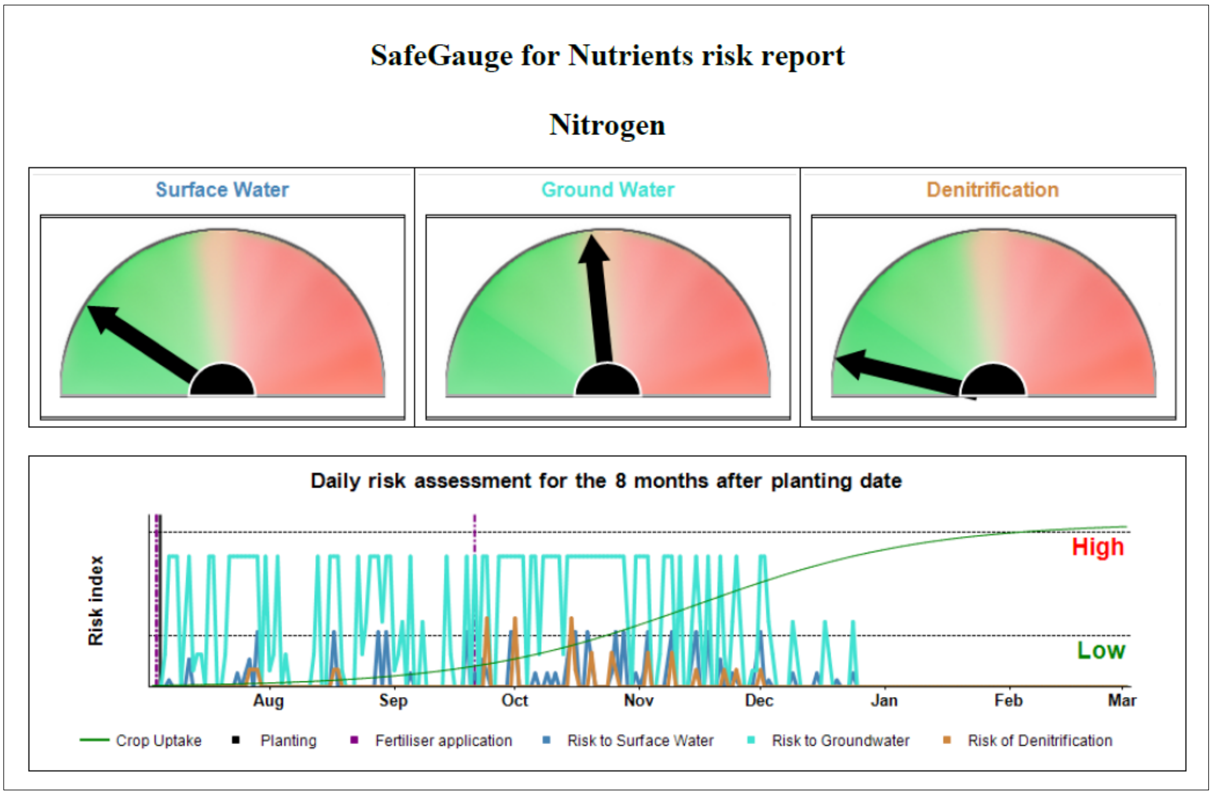

Figure 5: How the environmental risk associated with fertiliser practices of a northern Queensland sugar cane farm is displayed to farmers in the SafeGuage for nutrients tool.

4.4 Summary

This case study highlights how agricultural systems modelling and simulation can be used to guide crop production decisions in the face of uncertainty around climate and soils performance. The example used was crop management (specifically sowing date and irrigation) in a new agricultural region that has a shortage of learned experience around appropriate cropping practices. It demonstrates that modelling is an effective alternative to field experimentation and that the presentation of modelling results to the decision-maker was effective in facilitating and informing decision-making. The case study then examines how this direct approach can be extended through the use of decision support systems so it efficiently reaches a broader audience of farmers and decision-makers. It highlights that the decision support systems focus and how information is conveyed can influence the use of scientific information in decision making. It also highlights that, in the case of decisions that relate to environmental and social impact, potentially sound economic behaviour in the face of uncertainty may mean the decisions supported by scientific evidence are not undertaken.

Decisions enacted in this case study (i) were informed by models, (ii) considered prevailing scientific evidence, (iii) considered scientific uncertainty, (iv) and were precautionary in nature. The communication of uncertainty (through the presentation of probability distributions) was key to providing utility to the decision maker.

Case study 3: Communicating uncertainty in operational flood models to decision makers: challenges from the field (Author: MR)

4.5 Overview

Globally, floods are estimated to have claimed the lives of 500,000 people between 1980 and 2009[32]. Floods are the most common natural disaster in Australia, with the highest fatality rate after extreme heat events (Coates et al. 2014) and an average annual cost reported at $377 million (Wenger et al. 2013), with fatal and non-fatal drowning incidents continuing to occur regularly[33]. Flooding is a significant risk for Australia, and flood events will continue to occur; finding a balanced approach between flood mitigation and the cost of mitigation continues to challenge individuals and governments. Flood modelling is an integral part of flood mitigation and response activities. The role of flood modelling, and the interpretation of flood model outputs, is highlighted by reports such as the Queensland Floods Commission of Inquiry[34] and the Victorian Floods Review (Comrie 2011).

In 2013, the federal government announced the Bushfire and Natural Hazards Cooperative Research Centre (BNHCRC), which expanded the work of the Bushfire CRC to include other hazards, including floods. One focus of the BNHCRC is the scientific diversity, scientific uncertainty and risk mitigation policy and planning project, which considers the impact of uncertainty on decision making. Their investigations highlight that while "uncertainty is a necessary element of scientific methods", "being able to describe scientific uncertainty is a vital aspect of internal and external risk communication" (Neale 2015).

[32] http://www.who.int/violence_injury_prevention/global_report_drowning/en/
[33] http://www.watersafety.com.au/Portals/0/AWSC%20Strategy%202016-20/RLS_AWSS2016_Report_2016LR.pdf
[34] http://www.floodcommission.qld.gov.au/publications/final-report

Challenges that individuals in operational flood response had experienced relating to communicating uncertainty were discussed with one of the authors (MR). This case study, rather than focussing on any specific event or series of events, captures these personal communications. Two perspectives are discussed: the analyst's or provider of scientific advice, and the decision-makers, who acts as a result of the advice.

Advice that informs flood response is provided by people in many different roles, for example weather forecasters and flood modellers from the Bureau of Meteorology who predict future rain and flood levels; dam operators and river catchment managers who provide advice on current water storage and the expected impact of additional inflows; council engineers who understand the storm response capability of storm drains and other local infrastructure; community groups and NGOs who have information on vulnerable people and local resources etc. Decision-makers, or the recipients of advice, include the above-mentioned groups, as well as emergency managers, responders, business operators, and community members. In this case study, our analysts are flood modellers who have been called upon during disasters to provide flood predictions, and the decision-makers are people with an emergency management role in local council.

4.6 The Victorian Total Flood Warning System

The Victorian Total Flood Warning System highlights the fundamental role of prediction in any flood warning system. As shown in Figure 6, the flood warning system is predicated on the interpretation of data and predictions. Predictions of flood impacts are fundamentally reliant on modelling, which is inherently uncertain. While the Total Flood Warning System relates specifically to the external communication of flood risks, internal communications are equally relevant to other planning and response activities. Uncertainty must be a key consideration in the interpretation of flood predictions, and hence in the communication of these risks to aid in identifying an appropriate response to flood risks and flood events.

Figure 6: Victorian Total Flood Warning System (Comrie 2011).

4.7 Operational flood forecasting and uncertainty

Flood modelling is the process of using mathematical models to describe the accumulation or flow of water over the environment, and is an essential component of flood planning, preparation and response. However, it is inherently uncertain. In the context of the suitability of ensemble prediction systems, Cloke and Pappenberger (2009) identify the main forms of uncertainty associated with flood modelling as:

- measurement error, including current events and historical record, is imperfectly recorded, particularly with regard to the spatial correlation of events;
- the non-stationary nature of events, including catchment features that impact flood behaviour, such as surface material distribution or engineering solutions for river management, vary with time;
- non-linearity due to overtopping, including how flow processes change non-linearly when the bank is breached (models are often not able to accurately capture this change in flow processes), which are predominantly associated to the rarity of such events.

An additional key source of uncertainty is model choice. Writing from a statistical modelling perspective, but equally applicable to other forms of modelling, Draper (1995) highlights that model uncertainty involves both structural uncertainty and parameter uncertainty. Parametric uncertainty refers to the choice of parameters, which are ideally measured from the environment or fitted to data. In the context of flood modelling, with high spatio-temporal variation, model parameters usually contain a high degree of uncertainty. One example of parametric uncertainty is soil saturation, i.e. the degree to which the soil is wet. A high degree of saturation means that additional rainfall will lead to rain accumulating on the ground (flooding) rather than soaking in. As opposed to parametric uncertainty, structural uncertainty refers to the uncertainty arising from assumptions that are incorporated within the model itself. Such assumptions cover the inclusion or exclusion of different factors (e.g. time, spatial dimensions, or physical properties such as buoyancy), how different terms are assumed to relate to each other, and even the resolution used in numerical solution methods. Models require a number of simplifying assumptions of real-world processes in order to be tractable. While necessary, these simplifying assumptions nonetheless introduce uncertainty as the real-world is assumed to behave as per the model. An example of structural uncertainty is adopting the 1D Saint-Venant equation under the assumption that the vertical velocity of the flood water is small. A second example is the choice of mesh resolution for the computational solution, as this limits the physical features that are able to be resolved.

Options to address model uncertainty include scientific advancement (e.g., improved understanding of the processes that lead to flooding), data advances (e.g. improved spatio-temporal resolution, reduced or quantified measurement error), and model improvements (e.g. ensemble methods, numerical solution techniques). There have been many recent advances in knowledge of flood processes, climate change, and hydroinformatics, and increased computational capacity available to engineering hydrologists[35] (Pechlivanidis et al. 2011).

However, during an event, flood analysts are rarely in a position to incorporate new techniques or data sources to help address model uncertainty. From an operational perspective, a flood modeller must balance uncertainty quantification and reduction with the pressures of time and available resources. For example, a modeller may trade the spatial resolution of a model for computational speed, or use readily available (but less accurate) data rather than wait for more useful data to become available. During flood operations, the key role of a flood modeller or flood analyst is to provide insight into the expected behaviour of flood waters, such as the magnitude, location and timings of key events, within the intelligence function of Australasian Inter-Service Incident Management System (AIIMS). Insight is gained by interpreting outputs of flood predictions and other knowledge, including knowledge of vulnerable communities, critical businesses, and the distribution of resources (human and physical) for mitigation and response. In the next section, we address issues that arise in the communication of flood insight in an operational setting given the ever-present uncertainty within the models and other data sources.

[35] http://book.arr.org.au.s3-website-ap-southeast-2.amazonaws.com/

4.8 Providing flood insights: Challenges in communicating uncertainty

In preparation or response to a flooding event, the intelligence function within AIIMS provides insights on the predicted flood behaviour to other functions within the Incident Management Team (IMT). These insights are used to identify and trigger actions by the responders such as building a levee, releasing dam water, evacuating an area, or advising people to shelter in place. Effective communication between analysts and decision makers is essential for an appropriate, risk-balanced response to a flooding event. We discuss three situations where flood insights have been provided or received, and challenges have arisen in effectively communicating the uncertainty associated with those insights. The first example deals with challenges in communicating the relative uncertainties between high and low fidelity models, the second with compounding errors between linked models, and the third with how to communicate uncertain flood models.

4.8.1 Low vs high fidelity models

Model selection involves a trade-off between the cost of a model and the accuracy of the results obtained for a particular scenario. Typically, a flood modeller can select different flood models (or model options) for different scenarios, trading the accuracy of the results obtained with the cost of the model given the flood behaviour of concern (for example, flash flooding vs riverine flooding). Model cost is a combination of the data requirements for running the model and the time it takes for the model to produce a meaningful result (computational run-time). A low-fidelity model generally runs quickly and has minimal data requirements, providing only a general indicator of the flooding event, while a high-fidelity model is generally data intensive and takes longer to run, providing detailed and accurate indicators of the flood behaviour. Thus, while a high-fidelity model may be available, the run-time may make its use prohibitive. For example, the ANUGA open source flood model[36] provides detailed flood models, including flow around buildings; however their case study of the Towradgi Creek Catchment takes tens of hours to run (Roberts et al. 2015). Thus, the ANUGA configuration is more suited to planning or post-event analysis, rather than operational forecasting.

An analyst may choose to use a combination of low and higher fidelity models, with low fidelity models providing rapid insight to inform future modelling and immediate decision making. For analysts experienced in operational flood modelling, this is routine. However, downstream decision-makers may be unfamiliar with the specifics of the different models and importantly, limitations on the applicability of the models in different circumstances and the associated uncertainty in the results. Therefore, it is essential that the analyst is able to clearly communicate the contextual information, the uncertainty and model limitations, together with the predicted flood levels in a way that is meaningful to downstream decision-makers. As an example, a low fidelity model may indicate that a nursing home is at risk of flooding. The

[36] https://anuga.anu.edu.au/

IMT may decide to contact the nursing home and have them initiate preparations for an evacuation, in accordance with the nursing home's emergency management plans. While evacuation preparations are underway, this provides time for additional evidence to be collected to determine the likelihood of inundation or isolation for the nursing home, and therefore whether residents should be evacuated. Evacuations, particularly of vulnerable people, are complex events that come with their own risks to the life and safety of the evacuees. Information that would be useful for the IMT to make an informed decision about the evacuation of the nursing home includes when additional predictions will be available, how uncertain is the current prediction and what about the prediction is uncertain, and how likely new information will change the decision being made (that is, to evacuate the nursing home). Such information requires a dialogue between the decision-maker and the analyst, to ensure that the analyst can provide a prediction that is meaningful for the intended use (here, determining whether to evacuate a nursing home), and so that relevant contextual information is communicated. How common such dialogues between analyst and decision-maker are is unknown.

Where that dialogue is absent, challenges can arise. This was highlighted to MR in a discussion with a flood modeller. During an event with localised flooding, the flood analyst was called upon to provide predictions of the flood behaviour for decision-makers in the local IMT and council. The flood modeller decided to use a low-fidelity model to provide a quick overview of the event while awaiting the output of their more detailed high-fidelity model. The analyst was asked for their latest forecast and provided the low-fidelity model (the high-fidelity model was not yet available), being unaware of the intended use of this forecast. This forecast was subsequently passed on to senior decision-makers and communicated to groups outside of the IMT, but without any caveats on the results obtained. The contextual information of the forecast, including the uncertainty, was not shared, and decisions were made without that information. The analyst felt that the forecast was used inappropriately, given the high uncertainty associated with the result. The analyst recognised that they had not been effective in communicating the uncertainty associated with their result, but expressed a lack of knowledge in how to provide this information to people outside of their technical field. While it is not known whether the high-fidelity model would have resulted in different decisions being made at that stage, this example highlights the importance of providing tools to scientists to aid them in communicating the uncertainty associated with their results.

4.8.2 Cascading margins of error

During or in preparation for a flooding event, flood modelling is used to inform many decisions including evacuations, the allocation of resources, and communications to the public. Such modelling may be dependent on observations or measurements from the field (e.g. river heights, rainfall), other forecasts (e.g. weather forecasts), or a combination of both. These inputs are all subject to uncertainty, that may or may not be well quantified. Moreover, the outputs of flood models (typically water heights as a function of space and time) may be inputs to other models.

Under the pressures of an unfolding natural disaster including the likelihood of having to account for the evidence provided to official enquiries[37] (Comrie 2011), courts[38] news media[39] and other forums, the expected uncertainty in model outputs may be accounted for through the inclusion of a 'margin of error'. Formally, the margin of error refers to the observational error in measured quantities. However, colloquially, this term is also used to describe an extra amount allowed for because of mistakes or uncertainty in a calculation. As an example, a forecast may indicate a maximum river height of 4.1m, however a margin of error of 0.2m is added to this forecast to account for any under prediction. Where multiple models or decision processes are linked, these margins of error may compound, impacting the decisions made.

One decision-maker expressed frustration with this situation regarding the need to make decisions without a clear understanding of the likelihood of the scenario presented. A lack of clarity as to how uncertainty has been accounted for limits the ability of a decision-maker to take appropriate actions. Such a risk-adverse approach enacted at each link in the chain could potentially result in decisions that are more dangerous for residents. For example, the significant over-prediction of flooding in an area may result in an evacuation being recommended, which may be more dangerous than sheltering in place for a less severe flood.

The decision to evacuate relies on information from many different sources. A key piece of information is whether or not the area is likely to be inundated or isolated by the flood. The flood forecast uses information about the terrain (e.g. slope, soil saturation, and surface roughness), the current state of the catchment (e.g. river heights and storage capacity) and the weather forecast as key inputs. This input information is itself uncertain. The decision-maker described an example scenario where a margin of error is added to the current river height data and to the forecast rainfall before being used by the flood model. The flood analyst then adds a margin of error to the predicted flood heights to account for error in their forecast and possible errors in the input data. This information is then passed to another person who identifies the area to be evacuated, adding their own margin of error. The decision-maker described being potentially faced with advice that will bear little resemblance to the actual event, as each link in the information chain adds their own buffer because of uncertainty, but without communicating this information along the chain. In the decision-maker's experience,

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[37] http://www.floodcommission.qld.gov.au/publications/final-report/

[38] http://www.courts.qld.gov.au/__data/assets/pdf_file/0019%2F152362%2Fcif-seq-floods-20120605.pdf

[39] http://www.couriermail.com.au/news/queensland/bureau-of-meteorology-under-fire-after-a-weekend-of-wild-weather-and-storms-in-queensland-left-many-unprepared/news-story/d9cc7f437770f3dc22fe95a45516e0d9 ; http://www.abc.net.au/news/2017-03-22/locals-query-why-no-warning-was-given-for-heavy-rain/8377698

how error was accounted for and the magnitude of any 'corrections' was not something routinely communicated.

The operation of the Wivenhoe Dam during the Queensland Floods is a high-profile example of the consequences of under-prediction. The manner in which the dam operators dealt with uncertainty in the rain forecasts resulted in a forecast dam lake level that remained below the threshold for dam water releases (Van den Honert and McAneney 2011). Had the forecast indicated the threshold would likely be exceeded, it is reasonable to presume that different decisions would have been made in dam management.

A significant over prediction of a flooding event can also have negative consequences; impacting resourcing decisions and response options, as well as the risk to both responders and the community during an evacuation. Emergency managers continue to have concerns over the impact of 'false alarms' on future response, which is known as the 'cry-wolf effect'. In laboratory experiments, Breznitz (1984) identified a cry wolf effect where false warnings lead to the alarm system losing credibility; however, these results have been questioned in a natural hazard context (Barnes et al. 2007). For example, research by Dow and Cutter (1998) on hurricane warnings in South Carolina did not find that previous false alarms were a significant factor in the decision-making process for whether to evacuate.

In relating these stories on cascading uncertainties, the decision-maker not only identified a need for scientific methods to handle uncertainty between linked data and models, but also for ways to communicate this information to decision-makers. The need for improved scientific methods to handle uncertainty in the decision-making process for flood events was highlighted by the Queensland Flood Commission of Inquiry, who recommended using a stochastic, Monte Carlo or probabilistic approach in the determination of the design hydrology[40] in a specific response to how uncertain rainfall forecasts were incorporated into the decision-making process at Wivenhoe Dam (Van den Honert and McAneney 2011). Such methods will assist in quantifying the uncertainty. However, the communication of this uncertainty through to decision makers, who may not be familiar with such techniques, must be addressed.

4.9 Standardised approaches for communicating uncertainty

The above two concerns raised by individuals involved in operational flood modelling, as either a decision-maker or provider of scientific advice, are ultimately centred on communication in the context of uncertainty. These examples highlight the need for tools to assist analysts in communicating with decision-makers under uncertainty. Both the analyst and decision-maker expressed a desire for more meaningful communication of the uncertainty within a forecast or result. In the first case, the analyst needed a way to explain the limitations of their low-fidelity model, while in the second case the decision-maker was

[40] http://book.arr.org.au.s3-website-ap-southeast-2.amazonaws.com/

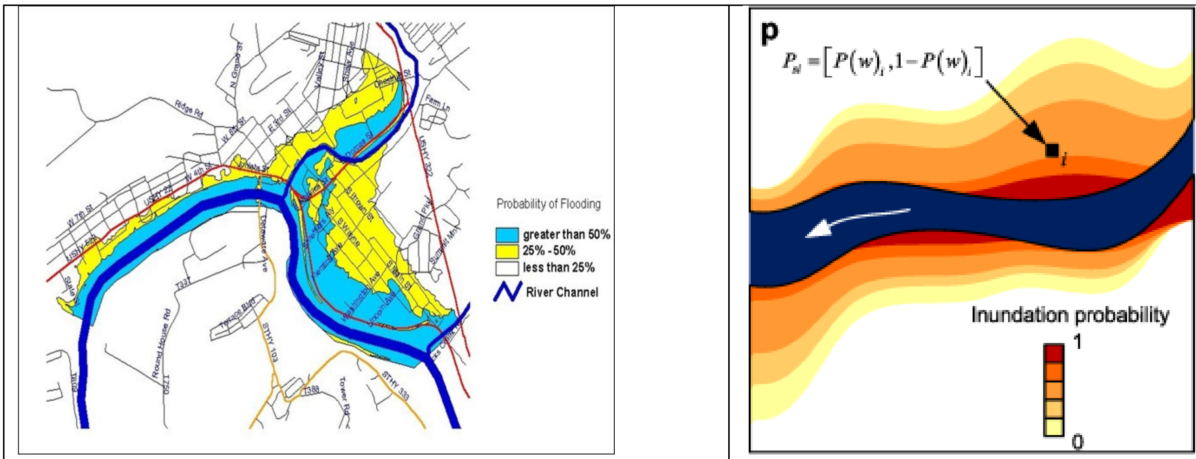
looking for a way to know how likely a particular scenario is, and how uncertainty has been accounted for in a forecast.

Knowing how to communicate forecasts under uncertainty was a key issue raised by one flood analyst. The analyst expressed that they did not know how to communicate the outputs of their models in a way that would ensure the information was appropriately re-communicated to decision-makers within the IMT or externally, for example to residents or local businesses. They described an incident where flood forecasts with high uncertainty were communicated to the public by a non-technical person. The analyst expressed frustration with the loss of information that occurred, as details of the uncertainty associated with the flood model was not included in that communication. They expressed concern that the forecast would cause confusion for the public or a loss of confidence in the emergency management team due to a high error rate (cry-wolf concern). In this case, the analyst explained that they were asked for the output of a model. However, they were not aware of the intended use of the forecast and there was no opportunity for dialogue to interpret the results. The uncertainties associated with this forecast were not clearly communicated, and the forecast output was used by a third party (to communicate a warning to the public) without any of the context of the forecast.

Whether the communication made to the public was appropriate involves many other highly relevant factors. However, the analyst's comments highlight that they did not believe that the science was best represented in that instance. This concern was not due to a pedantic interest in technical accuracy, but came from a belief that this information was essential for identifying an appropriate emergency response. The analyst and their colleagues lacked the tools and training to provide information about forecast uncertainty to other functions of the IMT in a way that aids decision making.

Standardised methods to communicate uncertainty in flood forecasts would aid both analysts and decision makers. Options for standardisation could include mapping methodologies, or pro forma documents, that explicitly address uncertainty. Figure 7 provides two examples of probabilistic flood maps, where the uncertainty in the forecast is expressed in terms of the inundation probability. A high probability (near 1, or 100%), indicates that the area will most likely flood, while a low probability (near 0 or 0%) indicates that flooding is highly unlikely. Such an approach would however require the use of probabilistic flood modelling techniques[41] (Apel et al. 2006; Nathan et al. 2003), which may not always be practical.

[41] http://www.watersafety.com.au/Portals/0/AWSC%20Strategy%202016-20/RLS_AWSS2016_Report_2016LR.pdf



(a) Adapted from Taylor (2017)[42].	(b) Adapted from Figure 1b of (Alfonso et al. 2016).

Figure 7: Examples of probabilistic flood maps adapted from the literature: (a) shows a flood map for a city region with the inundation probability separated into three criteria; (b) shows a hypothetical flood map with five graduations. Probabilistic flood maps capture the uncertainty in flood modelling by providing information about the calculated likelihood of flooding, as opposed to a single predicted water height.

To ensure consistency between events and personnel in IMTs, it is essential that any standards adopted for use in operational flood modelling are documented and training is provided. Before adopting any one standard, the effect of the visualisation on decision making should be investigated. Cheong et al. (Cheong et al. 2016) considered this question in a laboratory review of the effect of visualisation on decisions to stay or go (evacuate or stay and defend from a bushfire) under time pressures, and found that the choice of visualisation affected the decisions made.

4.10 Summary

This case study reports a number of issues that have arisen in the context of communicating scientific outputs with significant uncertainty during flood preparation and response. The experiences shared with one of the authors (MR) reinforces the need for scientists and decision-makers to have standardised ways to communicate the uncertainty associated with their results, and the limitations of their work. Standardised methods of communicating forecasts, even within a single discipline such as operational flood response, will greatly assist both analysts and decision-makers in their roles.

Decisions enacted in this case study (i) were scientifically informed, (ii) aligned with prevailing scientific evidence, (iii) were informed by models, and (iv) were precautionary in nature. The absence of uncertainty in the communication of scientific results is acknowledged as a limitation in the decision-making process, and a key motivating factor for

[42] http://slideplayer.com/slide/4943891/

the scientists and decision makers featured in this case study. The absence of uncertainty in the communication motivated a precautionary approach for some of the decision makers.

5 Case study 4: Developing a state-wide natural disaster risk assessment for Tasmania, Australia (Author: CW)

5.1 Overview

The 2016 Tasmanian State Natural Disaster Risk Assessment (TSNDRA)[43] is the first state-level assessment in Australia that adheres to the recently updated National Emergency Risk Assessment Guidelines (NERAG)[44]. It was undertaken to provide the emergency services with key information to help prepare for and reduce the impact of disasters, including bushfires, floods, severe storms, earthquakes, landslides, coastal inundations, heatwaves and influenza pandemics. It contributes to disaster resilience by delivering an increased understanding and awareness of natural disaster risks affecting Tasmania, and informs decision-making across the Tasmanian emergency management sector, particularly in relation to disaster risk reduction and mitigation activity priorities. The TSNDRA report (White et al. 2016a) and its accompanying summary report (White et al. 2016b) are primarily aimed at informing the State Emergency Management Committee, but their findings are also relevant to a range of authorities, agencies and individuals with responsibilities for emergency risk management.

5.2 Effective communication = collaboration

Unusually, the risk assessment process was not led by State Government agencies, but by natural hazard and risk assessment researchers led by author CW from the University of Tasmania, along with researchers at RMIT University and the Antarctic Climate and Ecosystems Cooperative Research Centre. The team of researchers worked in close collaboration with hazard experts, emergency managers and decision-makers from the Tasmania State Emergency Service, Tasmania Fire Service and related Government agencies, and other stakeholders including the Bureau of Meteorology, the Australian Red Cross and Engineers Australia. This interdisciplinary, academia-led approach allowed a diverse range of expert voices to come together in an open and unbiased workshop setting to inform the identification and assessment of Tasmania's 'state level' priority emergency risks across the consequences categories of People, Economic, Environmental, Public Administration and Social Setting (each with their own sub-categories).

The risk assessment process took place over 12 months beginning in March 2015 and consisting of a series of online surveys and workshops involving stakeholders, experts and

[43] http://www.ses.tas.gov.au/h/em/risk-mgmt/tsndra
[44] https://knowledge.aidr.org.au/resources/handbook-10-national-emergency-risk-assessment-guidelines/

decision-makers with responsibility within each natural hazard. Each hazard workshop considered the underlying risk of different natural hazards, as well as considering the consequences of worst-case, large-scale scenarios for each hazard, such as the 1967 bushfires or the 1929 Launceston floods. A separate workshop developed a portfolio of potential treatment options for the most at-risk sectors to enable issues to be communicated effectively and to help prioritise new risk-reduction actions across Tasmania.

The hazard specific workshops, led by the TSNDRA project team, consisted of four key stages: 1) initial collation of current controls; 2) confirmation and assessment of current controls; 3) scenario consequence rating; and 4) subsequent likelihood rating of those consequences on any given day (not in the instance of an event, i.e. residual risk). Crucially, following on from initial breakout discussions of both hazards and consequences categories, including communicating details of a consensus on the thresholds for consequence categories (from ‘insignificant’ to ‘catastrophic’), each group was asked to identify who would be best suited as expert representatives (beyond those present in the room) for assessing each hazard’s probable consequences and the likelihood of these consequences occurring. This included: 1) the key experts or expert organisations related to each priority natural hazard; and 2) organisations or individuals that would be familiar with or able to qualitatively consider the consequence categories in relation to these hazards. With multiple breakout groups, the potential to have differing results was introduced, therefore, an average value for the ‘consequence’, ‘likelihood’ and ‘confidence’ ratings of each sub-category was required from the values provided by the different working groups.

The risk assessment process determined bushfire to be the greatest aggregated natural hazard risk to Tasmania (Figure 8). It is a ‘high’ or ‘extreme’ risk across all sectors of society, often with catastrophic consequences expected every 30 years. However, bushfires are expected to become more frequent with climate change, based on evidence from experts and the most recent climate projections presented to the decision-makers in the workshop settings, transitioning at least into the ‘likely’ category by the end of the 21st Century, and potentially into ‘almost certain’ category.

Earthquakes are the lowest risk hazard due to their ‘extremely rare’ likelihood and the ‘moderate’ level consequences across the sectors, given the anticipated magnitude of an event. The most catastrophic impacts were determined to be dependent on an earthquake-induced major dam failure that was deemed by experts even less likely than the earthquake itself. Interestingly, workshop participants perceived that if the seismic monitoring system throughout Tasmania were decommissioned, all consequence and likelihood estimates would be substantially increased due to increased uncertainty in the knowledge of the hazard. It was identified that the Tasmanian seismic monitoring system is in urgent need of review and management, as it is mostly operated by the private sector with no obligation to continue. This system ensures high confidence surrounding the likelihood of geological events, and the absence of this system would increase the risk level and priority of treatments for these hazards in future risk assessments.

5.3 An issue of confidence

The use of a confidence rating — a new addition to the NERAG assessment process — allowed for uncertainty in data (such as the relative likelihood of an event occurring, or the impact of an event scaled to the State level), or disagreement between experts to be recorded and included in the assessment. For example, bushfire risk is fairly well understood in Tasmania given the state's long history of bushfire occurrence and measures in place to manage and treat the risk. However, other hazards, such as heatwave or earthquake, are relatively poorly understood in the Tasmanian context due to only the recent emergence of science in this area, or the relatively low likelihood of their occurrence meaning there are limited (or no) observational records on which to ground the information. Therefore, the confidence rating enabled the TSNDRA team to identify and communicate gaps in overall knowledge about different natural hazards and to weight the advice and responses of different stakeholders appropriately.

However, the integration of expertise and confidence into a single confidence value was found to be a limiting factor of the Tasmanian risk assessment process. In some cases, experts in emergency management were certain of a 'very low confidence' rating due to either a lack of knowledge or an understanding of complexities, therefore underestimating their confidence. Similarly, others were unaware of complexities and thus overestimated their confidence. This was identified by the TSNDRA team as a limitation of the NERAG process, recommending that future iterations communicate this issue with the participants at the outset, and explicitly rate the expertise of different workshop groups or individuals separately to confidence.

5.4 Developing a multi-hazard comparison

Each hazard presents its own unique profile of risks to the State. However, stakeholders and practitioners from across the emergency management sector required an overall assessment to support a total perceived risk comparison across all hazards and sectors. Figure 8 was produced using an aggregated approach, presenting a range of risk for each hazard to support the communication of this multi-hazard summary as effectively as possible. For example, Landslide (L) shows a range that spans all of the consequence scales and almost all of the likelihood ratings. When Figure 8 was shown in a summary workshop towards the end of the risk assessment process, decision-makers, including those who had requested such a figure be produced, determined that although it was of interest, the approach was not viable as a method to communicate risk and uncertainty. The overall average positions within the risk matrix do not reflect the most operationally-important components of the risk profile across the hazards and within each sector. Therefore, it was determined that overall assessments require reference to a particular sector (people, economic, etc.) to provide context. Subsequently, although Figure 8 was included in the final report, the remainder of the risk assessment presented its findings by sector.

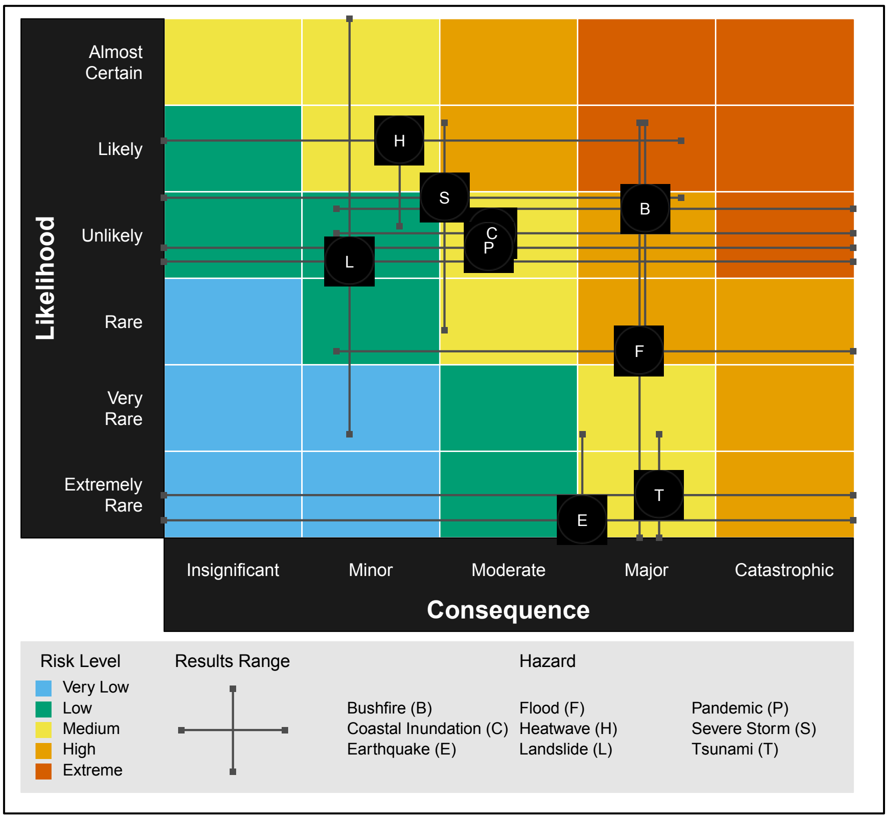


Figure 8: Summary of the risk posed by each hazard as assessed in the 2016 TSNDRA. The central position is the average across sectors for both consequence and likelihood, and the whiskers represent the minimum and maximum ratings across all sectors for each hazard. Figure reproduced from (White et al. 2016b).

5.5 Identifying knowledge gaps

Complementary to the multi-hazard comparison, the frequency and severity of multi-hazard coincident or 'compound' events (Leonard et al. 2014; Wahl et al. 2015) were identified as a knowledge gap in the NERAG process, as it was designed for single hazard assessment only. For example, the occurrence of heatwaves and bushfires are known to be linked, but this interaction is not currently incorporated into existing emergency management exercise scenarios. Other links, such as bushfire and flood (such as the devastating bushfires in the Tasmanian Wilderness World Heritage Area occurring simultaneously with floods on the east coast of the State in January 2016, stretching the emergency services to their limits), are perhaps less obvious, with the expected likelihood of such a co-occurrence poorly understood, especially when the influence of climate change is taken into account (White et al. 2010; White et al. 2013). Whilst it was identified that hazards can co-occur, the combined uncertainty of their causes, likelihood and consequences, meant that communicating the complexity of these types of events to decision-makers was not achievable within the Tasmanian risk assessment process. It was recommended by the TSNDRA team that compound events should be incorporated into a cross-agency risk assessment process to ensure state-wide capacity is assessed under different multi-hazard situations to identify areas for improvement. A multi-hazard approach to exercises and business continuity planning within Government was also agreed to be important, with training recommended for key incident management personnel (e.g. incident controllers) as well as formalising arrangements to guide decision-makers in times of crisis to ensure rapid decision-making.

5.6 Summary and key messages

Overall, the TSNDRA team felt that the report significantly benefitted from its basis on interdisciplinary cooperation and collaboration, as opposed to science communication only. The use of a 'confidence' rating in the report allowed for uncertainty in data or disagreement between experts to be accounted for. However, the lack of provision to be able to combine expertise with confidence into a single value was found to be a limiting factor. It was found that use of a cross-sector multi-hazard likelihood–consequence risk matrix provided interesting insights, but that it was limited by uncertainties in the science and the existing single-hazard risk assessment approaches.

Decisions enacted in this case study (i) were scientifically informed, (ii) aligned with prevailing scientific evidence, (iii) considered some estimations of uncertainty, (iv) were partially informed by models, and (v) were precautionary in nature. The risk assessment process considered estimates of uncertainty using a workshop-based approach for the determination of consequence categories (ranging from 'insignificant' to 'catastrophic'), enabling decision-makers to understand value of a consensus-based approach.

6 Case study 5: Science contributions to decision making related to deep sea mining in New Zealand's Exclusive Economic Zone and continental shelf (Author: PD)

6.1 Overview

This case study examines the contribution from science in the decision-making process for the Chatham Rock Phosphate (CRP) mining consent application for seabed mining along the Chatham Rise in the New Zealand's Exclusive Economic Zone (EEZ). We review how science was used to describe and understand the marine environment, the resources under question (phosphate nodules) and the effects of the mining process on the environment. The CRP mining consent application was submitted to the Environmental Protection Authority of New Zealand (EPANZ) in May 2014. Significantly, this was the second time an exploration and mining company had applied for marine mining consent in New Zealand's EEZ, and the second time such an application was refused by an EPANZ, board-appointed decision-making committee (DMC) within a 5-month timeframe (June 2014—Feb 2015).

6.2 The Quest for Seabed Mining in New Zealand's EEZ

The first marine consent application for seabed mining in New Zealand's EEZ was submitted by Trans-Tasman Resources (TTR) in November 2013 to mine iron sands off the Taranaki coast[45]. The TTR application was refused because the DMC was '*not satisfied that the life-supporting capacity of the environment would be safeguarded or that the adverse effects of the proposal could be avoided, remedied or mitigated, nor do we consider that the proposed conditions (including the adaptive management approach) are sufficiently certain or robust for this application to be approved, given the uncertainty and inadequacy of the information presented to us about the potential adverse effects*'[46]. The DMC's overall impression was that the application was submitted prematurely and more work was warranted to better understand the mining process and impacts on the environment and to '*engage more constructively*' with relevant third parties[47].

On 23 August 2016, TTR lodged a second, revised marine consent application with the EPANZ after undertaking more than two years of '*additional science and engineering work*' programmes and '*extensive engagement and consultation with a wide range of stakeholders, regulators and interest groups, as well as the EPA…*' to address the previous DMC's concerns [48,49]. The Hearing took place over 27 days from 16 February 2017 under a new EPANZ appointed DMC. On 10 August 2017 the new DMC reversed the decision made in the first application and granted a 35-year mining consent, on the condition that TTR carry out an additional two years of environmental monitoring and present the results to the EPA before mining activities commence (Environmental Protection Authority NZ 2017)[50]. The EPANZ DMC decision was appealed by 11 parties on eight different grounds and was referred to the High Court of New Zealand in: The appeal of The Taranaki-Whanganui Conservation Board versus the EPZNZ[51]. The High Court upheld only one of the grounds of appeal; that relating to the legal meaning of the term 'adaptive management' and held that the DMC's '*narrow interpretation*' was inconsistent with the meaning of that term derived from s61 of the EEZ Act and found this '*error was material and may well have influenced the outcome of the consent application*'. The DMC decision was quashed and referred back to the DMC '*for reconsideration, applying the correct legal test in relation to the concept of adaptive management approach'*. As of 21 September 2018, TTR have lodged a notice to the Court of

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[45] https://www.epa.govt.nz/database-search/eez-applications/view/EEZ000004
[46] https://www.epa.govt.nz/assets/FileAPI/proposal/EEZ000004/Boards-Decision/EEZ000004-Trans-Tasman-Resources-decision-17June2014.pdf
[47] https://www.epa.govt.nz/assets/FileAPI/proposal/EEZ000004/Boards-Decision/EEZ000004-Trans-Tasman-Resources-decision-17June2014.pdf
[48] https://www.ttrl.co.nz/fileadmin/user_upload/TTR_Media_Statement_Marine_Consent_Application_23Aug16_-_updated.pdf
[49] https://www.epa.govt.nz/public-consultations/decided/trans-tasman-resources-limited-2016/
[50] https://www.ttrl.co.nz/fileadmin/user_upload/TTR_Media_Statement_DMC_Decision_10Aug17.pdf
[51] https://www.courtsofnz.govt.nz/cases/the-taranaki-whanganui-conservation-board-v-the-environmental-protection-authority/@@images/fileDecision?r=222.009077804

Appeal to seek leave to appeal the High Court judgement on the grounds that the EPANZ did follow a legally correct approach in granting a marine discharge consent[52].

TTR's pursuit for seabed mining consent is ongoing and both pre- and post-dates the CRP case study presented here. TTR's experience significantly foreshadows the hurdles CRP will have to overcome to counter the initial findings of the DMC in any subsequent applications. The overwhelming perception that there was inadequate information, and unacceptable risks and uncertainties associated with seabed mining was pervasive among external interested parties and the DMC in the CRP application. CRP's adaptive management plan, which sought to avoid, mitigate and minimise impacts on the environment associated with the mining operations was viewed as inadequate due to knowledge gaps with respect to baseline data and environmental impacts. These findings strongly mirror many aspects of the TTR case and in both instances these perceived knowledge gaps are intended to be filled by additional and ongoing science programmes. The implicit assumption is that the collection of more data can address and sufficiently reduce the perception of the risks and uncertainties related to seabed mining to allow mining activities to occur. This puts a premium on the role of science in decision making but does not guarantee that science will be prioritised in the decision-making process.

6.3 Chatham Rock Phosphate's application to mine phosphorite nodules

In May 2014 a New Zealand-based company Chatham Rock Phosphate (CRP) applied for a marine consent to mine phosphorite nodules from the crest of the Chatham Rise, based on an inferred resource of 80 million tonnes of phosphorite nodules, averaging 290 kg m^{-3} and containing 23.4 million tonnes of phosphorite (Figure 9) (Golder Associates Ltd 2014b; Golder Associates Ltd 2014c; Sterk 2014)[53]. Mining would occur at water depths from 250 m to 450 m in an area located about 400 km east of Christchurch and would initially take place within an 820 km^2 area for which it holds a mining permit (Golder Associates Ltd 2014b). Mining was proposed to extend to parts of the prospecting licence area of 5,207 km^2 if further resources could be identified and another marine consent obtained (Environmental Protection Authority NZ 2015; Golder Associates Ltd 2014b). Mining phosphorite nodules would involve the use of conventional trailing suction hopper dredger or drag-head to capture the nodules off the seafloor (Golder Associates Ltd 2014b). After extraction of the phosphate nodules the remaining sediment would be returned to the seafloor via a sinker pipe equipped with a diffuser positioned 10 m above the seafloor (Golder Associates Ltd 2014b). CRP aimed to produce 1.5 million tonnes of phosphorate nodules per year from a sequence of mining blocks. Over the proposed 15-year life of the mining operations approximately 450 km^2 of the seafloor would be mined (Golder Associates Ltd 2014b). By CRP's accounts, an area equivalent to 0.1% of the entire Chatham Rise would be directly impacted by mining.

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[52] https://www.ttrl.co.nz/fileadmin/user_upload/TTR_Seeks_Leave_to_Appeal_21_September_2018.pdf
[53] https://www.epa.govt.nz/database-search/eez-applications/view/EEZ000006

6.3.1 Why mine the seabed for rock phosphate in New Zealand?

New Zealand imports about one million tonnes of rock phosphate per year as a source of phosphorous, a primary component of commercial fertilisers. The use of commercial fertilisers has greatly contributed to a growth economy due to increased agricultural productivity globally including New Zealand (Golder Associates Ltd 2014b).

Phosphate is considered a moderate risk industrial mineral (Behnam and Visbeck 2014) that is currently sourced from only a small number of countries in West Africa, Tunisia and in particular, Morocco, which controls 85% of the global rock phosphate supply. CRP argues in the interests of national security, and economic and environmental benefits that New Zealand should move towards developing its own source of phosphatic fertiliser (superphosphate and other phosphate fertilisers) on which it depends for over 40% of fertiliser used for agricultural productivity (Golder Associates Ltd 2014b). Further, the rock phosphate from the Chatham Rise has an extremely low level of cadmium and field trials have shown it is less likely to leach into waterways because reactive rock phosphate is less soluble than superphosphate (McDowell et al. 2010; Syers et al. 1986; Wood and Falconer 2016).

Mining reactive rock phosphate in New Zealand waters would increase the security of supply of a strategic resource, decrease the rate of accumulation of cadmium in soils, improve soil resilience, reduce phosphate runoff to waterways, and reduce the carbon footprint of New Zealand's phosphate usage (Wood and Falconer 2016).

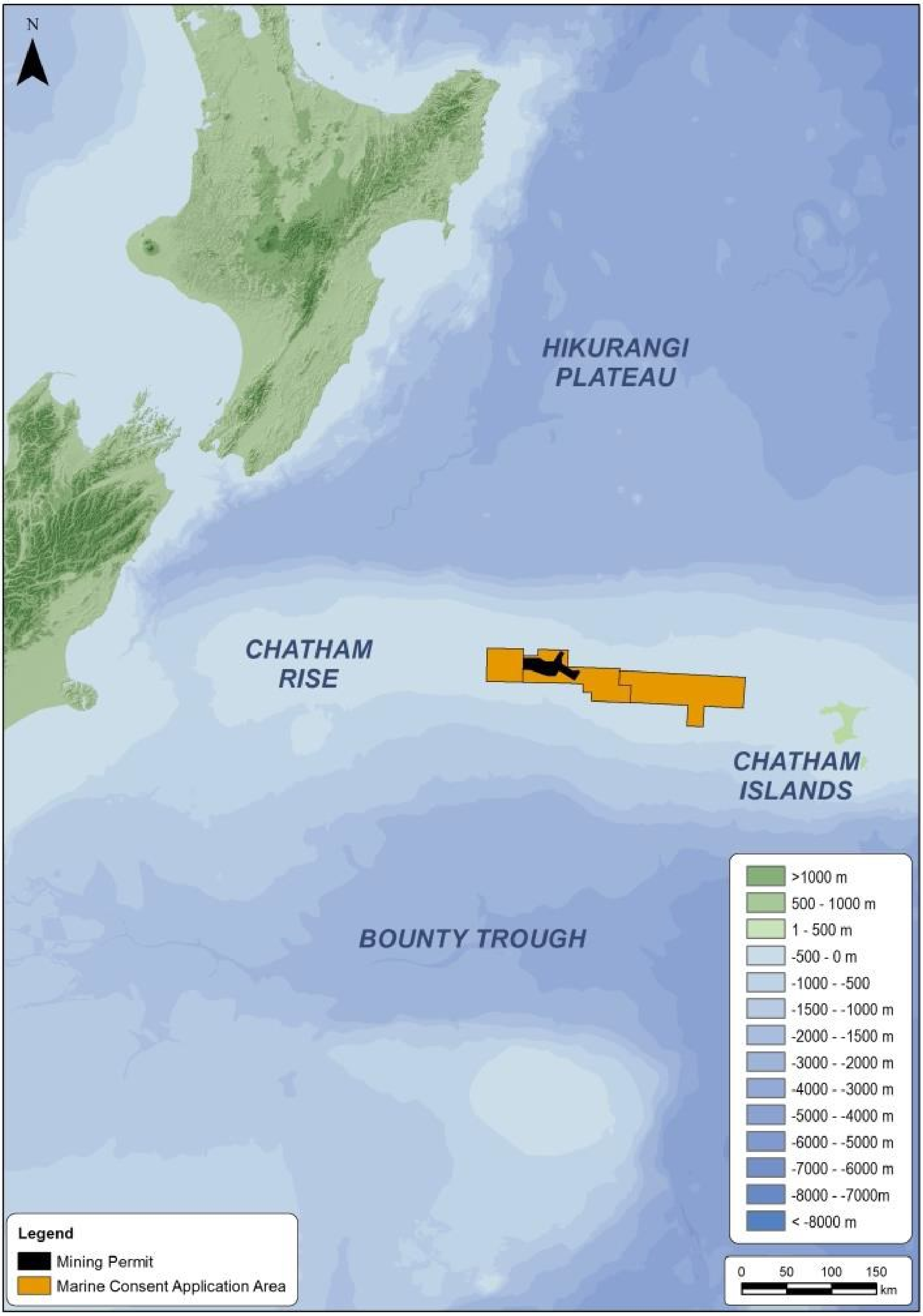


Figure 9: The Chatham Rise and CRP's marine consent application area, including the mining permit area (MP 55549, in black) (Golder Associates Ltd 2014b).

6.4 Science Evidence in CRP's EPANZ Mining Consent Application

CRP was required to demonstrate that it understood the current state of the environment, scope the potential environmental issues associated with seabed mining activities and prepare environmental impact assessments (EIAs) for these issues[54] (Golder Associates Ltd 2014b; Golder Associates Ltd 2014c). The EIAs document the impacts of seabed mining on the following key areas: oceanography/hydrodynamics; sediment plume dynamics and sedimentation; species' trophic relationships; operational noise propagation and marine mammals; benthic species' distribution; commercial fish species distribution and population; habitat prediction and spatial planning; benefits to the New Zealand economy; ecotoxicology and human health, and the mining operation itself at depth. The proposal and EIAs were based on numerous scientific studies relating to geology, biology, oceanography, chemistry and physics. The studies required input from experts across many scientific disciplines to compile, collect and analyse data, and present the findings. Presenting information on all the EIAs, which consisted of 36 appendices to the application, and the specific details of the models that were created is beyond the scope of this case study but can be viewed and downloaded at the EPA website[55].

Lastly, CRP was required to consider and present the activities that it would undertake to ensure any negative impacts on any of the key areas and existing interests are avoided, mitigate and/or remedy. The EIAs revealed the potential impacts on benthic habitat and fauna loss within the mining blocks was serious, and sedimentation impacts on benthic habitats from mining would create high environmental risks. Their potential likelihoods were deemed '*almost certain*' even after applying strategies of avoidance, remediation and mitigation measures outlined in their Environment Management and Monitoring Plan (EMMP) (Golder Associates Ltd 2014a). These potential impacts generated much attention and had the largest effect on the final DMC decision.

6.5 Modelling the Unknown

The Chatham Rise is one of the most comprehensively studied parts of New Zealand's EEZ (Boskalis Offshore 2014a; Boskalis Offshore 2014b; Chiswell 2014; CRP 2014; Hughes-Allan et al. 2014; Wood 2014; Wood and Falconer 2016), but one of the main challenges CRP faced was a perceived dearth of environmental baseline data and indicators of how the environment would respond to mining operations. In the absence of additional baseline data sets and empirical observations, the use of various types of models became one of the main methods for conducting impact assessments in the following areas: oceanography and hydrodynamics; sediment plume dynamics and sedimentation; species' trophic relationships;

[54] See applicant proposal documents at https://www.epa.govt.nz/database-search/eez-applications/view/EEZ000006

[55] See Applicant proposal documents at https://www.epa.govt.nz/database-search/eez-applications/view/EEZ000006

operational noise propagation and marine mammals; benthic species' distribution; commercial fish species distribution and population; habitat prediction and spatial planning; economic benefits; ecotoxicology and human health; and the mining operation itself at depth (Environmental Protection Authority NZ 2015).

Models based on knowledge of physical and biological systems were used to predict the marine environment and the likely effects of disturbances on it (Wood 2014). The behaviour of these systems is not predictable in detail, but because they are based on physics, chemistry and biology and are not random (i.e. there are limits to current velocities and factors controlling the health and distribution of organisms, etc.), their general range of behaviour can be predicted (Golder Associates Ltd 2014b; Wood 2014). In some cases, the models are robust (e.g., oceanography) and in others they contain significant gaps (e.g., natural turbidity) that made it more difficult to assess the significance of the mining operations (Golder Associates Ltd 2014b). CRP proposed to address the uncertainties inherent in any marine development proposal through an adaptive management process that initially focused on gathering background environmental data, followed by extensive environmental monitoring and a requirement to stop mining if the target level of environmental effects could not be met (Golder Associates Ltd 2014a; Wood 2014). The consequences of uncertainties in the models were significant. The uncertainty about the modelled distribution of coral thickets, for example, led the DMC to conclude that the potential impacts of mining were too great to grant a consent (Environmental Protection Authority NZ 2015).

The DMC showed considerable discomfort with the degree to which the EIAs depended on modelling and monitoring, in lieu of more comprehensive, pre-existing or new baseline data, or empirical observations collected by conducting in situ trials and surveys, even going so far as to call this aspect of the CRP application `unusual'. According to a CRP representative, some of this criticism may have been warranted (e.g., a lack of calibrated measurements of background turbidity) but expectations of in situ trials to assess sediment plume behaviour may not have been consistent with section 61, part (5) of the EEZ Act, which describes "*best available information*" as that which, "*…in the particular circumstances, is available without unreasonable cost, effort, or time*" (pers. comm. R Wood 2017). Likewise, science and models can help predict the likely outcomes of an activity but this is only part of the discussion that underpins the decision about whether the activity is acceptable to society (Environmental Protection Authority NZ 2015).

It is difficult to understand what the DMC may have considered 'usual' when the proposed activity has no national or international predecessor and cannot be directly compared to consent applications for similar onshore activities. Most significantly, the DMC stated "*…there were other uncertainties stemming from the fact that this would be the first seabed mining project ever undertaken at such depths anywhere in the world…*" (Environmental Protection Authority NZ 2015). The DMC and CRP could not look elsewhere for direct reassurances, confirmation, or validation regarding any of the modelled scenarios and likely outcomes. However, other activities including offshore diamond mining and non-mining related activities such as port dredging, may serve as analogues for understanding the disturbance of seafloor sediments, the generation of sediment plumes and how they behave (Grogan 2017). Being the first to attempt to mine phosphorite nodules from depths of 250 – 400 m in a marine setting was, in the end, too much to overcome, even in instances when the CRP experts and the DMC experts, as documented in most of the joint-witness statements, were in agreement about the degree to which there would be negative outcomes in the short-term but that would likely be reversible in the long-term[56].

6.6 Uncertainty, Ignorance and Partial knowledge – In a Marine Setting

The 2014 CRP mining consent application, and others like it, face an ongoing problem. Despite how well traversed our oceans are on the surface, various types and degrees of uncertainty, ignorance and partial knowledge (and the perceptions thereof) of the deep marine environment persists in hampering the ability to make decisions about how to manage, regulate, and responsibly (i.e. sustainably) extract the natural mineral resources within it (Behnam and Visbeck 2014; Durden et al. 2016; Gjerde et al. 2016; Grogan 2017; Halfar and Fujita 2002; Tremlett 2015; Wedding et al. 2015). It should be acknowledged that scientists do, in fact, have a reasonable and rapidly growing understanding of a wide range of deep marine environments, from both models, field samples and empirical data, but this is typically at a lower spatial resolution when compared to our knowledge of terrestrial environments (Tremlett 2015). By comparison to land-based research, our oceans, even within EEZs, are vast and inaccessible (Moritz Bollmann et al. 2010). The collection of marine data is orders of magnitude costlier, more time consuming to collect, and relies to a much larger degree on remote sensing and sampling that can only statistically represent the complexity of a natural marine system (pers. comm. R Wood 2017) (Tremlett 2015). In this respect, and to put it in perspective, the challenges faced in building our knowledge of the deep marine environments and ecosystems is, in many respects, more similar to challenges faced in exploring outer space than it is for any terrestrial environment. It is erroneous to apply standards of knowledge derived from analogous land-based activities to define what constitutes adequate information (i.e. the amount of available baseline data) and acceptable measures of risk and uncertainty in a marine setting.

Further, these challenges have not hindered our ability or willingness to permit and regulate how other types of resources, such as fish, sand, diamonds, petroleum and gas hydrates are mined from a diverse range of marine environments globally (Behnam and Visbeck 2013; Behnam and Visbeck 2014; Moritz Bollmann et al. 2010). In relation to the EPANZ EEZ Act, the implications of these challenges should be understood and translated into context-focused policy guidelines for decision-making criteria pertaining and relevant to marine

[56] See Boards decision at https://www.epa.govt.nz/database-search/eez-applications/view/EEZ000006

mining activities, and associated uncertainties and risks (Gluckman 2014; Grogan 2017). Scientists and other experts who understand the inherent uncertainty of science data in a marine setting should assist in providing clearer guidance in applying the decision-making criteria, outlined in section 61 of the EEZ Act, in these unique and pioneering applications for deep sea mining. It is not reasonable to rely on pre-existing understandings of what constitutes "*best available information"* (available without unreasonable cost, effort or time), how to "*take into account any uncertainty or inadequacy in the information available*", how to "*favour caution and environmental protection*", and how to "*first consider whether taking an adaptive management approach would allow the activity to be undertaken*" as stated in section 61 of the EEZ Act (Environmental Protection Authority NZ 2012).

6.7 Science Communication

Scientific evidence was not the only type of evidence presented by CRP or other expert and non-expert submitters, but science underpinned the majority of topics under consideration by the DMC (Golder Associates Ltd 2014b). How the science was communicated to the DMC and other parties with existing interests and how various opinions on the science were weighed by the DMC had a strong bearing on the final decision, which was to refuse the mining consent (Environmental Protection Authority NZ 2015). Complex scientific issues and the associated risks and uncertainty that constrain our understanding of the deep marine environment and the impacts of deep sea exploration and mining can either be exacerbated or reduced depending on how the science is communicated to its target audiences.

During the hearing, CRP representatives admitted they sometimes found it difficult to present spatially and temporally varying data, for example in relation to the plume model results, in a way that could be easily understood (Lescinski 2014) and could have been presented in a more streamlined way (Gluckman 2014). CRP have also acknowledged that the descriptions of the project, the environment and the likely effects were complex and could have been presented more clearly (pers. comm. R Wood 2017). To compound matters, the hearing process is designed to allow additional data to be presented to the DMC in a piecemeal manner beyond what is put in the application. This data can lead to conflicting opinions and/or can be used to over-emphasise the uncertainty associated with science presented by the applicant (pers. comm. R Grogan 2017). Finally, the Crown appeared to make a balanced submission at the start of the consultation process for the project, which included comments on environmental concerns and economic benefits. However, during the hearing the Crown's interest was entirely represented by the Department of Conservation (DoC), who emphasised their environmental concerns (pers. comm. R Wood 2017).

Importantly, the choice of terms, specific wording and phrases used, are not likely to be universally understood (by all parties) and can have different meanings to different people. This can lead to a build-up of linguistic uncertainty if these word choices are presented without explicitly defining what they mean and the context in which they are being used.

Language used in the application and subsequent hearing process contributed to a build-up of linguistic uncertainty related to the science and descriptions of the mining process. This had a negative impact on the likelihood of the application being approved (pers. comm. R Grogan 2017). A good example of this was the use of the words/phrases “tailings”, “mine tailings”, and “processed waste materials” by CRP and others to describe the sediment that was being returned to the seafloor after the removal of the phosphate nodules (Environmental Protection Authority NZ 2015; Golder Associates Ltd 2014b; Lescinski 2014). Each of these words and phrases connote an overwhelmingly negative image of pending toxicity or pollution as they are typically used to describe an unusable mining by-product that has undergone intense refining processes involving chemical additives to aid in the separation of gangue (waste material) from the economic portion of the ore. However, according to Renee Grogan (an environmental consultant contracted by CRP), the CRP project doesn’t actually have a tailings stream because what is being returned to the seafloor is the same unaltered sediment (minus the phosphate nodules) that was picked up from the seabed along with the phosphate nodules (pers. comm. R Grogan 2017).

6.8 Decision-making for Deep Sea Mining Under the EEZ Act

The final decision was to refuse CRP’s application for mining consent. The main concerns cited by the DMC were related to the impact of the drag-head on the seabed, and the benthic fauna in and on the seabed. The DMC concluded that there was likely to be: significant and permanent damage to the benthic environment; modest economic benefits compared to environmental effects; and significant effect on the Benthic Protection Area (BPA) (Environmental Protection Authority NZ 2015). This was undoubtedly a complex application and resulted in a complicated decision-making strategy (Quigley et al., Minerva, in review; Figure 3). The jobs of CRP and DMC were possibly made more difficult by a number of features of the EEZ Act including the details of the decision-making criteria (Sections 59 and 60), and clarity on how to apply the information principles (Section 61) (Environmental Protection Authority NZ 2012).

The application was assessed as being complete; however, there were a subsequent 44 requests for further information on many topics, which speaks to three salient issues. First, it was perceived that the science wasn’t comprehensive enough. Second, it pointed to a missed opportunity, by CRP, to present its application in a better, more understandable and streamlined way. Third, it suggested there was a lack of expertise within the DMC to be able to understand the complexities of the deep marine environment in general, and to be able to judge the value and context of the type of data they were expected to assess and base their decisions on, which led to a type of decision uncertainty.

Uncertainty, primarily associated with the models, contributed to DMC’s decision. The consent process included caucusing by scientists representing all interested parties. These were especially valuable as they identified areas of consensus and highlighted areas of concern. Significant concerns were not expressed for most issues, and, overall, joint-witness conference results showed a consensus that the methods used to characterise the environment and the impacts from mining were adequate and modelling parameters were reasonable and/or sound (Environmental Protection Authority NZ 2015). Even though the reviewing experts agreed that CRP's models were sound and reasonable, the DMC strongly expressed almost unanimous critique that the results carried an inherent uncertainty because the models were not calibrated and lacked validation through ground-truthing via trial surveys.

As pointed out in point 155 on page 51 of the decision document, "The hearing produced two main schools of thought on the matter of field validation: those who thought that this could reasonably be accomplished as part of operational mining with the necessary review loops, and those who thought it must be done prior to operational mining so that the activity would avoid unanticipated adverse consequences and not have to resort to reactive management of those consequences". CRP thought the uncertainties were minor and could be addressed by conditions on the consent, including surveys prior to mining and modifications to the mining process (including stopping mining if necessary) (pers. comm. R Wood 2017) (Wood 2014). The DMC thought they were fundamental and must be addressed before consent could be granted (Environmental Protection Authority NZ 2015). This divergence in viewpoints may point to a need for a more explicit dialogue between science contributors and decision-makers, regarding the knowledge and assumption that are used in modelling scenarios for which there are risks and uncertainties (Colyvan et al. 2017).

In the EEZ Act, the DMC was required to favour caution and environmental protection and the impacts were viewed as unavoidable and could not be remedied or mitigated by the proposed adaptive management measures in the EMMP. However, adaptive management is set up to regulate the process, which is becoming an outdated approach and is increasingly being abandoned in favour of performance or outcome-based regulations (Grogan 2017) . This means CRP had little to gain from their EMMP because the prescriptive tone of the act prohibits the type of flexibility needed to react to the full range of potential impacts identified as risks (Grogan 2017).

The EEZ Act also requires the DMC to consider the economic aspects of a project. This can be difficult to quantify, and uncertainties can make decisions more difficult (pers. comm. R Grogan 2017). The assessment of economic viability and benefits of a mining project is more directly the concern of other legislation, such as the Crown Minerals act, which is administered by New Zealand Petroleum and Minerals (NZP&M) as part of the Ministry of Business, Innovation and Employment and whose primary purpose is to maximise the utilisation and return on the State's mineral wealth. The DMC focussed on assessing the direct economic benefits (profitability and job creation), which were deemed to be not very significant. During the hearing both the DMC, CRP and NZP&M missed the opportunity to link the direct economic benefits of the project to indirect benefits such as securing a nationally significant strategic resource, environmental benefits and contributions to sustainable farming practices (Wood and Falconer 2016).

Importantly, science was only one component of decision making, and did not necessarily address society's values-based concerns. The DMC had to weigh the existing interests of other parties. The environmental (and economic) assessments were judged not only by the DMC and EPA but also by the community at large and other groups including representatives of: Treaty of Waitangi settlements; commercial fishing; marine eco-tourism, and; customary fishing and other vessels traversing the area. The DMC also considered the effects of the proposed mining activities on the Chatham Islanders and Maori and Moriori cultural interests. Public notification was delivered to a further 1,037 parties including 10 Government Ministers, Maritime New Zealand, 98 New Zealand authorities and others such as the Chatham Island groups, commercial fishers, the Deepwater Group, Seafood New Zealand, the Department of Conservation and Environment Canterbury, all of whom were invited to make submissions. NGOs — including Greenpeace, Kiwis Against Seabed Mining (KASM) and The Royal Forest and Bird Protection Society of New Zealand — were also involved in the hearing. Many of these non-expert submitters were vocal and expressed their own opinions and concerns about the science presented in the application.

Finally, the EEZ Act requires the DMC to consider relevant regulations and any other applicable law. For this project, the Mid Chatham Rise Benthic Protection Area (BPA), established under the Fisheries Act, was considered relevant by the DMC (Environmental Protection Authority NZ 2015). Under the Fisheries Act, bottom trawling is forbidden in a BPA but other activities such as mining are not excluded. BPAs were established to include regions of the seafloor representative of the Marine Environmental Classification areas, a regional classification scheme of the marine environment in New Zealand's EEZ (Golder Associates Ltd 2014b).

The BPAs were not established to protect sensitive environments such as the stony coral communities identified in the region of the proposed mining area (Golder Associates Ltd 2014b). Models predicted that habitat suitable for those stony coral communities were likely to be widespread on the crest of the Chatham Rise, but those models were not validated before the consent application was submitted. As a result, the DMC concluded these stony coral communities were rare and vulnerable ecosystems and that if mining were to occur then the hard substrate habitat offered by the phosphorite nodules would irreversibly "*be transformed wholly into soft sediment habitat*" (Environmental Protection Authority NZ 2015). The science submitted by CRP indicated that the significance of the impact on the stony coral communities was likely to be small, but the uncertainty arising from the lack of verification was sufficient to make this a significant factor in the DMC's decision to decline the application.

6.9 Summary

New Zealand is not the only country grappling with the implications of extracting mineral resources from the seabed, as global demand is forecast to climb for a number of metals and industrial minerals that are known to exist on continental shelves, in EEZs and in international waters (Hannington et al. 2017; Wedding et al. 2015). Science evidence plays a critical role in understanding marine environments and the potential impacts from the mining process and should, therefore, be instrumental in the decision-making process. This case study demonstrates what happens when the decision-making is: 1) hindered by uncertainty, ignorance and partial knowledge related to the baseline data (i.e. science evidence), science-based models and potential environmental impacts; 2) hampered by a science communication process that contributes to linguistic uncertainty and a piecemeal accumulation of scientific information; 3) restricted by a legislative framework that favours a precautionary approach over adaptive management, and does not provide guidelines for understanding the meaning of the criteria in the EEZ Act in relation to the type of activity proposed, or for weighing different types of evidence related to the activity.

In relation to CRP's 2014 EPANZ mining consent application, these issues led to the reprioritisation of the science in favour of precaution to ensure the preservation of the existing interests of other stakeholders. Decisions enacted in this case study (i) were informed by legislative framework of the EEZ Act, science, and existing third-party interests, (ii) were strongly aligned with the EPANZ DMC's interpretation of the legislative framework of the EEZ Act, (iii) strongly relied on estimations of scientific uncertainty, (iv) were informed by a wide range of models in the absence of empirical, in situ data, and (v) were precautionary in nature due to perceptions of science knowledge gaps.

7 Case Study 6: Locating and assessing sources of uncertainty in 3D geological models (Author: ML)

7.1 Overview

Three-dimensional (3D) models are important tools within the geosciences and frequently used for prediction, communication and decision-making. Predictions are made to determine the location or value of a resource for a given commodity, or to locate geotechnical hazards during engineering and construction projects. These predictions are communicated to decision-makers who then determine whether, e.g., a mine will continue to operate, a reservoir can be developed, a bridge can be built or building commenced. The predictions are typically communicated to the decision-maker in the forms of reports, often with sophisticated 3D visualisation to aid assessment of the issue at hand.

An aspect of 3D geological models (and models in general) that is often not communicated is the inherent uncertainty they contain. The source of this uncertainty is varied and primarily concerns epistemic and aleatoric uncertainty. Measurement errors, data inconsistencies and assumptions necessary when dealing with sparse data are considerations not just particular to geosciences, but many other disciplines (economics, astronomy, biology, medicine, etc.) that attempt to generate models to explain complex natural phenomena. The concepts which drive the initial assumptions are also subject to epistemic uncertainty. The geological structure of a particular region can often be explained by differing hypotheses, and the older the region (with correspondingly less data) the more controversy ensues. For example, much debate surrounds whether modern-day plate tectonic models apply to the Archean Eon (Martin 1999), or do we need to consider other models (Taylor and McLennan 1995).

A useful classification scheme is offered by Mann (1993) who defines three types of uncertainty specific to geoscientific modelling (Figure 10). Type 1 concerns error, bias and imprecision (aleatoric uncertainty), such as error in locating a boundary between rock types (possibly due to GPS inaccuracy or depth mis-estimation), or only collecting the location of a particular rock type, and not others, which would otherwise produce a more accurate model. Type 2 uncertainty concerns interpolation and extrapolation, i.e. making predictions between and away from data points, respectively. Type 3 uncertainty (epistemic uncertainty) concerns imprecise or incomplete knowledge and ambiguities in general, such as whether the unforeseen presence of a geological structure will change the nature of model prediction.

7.2 “New geological model decimates resource”

The recent resource revision of a gold deposit in Ontario’s Red Lake district is an example of the detrimental effects of uncertainty. The “F2” deposit, owned by Rubicon Minerals, was originally assessed to have indicated resources of 4.12 million tonnes grading at 8.52 grams of gold for 1.13 million contained ounces of gold. “F2” was subsequently modelled to have 492,000 tonnes of gold grading at 6.73 grams per tonne for 106,000 contained ounces of gold, effectively a resource downgrade of 91%. The stated issues leading to this significant downgrade are an incomplete understanding of the controls on gold mineralisation (Type 3 or epistemic uncertainty), inadequate drill spacing (Type 2 uncertainty) and an ill-defined drilling strategy that failed to detect the continuity of gold mineralisation (Type 1 or aleatoric uncertainty). The model-based downgrade has had negative effects on the financial position of investors, including the Canada Pension Plan Investment Board, and has resulted in an overall distrust of model utility in estimating resource potential. Part of the “tag” line accompanying the article describing these events (Saywell, 2016) has been used as the title for this section and indicates where some think the blame could be placed. While it is clear that the assumptions and data used in the preliminary 2013 assessment were insufficient, the new 2016 model is touted as “decimating the resource”. Rather, it was the 2013 model that inadequately represented the state of data, knowledge and uncertainty, and over-estimated the resource volume. Without properly representing these aspects of the data and the model, the model can end up being the scapegoat in similar scenarios, and the real problem of uncertainties resulting from data, sampling and model construction and their inappropriate used are left unexamined.

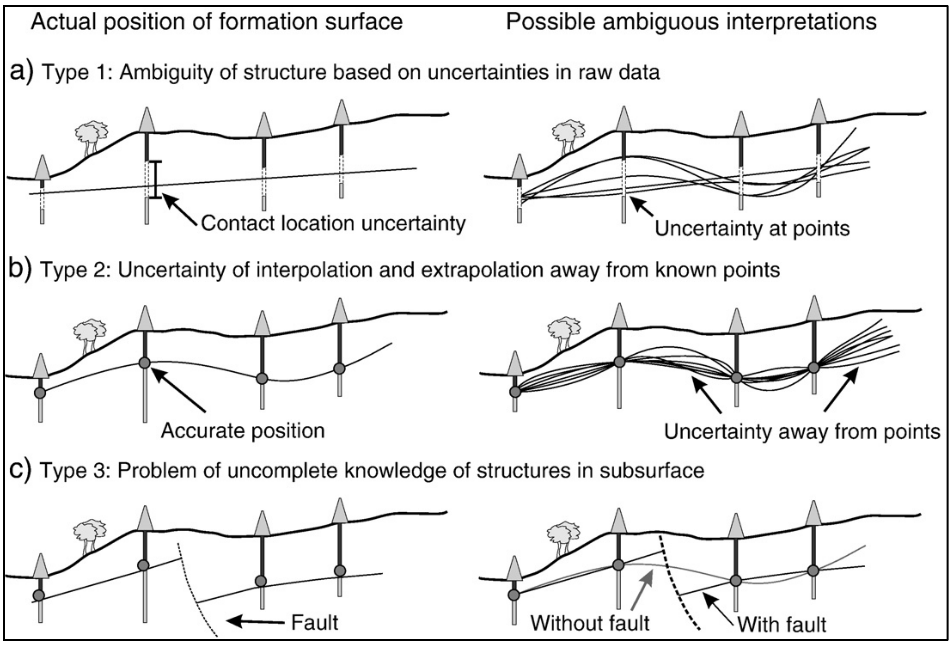


Figure 10: Classification of uncertainties developed by (Mann 1993) and their impact on geological modelling: (a) Type 1 or aleatoric uncertainty — the position of a rock type boundary (or contact) is not well-defined, and possible realisations of the contact based on location uncertainty; (b) Type 2 uncertainty — interpolation and extrapolation away from data points and; (c) Type 3 or epistemic uncertainty — the effect of incomplete knowledge on predicting the location of a contact. Triangles represent the location of wells, the vertical lines extending underneath represent drill paths. From (Wellmann et al. 2010).

7.3 Uncertainty assessments in 3D geological models

Predictions given by geological models constructed from potentially sparse, ambiguous and discrepant data contain uncertainty (Fig. 10). An assessment of these effects would thus be necessary, and recent work (Lindsay et al. 2012; Wellmann et al. 2010) present a method which shows this can be achieved. Firstly, the location and magnitude of the uncertainty is calculated through Monte Carlo simulation, where the data defining each model is allowed to vary within reasonable constraints related to measurement error, and the resulting models are then compared to determine the location and magnitude residuals between model predictions. The residuals, whether large or small, are considered to represent model uncertainty. This leads to an uncertainty assessment that can be communicate to the model builder or decision-maker, who can use the location, magnitude or volume of uncertainty to investigate detrimental sources of uncertainty in the input data and determine solutions to mitigate its effects. The model builder or decision-maker (though preferably together) can use the uncertainty assessment to qualify whether predictions made from the model meet accuracy requirements, and thus how well the model represents the target geology.

While this general procedure is not novel, and is performed in many workflows across disciplines, uncertainty assessments of 3D geological models typically involve a statistical summary of error directly obtained from the input data. This may be in the form of a mean error or standard deviation, possibly normalised when comparing datasets with different scales or units of measurement. Interpolation error can also be obtained if stochastic methods such as kriging are used. The estimates do not provide insight into geometrical or topological variability (Thiele et al. 2016) in the 3D model which may be due to interactions between inconsistent input data in order to answer the question "*should resource exploration an extraction strategies, volume estimates and value assessments use this model?* (Quigley et al., Minerva, in review) "

7.4 Combining geological modelling and uncertainty assessments

The Gippsland Basin is a Mesozoic to Cenozoic oil and gas field in south-eastern Australia (Rahmanian et al. 1990). The 3D model in Figure 11 represents a basement of Ordovician rocks and covers sequences of Oligocene Seaspray and Pliocene Angler formations. The Palaeocene to Late Miocene Latrobe Group, which includes the Cobia, Golden Beach and Emperor Subgroups are prospective for oil and gas (Bernecker et al. 2001), but have also been considered as carbon sequestration sites (Swierczek et al. 2015). The geological structure of the basin is displaced by the NNE to NE-trending Lucas Point Fault, Spinnaker Fault and Cape Everard Fault System, and the E–W trending Wron Wron/Rosedale Fault Systems. The purpose of building this model was to try to understand the structure of the basin and where rock formations are located. Some of the data used to build this model were measured from outcrop, but the majority were derived from geophysical interpretation as much of the basin is submerged in Bass Strait.

Geophysical interpretation is a technique commonly used in the geosciences, where different physical fields are measured from a region of interest and processed so that they reveal the spatial distribution of rock properties, which then can reveal geologic structure. Seismic data records energy as it travels through the earth. Where this energy is reflected, appropriate processing can translate these reflections into images, which a geologist can interpret in order to locate and estimate geometry of rock boundaries and faults (Herron 2011). Similarly, the magnetic and density properties of rocks can be measured and processed to produce images that geologists use to understand the structure of the subsurface. These techniques are necessary when the rocks of interest are covered by sand, vegetation, or in this case, water. Imprecision is inherent in the process and can creep in during each of the stages of surveying, processing and interpretation. The imprecisions have a compounding effect on the accuracy of the model, and thus the accuracy of the 3D model to represent what is known about the location and geometry of the petroleum target.

That models contain uncertainty is widely accepted and forms a central assumption of Lindsay et al. (2012). This is based on the presence of input data errors and that models are a simplification of the natural world. As models are uncertain, it follows that to generate multiple model realisations from a given dataset is a reasonable approach. The 3D modelling approach used the input geological data to interpolate rock boundaries and faults within the volume. From there, a Monte Carlo process was employed where the input data was varied within acceptable constraints simulating aleatoric uncertainty. The varied input data was then used to calculate a new set (or 'suite') of models. Each of the members of this suite of models looked similar, but, when compared with each other, differences could be observed in the location and geometry of rock boundaries and faults. The magnitude of difference (or residual) between the models was calculated and used to visualise and communicate uncertainty. As an example, Figure 11 shows are the Golden Beach and Cobia subgroups (green and red respectively). The prisms represent uncertain locations in the model and are colour-coded according to the magnitude of the residual, and thus uncertainty (lighter blues are low, and darker blues are high). Seismic sections are also shown to highlight the position of model inputs used to construct the model. Such sections provide important data that is interpreted to offer depth constraints for the modelled geology. These data and interpretations are subject to aleatoric and epistemic uncertainty.

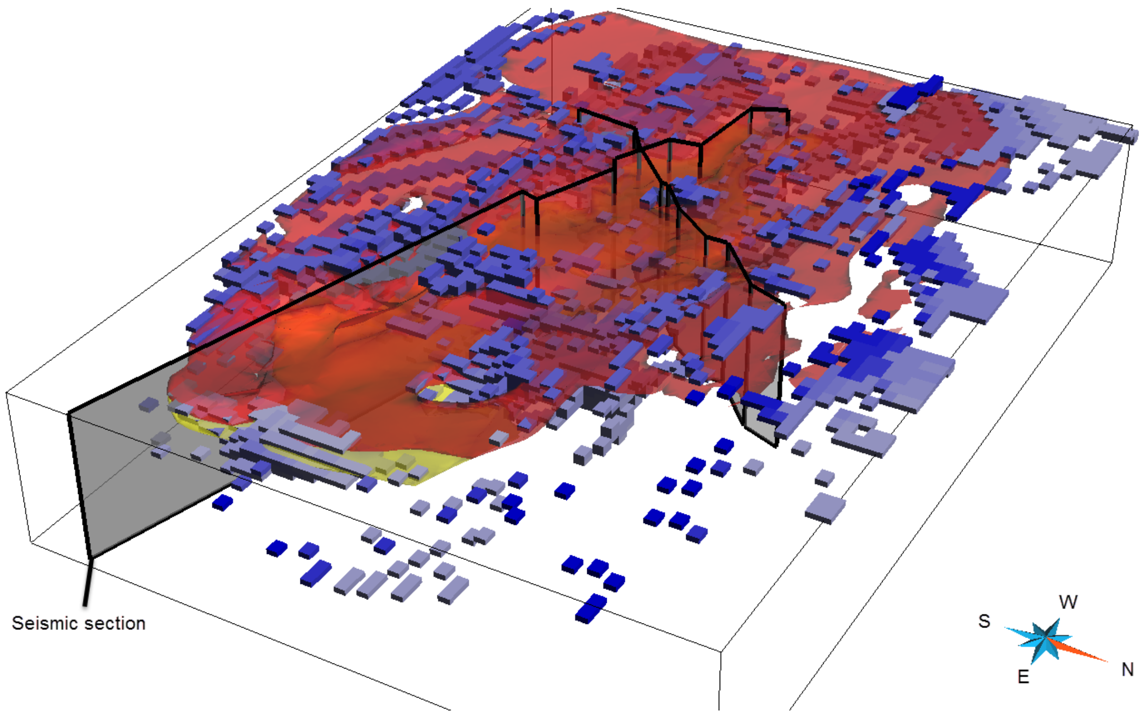


Figure 11: Oblique view looking southwest of the Gippsland Basin model constructed by (Lindsay et al. 2012), showing Golden Beach and Cobia subgroups (green and red respectively) as transparent to aid visualisation. The prisms indicate the location of uncertainty and are colour-coded to represent magnitude (light blue indicates lower uncertainty; dark blue indicates high uncertainty). The location of seismic sections (also transparent for visualisation) are shown as these were important sources of data.

Assessment of Figure 11 clearly shows that a significant amount of uncertainty is located near to or within the boundaries of the modelled Golden Beach and Cobia subgroups. This was initially surprising given the proximity of the modelled rock units to data constraints provided by the seismic sections. Moore and Wong (2002) describes the seismic data and highlights potential issues with an inadequate velocity model that was used in seismic data processing. The velocity model is a critical component in seismic processing, as it defines the velocity a given rock unit will transmit energy from a seismic event and largely determines at what depth a seismic reflection will be placed on an image used for interpretation. Velocity is often measured with a high degree of precision from drill core, however these velocities can vary away from the measured location properties due to heterogeneities within the rock volume. If the estimate within the velocity model is wrong, then the location of a seismic reflection will also be incorrect.

7.4.1 Sources of uncertainty in the Gippsland Basin model and a path to mitigation

Deeper analysis revealed that the depth of the Cobia and Golden Beach subgroups interpreted from the seismic section disagreed with the depths of the same subgroups measured from logged drill core obtained from exploration and production wells. This disparity resulted in greater variability in the location of these units, which was shown as greater uncertainty. The disparity between the seismic and drill core data was compounded in the southern and eastern parts of the model by a lack of data constraints away from the seismic section due to it being a deeper part of the basin. Accurate data is more difficult to obtain in deep locations, wells that would extend to the appropriate depth to sample rocks are very expensive. A lack of geophysical data in the south and eastern regions compounds the sparsity of data. Hope for reducing uncertainty has come in the form of an improved velocity model produced by the Geological Survey of Victoria (McLean and Blackburn 2013). The initial velocity model assumed the velocity structure of the region could be categorised into four rock types with an additional category representing sea water. Each of the four rock types were represented by an average velocity, which assumes no heterogeneity in the rock volume: an assumption likely to be false. The newer edition provides velocities for eight rock units and also allows for heterogeneities within a rock unit to be present. Re-processing of the seismic sections used in this model with the new velocity data would certainly reduce uncertainties in accurately locating seismic reflections on the images used to build the model, and thus rock unit boundaries represented in the 3D model. As these rock boundaries are more accurately imaged, they would likely have less misfit with the depths measured from the well logs, reduce uncertainty in the 3D model and improve confidence in its predictions.

7.5 Summary

That models are uncertain is well-known to anyone who generates or constructs them. The real challenge is appropriately communicating this uncertainty to those who are not intimately familiar with data or modelling methods. The model builder will probably know, purely through familiarity with the project and its data, where the untrustworthy parts of the model are, and can point them out to those who need to know. The extent and magnitude of this uncertainty is much harder to convey and when stakes are high, such as deep-water oil and gas exploration or construction of public infrastructure (tunnels and bridges) a quantifiable uncertainty assessment is needed. In this case study, previous workers had already acknowledged inadequacies in the data and models used in the region, but what effect they had on the accurately predicting 3D structure of the region was not well described. The type of visualisation shown here is simple enough that a lay-person can understand it, and thus could make a more informed decision based on required predictions. The quantification of uncertainty serves other useful purposes. When additional or reprocessed data is added during remodelling, changes in the magnitude of uncertainty can then inform whether the new data was effective. Cost–benefit analysis can follow where the reduction of uncertainty was deemed appropriate for the costs associated with acquiring the new data.

Decision-making, while not enacted by stakeholders in Gippsland Basin oil and gas exploration or carbon sequestration, was simulated in this case study as a proof-of-concept. Potential decisions relating to a reliable representation of the subsurface and thus exploration risk (i) were informed by models, (ii) considered prevailing scientific evidence, (iii) considered scientific uncertainty, (iv) and advocate taking a precautionary approach to uncertainty in resource exploration. The F2 deposit example describes the detrimental economic impact of not taking a precautionary approach to epistemic and aleatoric uncertainty. The method shown in the Gippsland Basin example provides an example of how the effects of uncertainty can be simulated, identified and mitigated if a precautionary approach is taken prior to making exploration decisions. The communication of uncertainty via visualisation of with a 3D geological model was key to providing insight to the source and magnitude of input data errors.

8 Case Study 7: Loads estimation and reporting in the Great Barrier Reef: communication and challenges (Author: PK)

8.1 Overview

The Great Barrier Reef (GBR) is one of the seven natural wonders of the world, but is undergoing significant changes due to global warming, land based pollutant discharge and the recent attacks of the crown of thorns starfish (Brodie 2012; De'Ath et al. 2012; Kroon et al. 2016). A recent publication by Hughes et al. (2017) highlights the main challenges for coral reefs as we move through the Anthropocene era. As stated in Hughes et al. (2017) and Hughes and Cinner (2017), the challenge is to sustain coral reefs for future generations and not just provide temporary fixes to ongoing problems. While the GBR and others like it are in trouble, we cannot “give up” – we need better ways to manage the changes and challenges presented. Solutions need to encompass a broader approach that not only includes the biology but considers the social implications of decision-making. With that comes uncertainty and a need for better approaches and demonstrated examples to communicate these uncertainties that can actively guide governance processes for clearer outcomes and decisions.

Pollutant loads are one of the primary challenges facing the GBR, which supports a highly diverse ecosystem, but strong inter-annual variability makes it extremely difficult to assess progress towards targets (Darnell et al. 2012). Characterising uncertainty helps to understand the temporal and spatial variability in load estimates. Sediment loads, in particular, are a major pollutant source generated from runoff on dryland areas with different degrees of hillslope and gully erosion and variable rainfall amounts and intensities (Jarihani et al. 2017). The GBR lagoon receives runoff from 35 catchments arising from six natural resource management regions along the Queensland coast in Australia. These catchments are responsible for the contributions of nutrients, sediment and pesticides as a result of anthropogenic disturbances (e.g. land clearing, farming practices, grazing, urban and industrial developments) that have occurred increasingly over the last 20 years.

For the past decade, funding through many government led initiatives have focussed on protecting the reef, including trying to halt and reverse the decline of water quality. Initiatives such as the Marine and Tropical Sciences Research Facility (MTSRF) and Reef Rescue along with the Reef Water Quality Protection Plan (Reef Water Quality Protection Plan Secretariat 2009; Reef Water Quality Protection Plan Secretariat 2013) have focussed on long term goals targeting the reduction of pollutants to the GBR lagoon. More recently, the focus for the reef has centred on the impacted coral communities due to global warming and crown of thorns starfish and discussions on various approaches for saving what is considered a dying reef (Brodie 2012). Throughout these various initiatives there has been a collaborative focus between "on-ground" activities, modelling and monitoring to determine sources of pollution. The primary modelling tool that has been used to capture pollutant loads (both sediments and nutrients) across the catchments has been Source Catchments (Armour et al. 2009): a Queensland State Government deterministic model that models catchment processes for sediment and nutrients, using monitoring data at key locations to assist with the calibration of the model. The current version of the model operates at a daily time step, modelling loads at Source Catchments links along a stream network of each catchment. This model was developed from a dynamic version of the Sednet model (Wilkinson et al. 2014), which focusses on mean annual load estimation and attempts to understand the sources and sinks of sediment and nutrients that are generating the load at the end of the catchment. Occurring in tandem, a monitoring program is targeting the collection of water quality and flow at end of catchment sites. The monitoring data is used to support the Source Catchments model, and also provides key information to the annual GBR report card (Queensland Government 2015): an annual reporting framework for conveying the status and trend of pollutant loads entering into the GBR to the community. In a decision-making context, the monitoring and modelling that underpins the report card and the scores that are derived are used to prioritise pollutants in the GBR and its catchments. This in turn is used to prioritise expenditure across regions and within regions. Irrespective of the type of modelling, the GBR report card has never included a quantitative measure of uncertainty. Only recently, has the report card entertained uncertainty as a mechanism for conveying the confidence in the reported loads

(Queensland Government 2015), however this has appeared as a qualitative assessment with no detail in terms of how the measure was obtained, what it means or how the loads can be interpreted in light of the uncertainty. The recent focus on uncertainty has stemmed from two independent reports of the paddock to reef monitoring and modelling program (Bosomworth and Cowie 2016; QAO 2015), where the quantification of uncertainty has been highlighted as a necessary component to reporting. For reporting, load estimates have tended to focus on "end-of-catchment" loads rather than "whole-of-catchment" loads to determine the sources of pollution. For this case study, we focus on whole-of-catchment loads and how information has been both solicited and offered up to decision-makers for the purpose of reporting and decision-making prior to the recent reviews. We discuss how information was disseminated, how it was received and how it could be used more effectively in the future.

8.2 Communication of uncertainty in GBR loads reporting

The communication of uncertainty in GBR loads reporting has failed miserably in recent times despite it being considered an important part of a report card framework (Bosomworth and Cowie 2016; QAO 2015). The often unrealistic timelines imposed on reporting frameworks to demonstrate progress that are heavily weighted by political constraints, makes the process challenging in terms of being able to quantify the uncertainty as well as to communicate it.

The first attempt at quantifying uncertainty in loads arose from a MTSRF funded project, where a statistical methodology was proposed for the quantification of loads (sediment, nutrients and pesticides) with uncertainties using monitoring data. The Loads Regression Estimator (LRE) is a generalized additive model implemented in the R programming language that attempts to mimic the hydrological process of flow at sites that are responsible for the generation of a load (Kuhnert et al. 2012). The method quantifies the uncertainty of the load by considering the uncertainty in the concentration and the flow, where the latter considered uncertainty in the positioning of the flow gauge as well as uncertainty in the flow rate. This modelling approach was used to provide load estimates for the very first GBR report card for end of catchment sites where it was deemed through workshop consultation that Source Catchments could not provide an accurate load estimate alone (Queensland Government 2009). In this exercise, uncertainties from LRE were expressed as 80% confidence intervals and were compared with Source Catchment estimates in an expert setting. Kroon et al. (2012) published the LRE estimates of loads to explore the impact of sediment, nutrient and pesticide loads since human intervention. While load estimates with uncertainties in the form of standard deviations and 80% confidence intervals were conveyed in this paper and offered up for reporting, these uncertainties did not make it into the first GBR report card and subsequent report cards that followed. Why? Put simply, water quality managers found it difficult to understand a standard deviation or a confidence interval.

Further, wide confidence intervals resulted in ambiguity around the estimates and managers were anxious around their potential miscommunication to a non-scientific audience.

Figure 12 compares some of the results shown by Kroon et al. (2012) and compares them to the information used in the 2009 GBR report card. Note, the report card only showed loads for total nitrogen (TN), dissolved nitrogen (DIN + DON), total phosphorous (TP), dissolved phosphorous (DIP + DOP) and total suspended sediment (TSS). This figure shows the 80% confidence interval for the mean annual loads for the Burdekin end of catchment site as estimated by the LRE package and compares this with “current” estimates extracted from Kroon et al. (2012) and used in the 2009 GBR report card (Queensland Government 2009). Without the estimates of uncertainty, we really do not have complete information that provides some certainty around the estimates. For example, take the TSS loads estimate for the Burdekin (right hand panel of Figure 12). The single estimate provided in the 2009 GBR report card was 4.7 million tonnes (Mt) per year (blue square in right panel of Figure 12). However, the 80% confidence interval provided for the LRE estimate of the mean annual TSS load ranged between 1.1 and 15 million tonnes. The wide confidence interval may reflect the amount of data, n, used to generate the interval (n=36) in addition to the complex processes being modelled and their inherent variability associated with it. A decision based on the single number of 4.7 Mt per year could be perceived quite differently to a decision based on an interval [1.1 – 15 Mt], especially if the estimate for the year was closer to the upper bound of that 80% confidence interval. For instance, a wide confidence interval may warrant closer inspection of the site being monitored to understand the cause of the variability in the TSS estimate. Why is the interval so wide? Are there sufficient samples being taken to understand the variability at that site? Should more samples be taken or is this a “hotspot” site and should we look at specific management regimes that may reduce the mean annual TSS load at this site over time?

While an uncertainty measure in the form of 80% confidence intervals was offered up for the 2009 GBR Report card, these intervals never made it into the technical report and instead, histograms showing the mean annual loads were produced to compare pre-European loads with “current” best estimates from Kroon et al. (2012). It was understood that the concept of an 80% confidence interval for a report card was challenging in terms of how it might be perceived by the public, particularly for constituents and sites where confidence intervals were wide.

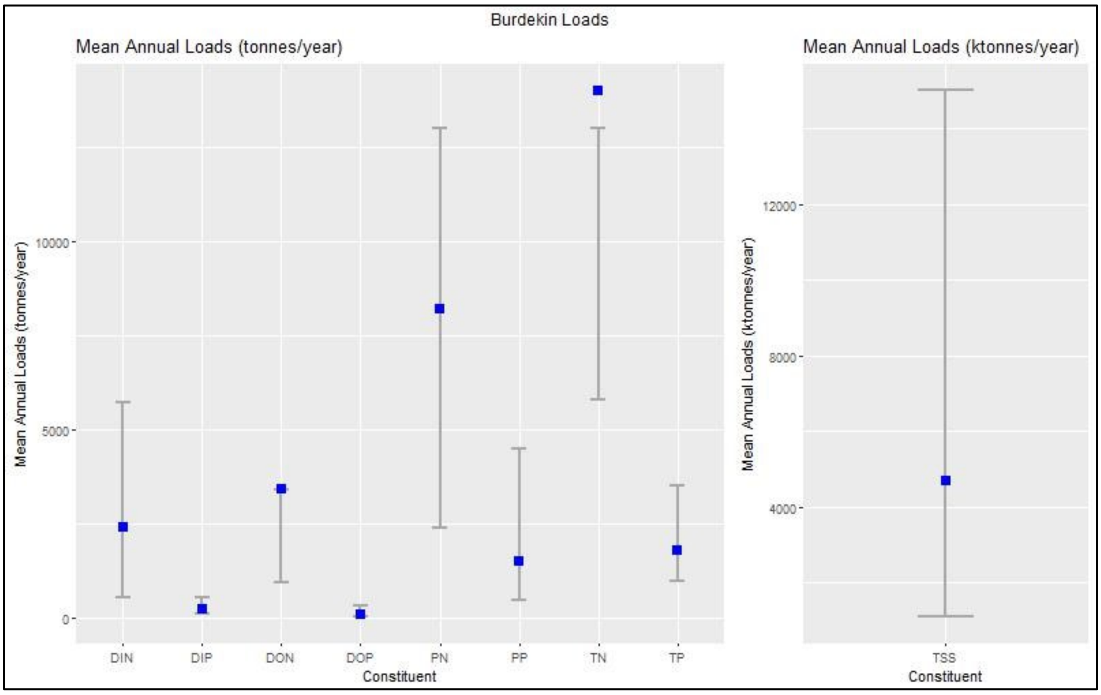


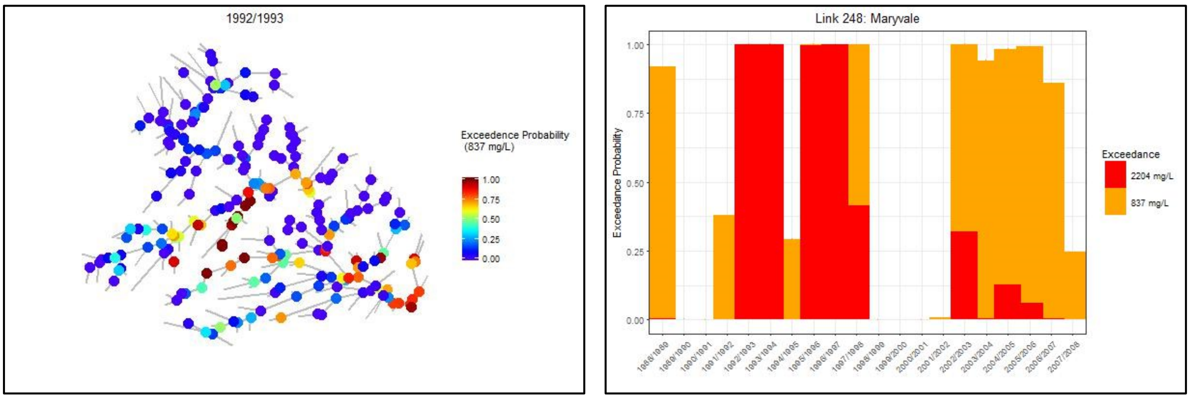
Figure 12: Comparison of mean annual loads for the Burdekin end-of-catchment site used in the 2009 GBR report card and appearing as "Current" estimates, Table 1 by Kroon et al. (2012) (blue square) with estimates produced from the LRE package that show 80% confidence intervals taken from Table 5 by Kroon et al. (2012) (grey lines). Nutrients shown are dissolved inorganic nitrogen (DIN), dissolve inorganic phosphorus (DIP), dissolved organic nitrogen (DON), dissolved organic phosphorus (DOP), particulate nitrogen (PN), particulate phosphorus (PP), total nitrogen (TN), total phosphorus (TP) and total suspended sediment (TSS).

8.3 How should uncertainty assist with decision-making?

While uncertainty provides an assessment of confidence around the estimate being reported, it is a concept that should be used to convey a much wider array of information used by managers to make decisions. As outlined by Kuhnert et al. (2017), uncertainty can be used to inform hotspots for monitoring, setting scientifically defensible targets and prioritising sites that may need immediate attention.

What is the best way to inform managers about which sites to prioritise, where in the catchment monitoring may need to ramp up or slow down, or how to set targets? Kuhnert et al. (2017) propose one approach, which is to express the uncertainty in a manner that managers can easily digest and one example of this is an exceedance probability. Kuhnert et al. (2017) outline how a space-time dynamical modelling approach using Bayesian methods (Gladish et al. 2016) could quantify the probability distribution of loads of total suspended sediment in the upper Burdekin catchment. A nice feature of Bayesian Hierarchical Models (BHMs) is the representation of outputs through a probability distribution. This type of representation allows the output to be summarised in different ways instead of just presenting a point estimate such as a mean with a standard deviation or confidence interval. In the context of loads, an exceedance probability is one statistical measure that may be more palatable for managers as their interest lies with detecting sites where loads are consistently exceeding thresholds of concern, i.e. thresholds that may result in changes to the biodiversity of the reef or increased toxicity levels in the water quality. Again, in the context of loads, exceedance probabilities were calculated for sites within the Burdekin catchment using published concentration thresholds given by Bartley et al. (2012). Once calculated, the exceedance probabilities could be expressed in different ways: spatially, through an exceedance probability map for a specific time period (Figure 7.2a); or a site-based exceedance probability calculated through time (Figure 7.2b). Kuhnert et al. (2017) also show how exceedance probabilities could be used to inform target setting by constructing exceedance probability curves that could be used in an expert setting to determine spatially referenced targets for example.

Why is this information not being used for GBR reporting? The concept of exceedance probabilities is fairly new in the GBR and methods like the one proposed by Kuhnert et al. (2017) are only just appearing in the literature. For this type of approach to be adopted, there is a period of knowledge acquisition followed by a demonstration of the approach to end users to see how this information could be used in practice, not only for reporting but how it impacts on decision making. Further, implementing this approach in practice requires model runs of Source Catchments (Armour et al. 2009), the Queensland State Government catchment model, which then need to be assimilated with monitoring data using approaches such as Gladish et al. (2016) . Finding the time to implement these changes also becomes challenging with changing political environments and priorities.



(a) (b)

Figure 13: Examples of exceedance probabilities calculated for (a) the Upper Burdekin Catchment in 1992/1993 and (b) a Source Catchments link (248) that showcases exceedance probabilities from 1988 to 2008.

8.4 Summary

Uncertainty plays a significant role in the quantification and communication of loads in the GBR. Although the demonstrated need for uncertainties first appeared in 2012 with the development of the LRE approach to loads quantification and more recently, through the review of the P2R modelling and monitoring review, it still has not become an integral part of GBR reporting. Moreover, it has not been considered as a tool for decision-making. Therefore, better approaches are required for communicating uncertainties to decision-makers and be much clearer on what the term “uncertainty” covers. It is easy for managers to look at all the sources of uncertainty and lump them together. However, the reality is that some will incorporate sources of uncertainty that others do not. Improving predictive uncertainty is the key to model improvement as it helps to identify where we need to instigate change and reduce the uncertainty and width of the predictive intervals, thereby improving a manager’s ability to make more informed decisions.

The decisions enacted in this case study are (i) largely informed by science and (ii) align with the prevailing scientific evidence. However, the current framework for reporting and decision-making does not consider scientific uncertainty. Decisions about priority load “hot spots” in the GBR region are informed by models, however these have been deterministic in nature and when model estimates have been accompanied with uncertainty estimates, these have been removed due to the difficulty in their interpretation or the concern about what large standard errors (or wide confidence intervals) actually mean. This has led to decisions that are precautionary in nature and often not useful for mitigating the effects of pollutant loads.

9 Summary of findings

This study presents detailed descriptions of case studies in the earth and environmental sciences, pertaining to the communication of scientific evidence (data, models, expert opinions) to decision-makers in cases involving risk and uncertainty. Scientific evidence may enter decision-making processes via diverse pathways, ranging from direct solicitations by decision-makers to scientists (e.g., case studies 1, 2, 5, 7) to requests from stake-holders to intermediate agents tasked to engage science communities (case study 2) to independent requests from stake-holders directly to scientists (e.g., case studies 1). The latter is evidenced to be stimulated by external factors, such as media coverage of research that affected parties perceived to be relevant to their circumstances (e.g. case study 1, 5). Acquiring highly specialized, pertinent scientific data of direct relevance to specific aspects of decision-making may not always meet the expedient demands of decision-makers (case studies 1, 3, 4, 5, 7); in these cases, decision-making may be incremented (e.g., case study 1) or delayed (e.g., case study 1), use scientific expertise and judgement to assist in decision-making with large epistemic (case study 1, 3, 4, 5, 6) or aleatoric uncertainty (case study 6), and provide opportunities for adjustment of decisions as additional information becomes available (case study 1, 5). If the likelihood of occurrence of potentially adverse future risks is perceived by decision-makers to exceed acceptable thresholds and/or be highly uncertain, precautionary decisions with adaptive capacity may be favoured, even if some scientific evidence suggests lower levels of risk (e.g., case study 1, 3, 5, 7). The efficacy with which relevant scientific data, models, and uncertainties contribute to decision-making may relate to factors including the expediency with which this information can be obtained (case study 1, 2, 3, 7), the perceived strength and relevance of the information presented (case study 1, 5, 7), the extent to which relevant experts have participated and collaborated in scientific messaging to decision-makers and stake-holders (case study 1, 5, 7), and the perceived risks to decision-makers of favouring earth science information above other, potentially conflicting, scientific and non-scientific inputs (case study 7, 5). The establishment of science provision teams and mechanisms that enable researchers with sufficient expertise and knowledge to collaborate and communicate internally, and with decision-makers and stakeholders, is viewed as a highly favourable aspect that should be further promoted.

To exemplify parallel findings and differentiations between the case studies in relation to the decisions enacted, we summarize the results from each case study in Figure 14 in terms of whether decision-making was (i) scientifically informed, (ii) aligned with the prevailing scientific evidence, (iii) considered the available knowledge on scientific uncertainty, (iv) informed by models, and (v) precautionary in nature. All decision-making was informed by science, but the utility of relevant and available models in decision-making varies. These case studies, drawn from scientists working across the earth sciences on topics as diverse as natural disasters, agriculture and the environmental impacts of mining, demonstrate many similarities in the communication of uncertainty to decision makers. Despite the different motivations for seeking scientific input, uncertainty was a factor for consideration at least partially in all cases. In contrast, the adoption of a precautionary approach and the use of models differed between case studies due to the different requirements of the decision-making process. Science is inherently uncertain, we anticipate that consideration of uncertainty will be increasingly part of the communication of scientific knowledge to decision makers. These case studies also demonstrate that systematic and standardised approaches to communicating uncertainty will benefit scientists and decision makers.

Case Study	Criteria (i) **Informed by Science**	Criteria (ii) **Aligned with Prevailing Science**	Criteria (iii) **Considered Uncertainty**	Criteria (iv) **Informed by Models**	Criteria (v) **Precautionary**
1	yes	yes	partially	yes	yes
2	yes	yes	yes	yes	yes
3	yes	yes	no	yes	yes
4	yes	yes	partially	partially	yes
5	yes	no	yes	yes	yes
6	yes	yes	partially	yes	partially

7	yes	yes	partially	no	no

Figure 14: Summary of science utility and decision-making aspects for the presented case studies

10 Acknowledgements

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